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# Bond Strength of Wood Adhesives: The Sensitivity of Standard Test Methods to Imperfections

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**Abstract**

The aim of this paper is to highlight some drawbacks and uncertainties related to possible imperfections associated with the use of key European and American standard test methods on shear strength measurement of wood adhesive bonds. For this purpose, a brief introduction is provided on adhesive bonding of wood materials and relevant failure modes under shear stress. Two standardized test methods for measuring the shear strength of wood adhesives are introduced, followed by a discussion around the drawbacks and imperfections related to the practical application of the two test methods. Finally, the research needs in this area are highlighted and some recommendations are made for addressing them in the future studies.

Key words: wood adhesives, bond strength, percentage of wood failure, bond line thickness, adhesive spread rate, growth ring orientation, imperfection.

## Introduction

Adhesive is an integral element in the production of a variety of engineered wood products (EWPs) such as cross-laminated timber, glulam, and laminated veneer lumber. The bond strength evaluation of wood adhesives is part of daily activities in the quality control laboratory of many EWPs manufacturing companies. Most companies follow the testing instructions provided by