Transfer of the Interlaminar Shear Test to Veneer Layer-based Composites for Qualitative Evaluation of Layer Adhesion

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This study aimed to investigate the suitability of the interlaminar shear (ILS) testing method for veneer-based composites. The ILS testing method is an established method for composite materials as a qualitative evaluation of the adhesion within the composite. The applicability of this method to veneer based composites enables a simple qualitative statement on the adhesion of the individual layers. The ILS method complements existing wood-based material tests that focus on bonding, using significantly smaller material dimensions.

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INTRODUCTION

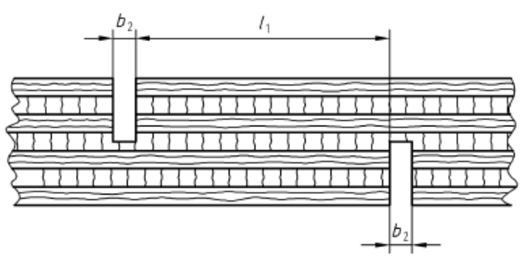
Wood and wood-based materials are established materials for a wide range of applications, especially in furniture and interior decorations (Marutzky and Sauerwein 2008). The strong material properties of wood are of increasing interest for new applications and processes, in part due to the sustainability of wood. In particular, veneer-based materials have been studied due to their flexible structure and exploitation of the inherent material properties (Eckardt and Eichhorn 2010; Kohl *et al.* 2014; Berthold 2016; Jost *et al*. 2018; Müller *et al.* 2020; Pramreiter *et al.* 2020; Heyner *et al.* 2021; Weißenborn *et al.* 2021). The use of veneer-based materials in new applications and processes has increased in recent years (Denes *et al.* 2017; Lignotube 2022; Lignoa Leichtbau 2021).

The technical term for wooden structures having a minimum of three bonded veneer layers is veneer layer products. Veneer layer products can be classified as plywood or laminated veneer depending on the orientation. Veneer plywood with a locked structure - a fiber orientation of 0/90 degrees - is called plywood (Bodig and Jayne 1993). In the case of laminated veneer, the fiber orientations of the individual veneer layers are in a parallel direction. Standard plywood usually has a veneer thicknesses of 1.3 mm and a total thickness of 6.5 to 12 mm (Marutzky and Sauerwein 2008).

The approach of combining veneer layers and adhesive is being adopted for new applications and processes. Therefore, variation possibilities of veneer thicknesses, orientations, and adhesive can be regarded as outside of the standard definition. Thinner veneers and alternative adhesive systems can be used. The veneer-based composites are built up to meet the requirements, similar to the laminate structure of fiber-reinforced composites. Accordingly, the new veneer-based materials are processed for other application areas (Feig and Eichhorn 2016; Lignoa Leichtbau 2021) and processing methods other than ordinary veneer plywood (Lignotube 2022).

The veneer layer structure is designed to resist the load, and the veneer thickness and ply angle vary according to the requirement to open these new applications. Therefore, the veneer fiber direction is in orientation of the load direction. These new applications are also accompanied by new demands for the adhesive. It is essential that these new material combinations of veneer and adhesive can be qualitatively tested with respect to adhesion for the intended use. In addition to investigations on the suitable adhesive selection, influences of process parameters on the adhesion properties of the bond are also relevant. The current bonding test methods that are used for testing plywood bonding are outlined by Bekhta *et al.* (2012). The ability to test small geometries effectively is of great interest for the selection of material variations for novel veneer-based composites or multi-material veneer laminates.

The EN 314-1 (2004) standard is used to test the bonding properties of plywood. This standard enables the classification of the plywood boards into different bonding classes according to the determined tensile strengths. The EN 314-1 (2004) standard is valid for the testing of plywood samples with three to nine plies. For testing, the specimens are cut on the surface (Fig. 1) and then tested in a tensile test device. This standard is not suitable for quality testing of the bonding of the novel veneer-based composites. Surface cutting is not reproducible possible for veneer thicknesses below 1.2 mm without damaging the lower layers.



b_2 2.5 mm to 4 mm (width of saw cuts)
l_1 ± 0.5 mm (length of the shearing surface)

Fig. 1. Test specimen cuts according to the EN 314-1 (2004) standard

Based on the tensile test, the EN 789 (2005) standard is used to determine the shear strength of laminated wood. To measure the shear strength of laminated wood, steel plates must be applied to the sample for preparation. This preparation is very elaborate and unsuitable for small samples. The influence of the adhesive used to apply on the steel plates on the test specimen is unclear.

This investigation aimed to find an easily manageable quality test for the evaluation of bonding within veneer-based composites. The test application was designed for the development process (material variation) and the series production process (quality assurance) for novel veneer-based composites. Test methods were established to evaluate adhesion within the composite exist for fiber-reinforced composites. The interlaminar shear (ILS) testing method is an established method for composite materials as a qualitative evaluation of the adhesion within the composite (Fig. 2). In order to use simple test specimens with small dimensions, the ILS test method lends itself as an alternative test method for veneer-based materials. The ILS test method is advantageous because a small sample can be taken from the manufactured plates in the series process, and no complex sample preparation is necessary.

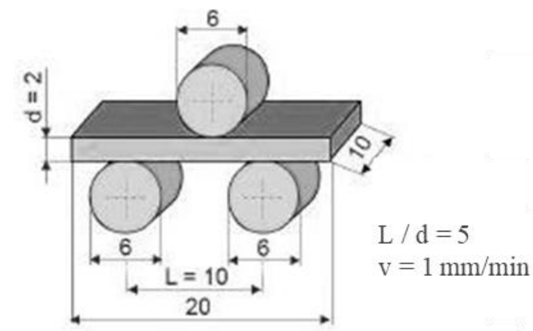


Fig. 2. The ILS test setup according to the EN 2563 (1997) standard (Grellmann and Seidler 2015)

EXPERIMENTAL

Basic Consideration

For a better understanding of the methods, the basic principles of the 3-point bending test and the ILS test are explained. The main difference between both tests is the distance between the supports. This causes different stresses to occur within the samples.

In the 3-point bending test (Fig. 3), the specimen bends in the *z*-direction due to the central force application (*F*). This leads to tensile (σ^+) and compressive stresses (σ^-) in the load application area of the specimen. The failure of the specimen occurs on the tensile side of the specimen (Fig. 4). The specimen properties were tested according to the ISO 14130 (1997), DIN 52186 (1978), and EN 310 (1993) standards. The shear stress reaches its maximum in the area of the neutral plane and has a parabolic distribution function (Fig. 3). To avoid impermissible shear stress influences, a defined support/thickness ratio of L/h = 16…20 must be applied in the bending test, which is specified in the corresponding ISO 14130 (1997), DIN 52186 (1978), and EN 310 (1993) standards. Due to the shear sensitivity of laminates, the bearing distance should be larger. The bearing distance as specified in the EN 310 (1993) standard is an L/h ratio equal to 20 to 25.

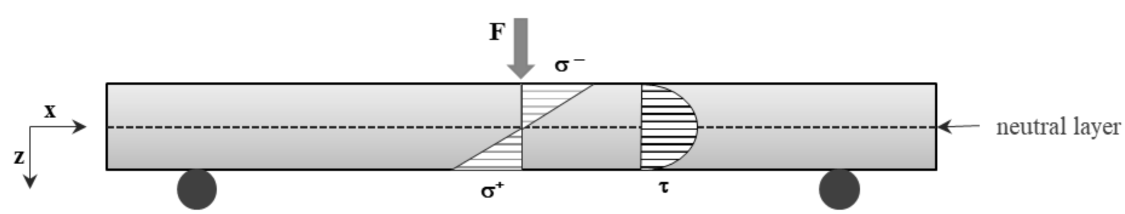


Fig. 3. The 3-point bending figure illustrating the force application and stress

Fig. 4. The failure mode bending

The ILS test uses the approach that with a small bearing distance and lower deflection in the bending test, the shear stress is the main influence. Therefore, the shear stress due to bending at a low bearing distance will lead to failure in the ILS test and not the tensile stress on the underside of the specimen as in the bending tests (EN 2563 (1997), ASTM D2344 (2000), ISO 14130 (1997), DIN 52186 (1978), and EN 310 (1993)). As a result of the acting force, the specimen is exposed to shear stress in the neutral plane, which leads to shear failure (Figs. 5a and 5b), in accordance with the EN 2563 (1997) standard. The test can be conducted according to the ASTM D2344 (2000), EN 2563 (1997), or ISO 14130 (1997) standards. The standards differ in the support/thickness ratio, the specimen length, the support dimensions, and the test velocities. As result of the ILS test, an apparent interlaminar shear stress is determined. Due to the superposition of compressive and shear forces during the short bending test, no absolute shear strength can be determined, but an apparent shear strength is determined (Berg *et al.* 1972; Adams and Lewis 1994; EN 2563 1997; Thielicke 1997; He and Makeev 2014). The apparent interlaminar shear strength is the maximum shear stress in half the thickness of the specimen at the time of the first failure (EN 2563 1997). The apparent interlaminar shear stress (τ) can be calculated according to Eq. 1,

$$\tau = \frac{3 \times F_{max}}{4(bh)} \tag{1}$$

where τ is the apparent interlaminar shear stress (MPa), F_{max} is the maximum force (MPa), h is the specimen thickness (mm), and b is the specimen width (mm).

Therefore, the ILS test is a quality test for the qualitative identification of the adhesion of the fiber-matrix composite (Adams and Lewis 1994; EN 2563 1997; Ganesan 2008; He and Makeev 2014). Considering the basic considerations above, this study considered three questions. First, is the ILS test also suitable as a quality test for veneer-based composites? Second, does shear occur in the adhesion plane according to Fig. 5a? Finally, is there a limit value for measuring when the adhesion content is high or low?

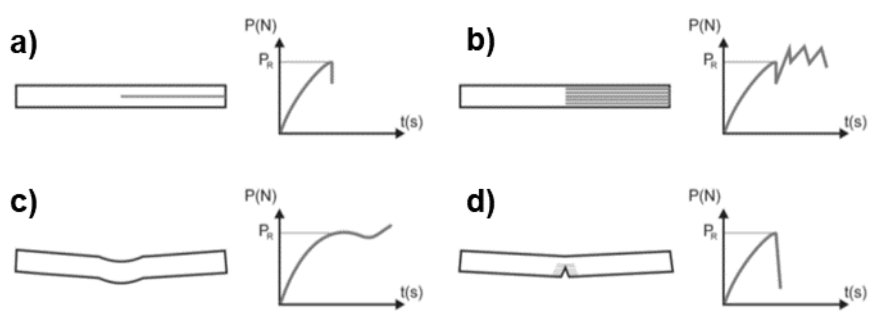


Fig. 5. Typical failure modes of a) shear failure in one plane, b) shear failure in several planes, c) inelastic deformation, and d) bending fracture after the short beam test (EN 2563 1997)

Methods

Concerning the considerations of the introduction, the bending and ILS test methods were conducted comparatively. To evaluate the layer adhesion, two-layered veneer composites with different adhesives were investigated. Two different thermoplastic films were chosen, a thermoplastic film optimized for wood adhesion (hotmelt) and a thermoplastic film without any adhesion promoters (bio-based polyethylene). Accordingly, the expected adhesion of the veneer layers with polyethylene was lower than with the hotmelt. The layers were bonded to the veneer composite by pressing with a Höfer H50 press (Höfer Presstechnik GmbH, Taiskirchen, Austria).

One thermosetting adhesive was investigated comparatively. Therefore, an industrial laminated veneer lumber (LVL) product made of European beech (BauBuche Panel; Pollmeier Massivholz GmbH & Co. KG, Creuzburg, Germany) was used. These samples were ground with a glue line in the middle to a sample thickness of approximately 2 mm. All the samples had a nominal thickness of 2 mm. An overview of the materials that were used in the tests can be seen in Table 1. One layer of sliced European beech veneer (*Fagus sylvatica* L.) with a thickness of 2 mm was used as a reference (native veneer). Two layers of sliced European beech veneer without bonding were used as a reference for the bonded two-layer series (native veneer 2 mm × 1 mm). Two layers of sliced European beech veneer were bonded with a thermoplastic biobased polyethylene film (Bio PE SHC 7460; Braskem, São Paulo, Brazil). The layers were bonded by pressing at 190 °C for 2 min at 1 MPa and labeled as “BioPE.” Two layers of sliced European beech veneer were bonded with an industrial hotmelt film based on modified polyolefins (Pontacol 20.800; Pontacol AG, Schmitten, Switzerland). The layers were bonded by pressing at 90 °C for 2 min at 1 MPa and labeled as “Hotmelt.” Industrial LVL based on 1.2 mm veneer layers (peeled veneer) was ground to a thickness of 2 mm, and the two layers of veneer and the phenol resin were bonded to create the “Phenol resin” specimen.

Table 1 shows the test series of both test methods, including the geometry and the test conditions. All the bonded samples were cut with the saw into the test dimensions (length × width). All the native samples were manufactured by a laser (Lasermax Maxi 1390; Winter Holztechnik GmbH, Leipzig, Germany). The samples were conditioned and tested at a temperature of 20 °C and a relative humidity of 65%.

Table 1. Sample Overview

Test	Sample Name	No. of Layers	Density (g/cm³)	Sample Thickness (*h*) (mm)	Sample Width (*b*) (mm)	Sample Length (*l*) (mm)	Bearing Distance (*L*) (mm)	No. of Samples
Bending	Native veneer	1	0.60	2.17	10	45	40	20
	Native veneer (2 mm × 1 mm	2	0.61	2.06	10	45	40	20
	BioPE	2	0.66	2.01	10	45	40	20
	Hotmelt	2	0.64	2.04	10	45	40	20
	Phenol resin	2	0.81	2.19	10	45	40	16
ILS	Native veneer	1	0.62	2.17	10	20	13	13
	Native veneer (2 mm × 1 mm	2	0.61	2.06	10	20	13	13
	BioPE	2	0.66	2.01	10	20	13	10
	Hotmelt	2	0.64	2.04	10	20	13	10
	Phenol resin	2	0.83	2.15	10	20	13	13

The tests were conducted with a Hegewald and Peschke Inspekt 10 testing machine (Hegewald & Peschke, Nossen, Germany). The length side of the samples were oriented in the parallel fiber direction of the wood. The bonding of the samples was checked before testing under the microscope, especially the quality of the edge areas (Fig. 6). For each series, the displacement of five samples was measured with an optical displacement measuring system using ARAMIS software (GOM, Braunschweig, Germany) to detect the displacement of the edges as a result of the shear failure. For the other specimens, the displacement was determined *via* the traverse distances of the testing machine. The results were statistically evaluated using the analysis of variance (ANOVA) method at the 5% significance level.

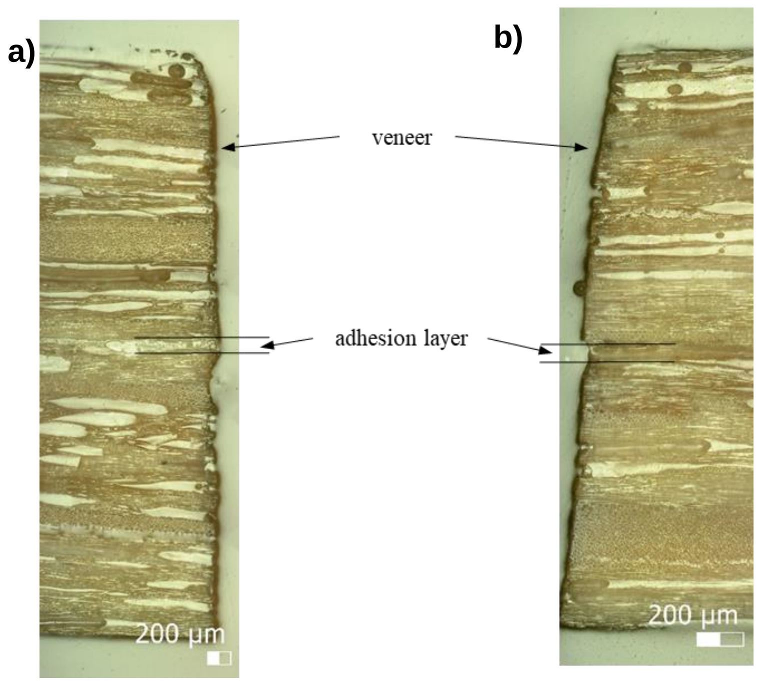


Fig. 6. The bonded a) BioPE and b) Hotmelt test samples before testing

Bending test method

The dimensions of the samples are shown in Table 1. The length (l) was equal to 20 × thickness + 3 mm (according to the DIN 52186 (1978) standard). The width was 10 mm, and the thickness approximately 2 mm. The bearing distance was equal to 20 × h which was equal to 40 mm. The supports had a diameter of 6 mm, and the test velocity was 2 mm/min. The native veneer samples have production-related surface cracks. They were positioned facing upwards.

The determined values were force (F) and deflection (w). The deflection was determined to prove the requirement of low deflection compared to the specimen thickness (Grellmann and Seidler 2015). The bending stress (σ) was calculated as the quotient of the bending moment and the section modulus of the sample (Eq. 2). The bending stress of a rectangular sample cross-section and center force (F) application with the bearing distance can be calculated according to Eq. 2,

$$\sigma = \frac{3\times F\times L}{2\times b\times h2} \qquad (2)$$

The ILS test method

Due to the handling dimensions (width of 10 mm) and the larger load application area (support of 6 mm diameter), the EN 2563 (1997) standard was selected as the setup for the investigation (Fig. 2). The sample dimensions were 10 mm × 2 mm × 20 mm (width × thickness × length). The supports had a diameter of 6 mm, and the test velocity was 1 mm/min.

The bearing distance was equal to 5 × h, as shown in Table 1. The determined values were F and w. The deflection was considered comparatively to the bending test. The apparent shear strength (τ_{12}) was calculated according to Eq. 1.

RESULTS AND DISCUSSION

Bending Test

The determined deflection and bending strength values are shown in Table 2. The deflection was in the same range for all the bonded samples, between 2 and 3 mm. The value of the deflection was in the range of values of the sample thickness, except for the unbonded veneer series. The deflection of the two layers veneer without bonding was much higher (Fig. 7). The higher deflection was expected considering the absence of bonding.

Table 2. Results of the Bending Test

Sample Name	Density (g/cm^3)	Bending Strength (MPa)	Deflection (mm)
Native veneer	0.60	98.60	2.30
Native veneer (2 mm × 1 mm	0.61	54.91	5.17
BioPE	0.66	121.79	2.56
Hotmelt	0.64	109.01	3.12
Phenol resin	0.81	144.50	2.30

The determined bending strengths are shown in Fig. 8. The determined bending strengths varied, and the strength of the unbonded series was the lowest. The determined bending strength of the native veneer was in the range of the bending strength of solid wood with 90 to 120 MPa (Sell 1997; DIN 68364 2004). The Hotmelt series was in the same strength range as the native veneer. There was no significant difference in the strength properties. The BioPE series had slightly better strength properties than the native veneer and Hotmelt specimens. A significant difference was verifiable, even though the strengths values were similar. Therefore, a differentiation of the thermoplastic series is possible. The BioPE series had a higher value than the Hotmelt series. Considering the lower adhesion of the BioPE to the wood without adhesion promoter, this result was not comprehensible. The strength value of the phenolic resin series was significantly higher than all the other series.

Finally, the bending strength as an indicating factor of the adhesion can already provide information about the bond. In relation to the varying strengths, it can be concluded that the unbonded samples (native veneer 2 mm × 1 mm) with the lowest strength also had the lowest adhesion. In addition, the phenol resin samples with the highest strength also had a higher adhesion than the other samples.

A further differentiation of the thermoplastic samples is not definitely possible because the results cannot be plausibly explained. No overall statement on the quality of the adhesion can be given.

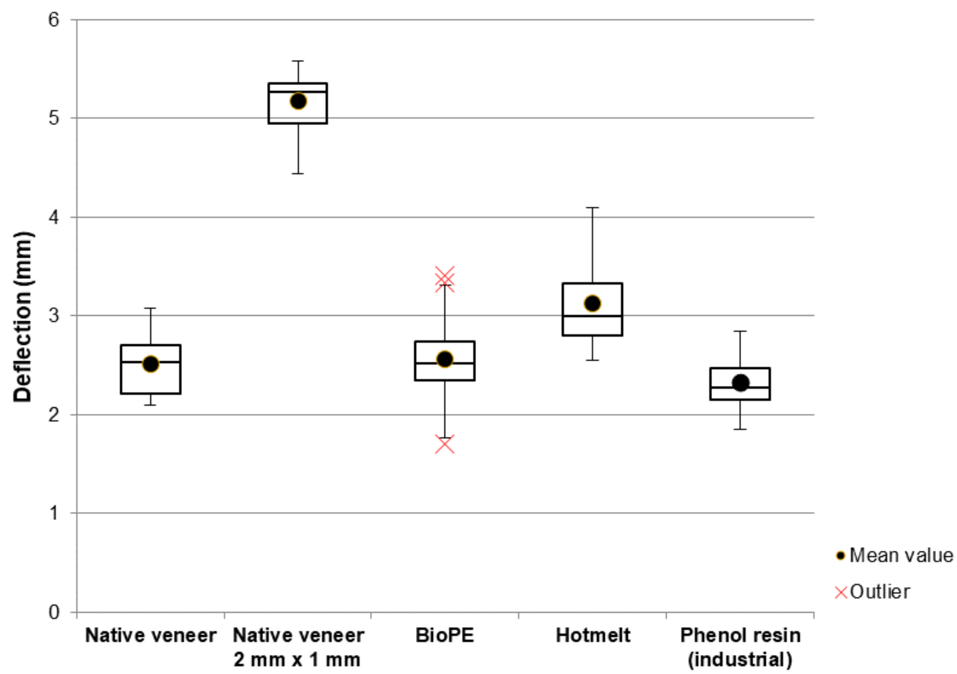


Fig. 7. Deflection bending properties of the different samples

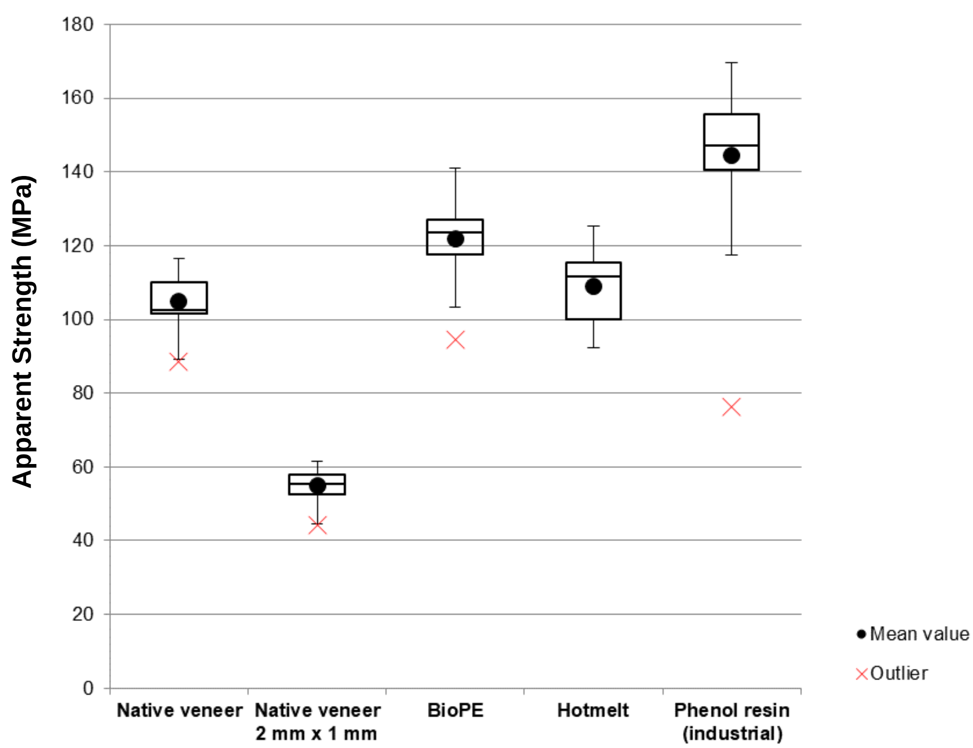


Fig. 8. Bending strength properties of the different samples

ILS Testing

The determined results of the ILS test are shown in Table 3. To verify the shear effect in the samples and to measure the resulting displacement of the edges, the ILS tests were partly carried out with the ARAMIS optical displacement measurement system (GOM, Braunschweig, Germany). The maximum shear stress in the adhesive layer plane could clearly be shown in the bonded samples (Fig. 9). As the result of the shear stress, the bonded specimens failed in the adhesive layer plane (Fig. 5a). Figure 10 exemplifies this with a BioPE image after failure. The shear failure is visible through the non-closed speckle pattern. The displacement of the edges is also clearly visible. In some cases, the shear failure (Fig. 5a) was followed by a bending failure of the remaining sample (Fig. 5d). The resulting fiber breakage was visible on the undersides of the samples.

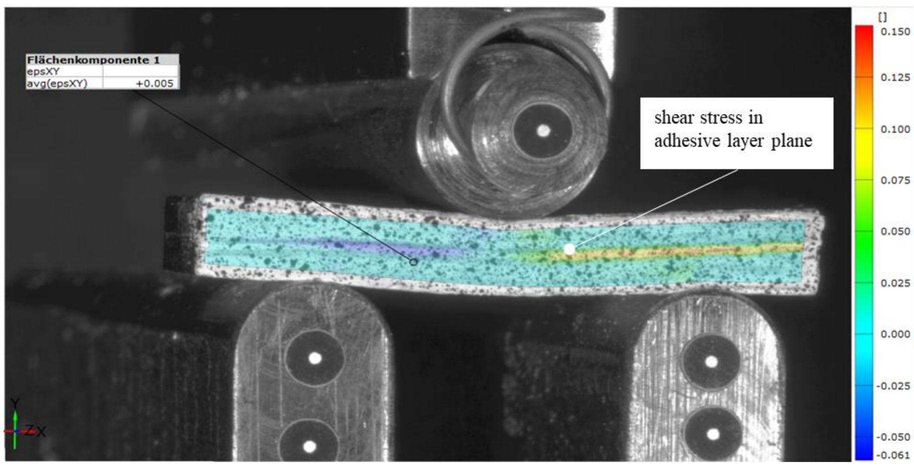


Fig. 9. ILS test of the BioPE sample illustrating the shear stress in the adhesive layer-plane

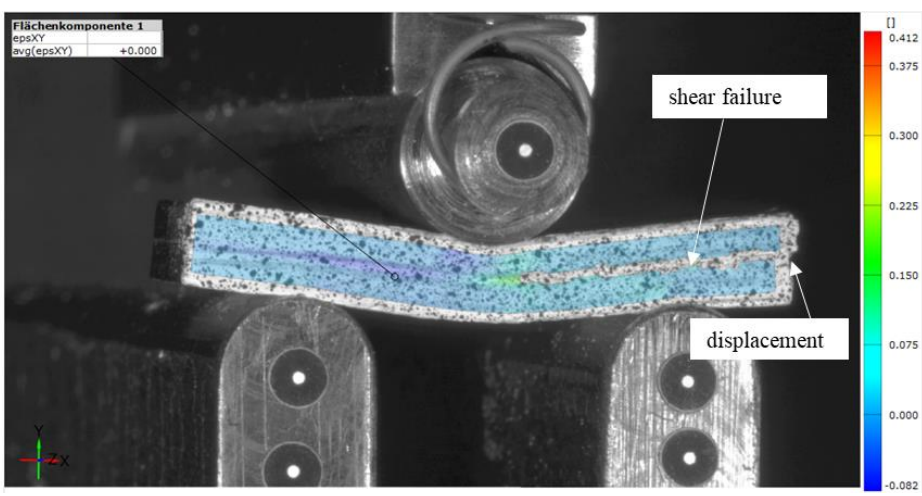


Fig. 10. ILS test of the BioPE sample illustrating the shear failure in the adhesive layer-plane

The native and unbonded series showed bending failure of the samples (Fig. 5d). The apparent interlaminar shear strength cannot be taken from these values. The tests of the bonded specimens fulfilled the standard's requirement that shear failure occurs in the adhesive layer plane (Fig. 5a). Accordingly, the ILS value can be determined for these series, although the ILS value for the native veneer and the unbonded specimens was not valid and was used here for reference purposes only.

The determined deflection of the ILS test was low compared to the sample thickness for all the sample series and lower than the bending deflection. The deflections of the series were similar, with values that ranged from 0.6 to 0.9 mm (Table 3 and Fig. 11).

The determined apparent interlaminar shear strengths varied significantly (Fig. 12). The interlaminar shear strength results allowed a direct, differentiated conclusion about the adhesion. As expected, the unbonded samples had the lowest shear strength. Although this value did not conform to the apparent shear strength, it clearly exhibited the lowest adhesion of the unbonded samples. The calculated value of the apparent interlaminar shear strength of the native veneer was 11.37 MPa. All the bonded series had higher values. The phenol resin series had the significantly highest value at 14.80 MPa. This result conformed to the results from the bending test. A differentiation of the thermoplastic bonding is possible. The BioPE specimen with an interlaminar shear strength of 12.27 MPa had a significant lower adhesion than the Hotmelt specimen, which had an interlaminar shear strength of 13.10 MPa. This corresponds to the theoretical expectations of bonding-quality, although these strength values were similar.

Table 3. Results of the ILS Test (*Bending Failure)

Sample Name	Density (g/cm^3)	Apparent Interlaminar Shear Strength (MPa)	Deflection (mm)
Native veneer	0.60	11.37*	0.82
Native veneer (2 mm × 1 mm	0.61	8.68	0.79
BioPE	0.66	12.27	1.13
Hotmelt	0.64	13.10	1.09
Phenol resin	0.81	14.80	0.75

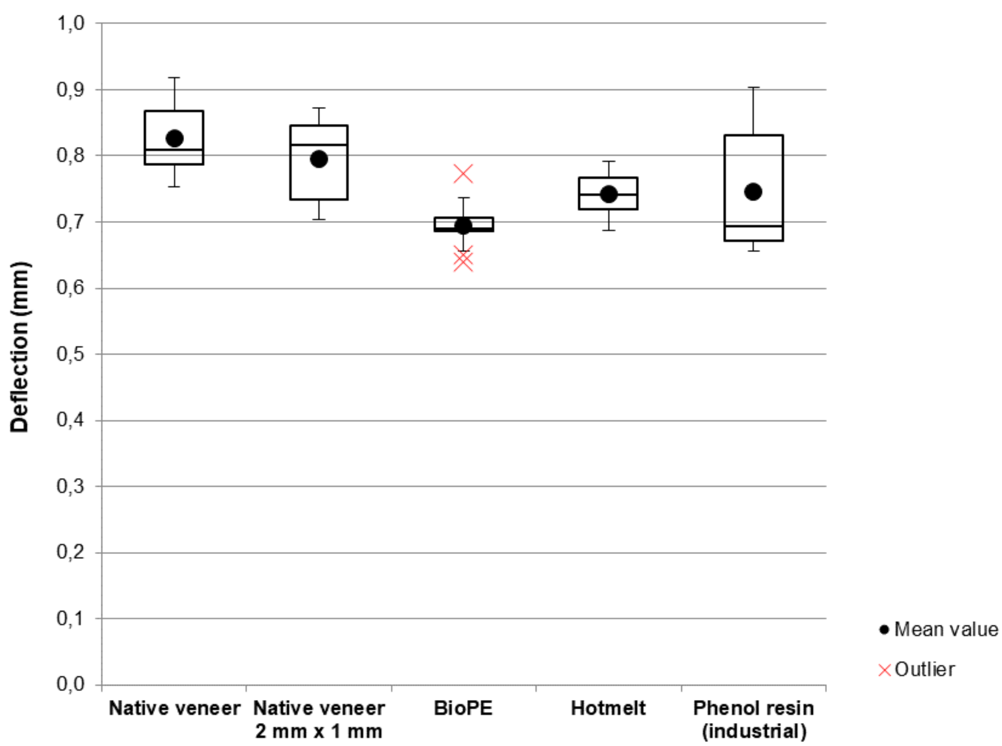


Fig. 11. Deflection properties of the different samples with the ILS test

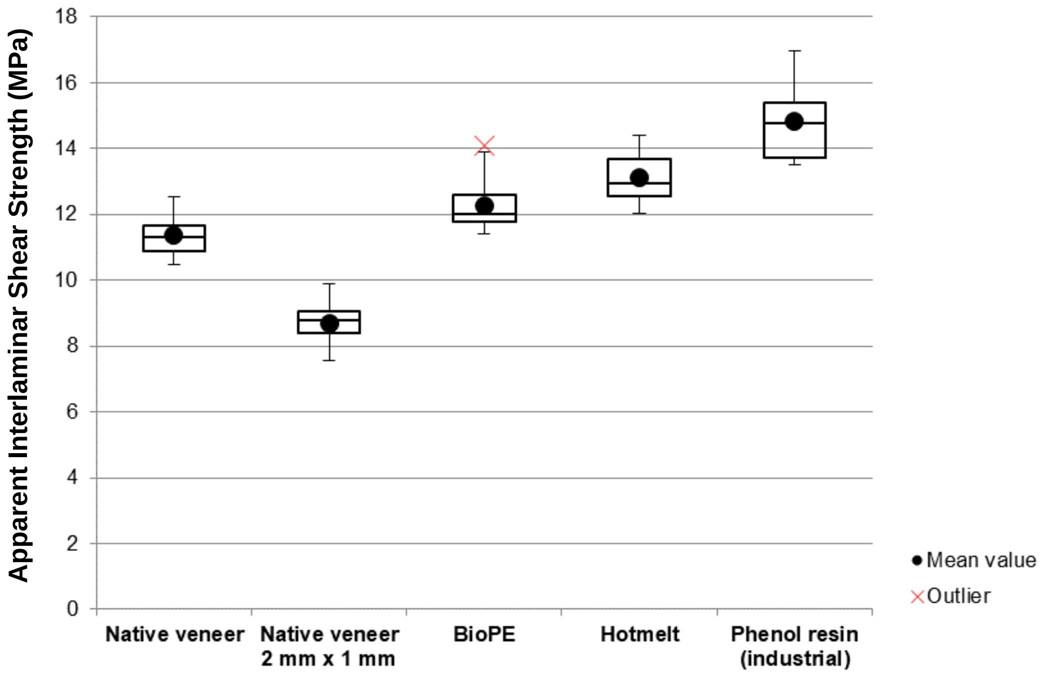


Fig. 12. Apparent interlaminar shear strength of the different samples

It can be concluded that the ILS test allows a qualitative comparison of the adhesion. A limit value that categorizes a certain result as offering sufficient adhesion or not is a question of reference. For the approach, the adhesion should reach the value of the native veneer, such that all adhesives are suitable. In case a comparison of adhesives should be conducted, the method is also suitable. In this case, the phenolic resin specimen was adequate. The thermoplastic adhesives differed slightly but significantly. The better thermoplastic adhesive in comparison was the Hotmelt specimen. Finally, the comparison and the statement on the limit value is a question that the user must decide.

CONCLUSIONS

1. The interlaminar shear (ILS) test is suitable as a quality test for veneer-based composites. The ILS test allows a clear quality statement with simple test specimens that can be applied to veneer-based composites with a thickness of 2 mm. A shear load in the adhesive plane was demonstrated in the ILS test according to the conditions of the EN 2563 (1997) standard. All of the determined apparent shear strengths were differentiated enough to provide definite quality statements.
2. The tests of the bonded specimens fulfilled the ILS standard's requirement that shear failure occurs in the adhesive layer plane (Fig. 5a). In some cases, the shear failure (Fig. 5a) was followed by a bending failure of the remaining sample (Fig. 5d).
3. There is no absolute limit value for evaluating adhesion. It is a quality test that enables the evaluation of adhesion in comparison. It is possible that the user defines an individual reference value as the limit value. Different scenarios related to that are possible. For example, if there is a quality requirement with an exact value, then this

value could be used as a limit value. A bonded reference material can also be tested as a reference, and the determined value of the reference material can be taken as the limit value. An absolute reference value can also be defined such as the limit value specified in the EN 204 (2016) standard with 10 MPa of force. Such an absolute reference value still must be verified.

4. The bending test with the determined bending strength can also result in a criterion as an indicating factor of the adhesion. It should be noted that in the bending test, a combination of bending and shear loads, can lead to failure. For a qualitative comparison of the adhesion of the adhesives, a firm statement is possible with the ILS testing method. This is not possible with the bending strength.
5. The ILS method complements existing wood-based material tests that focus on bonding, using significantly smaller material dimensions. The applicability of the ILS testing method to thicker veneer-based composites whose thickness differs from the EN 2563 (1997) standard has not been clarified.

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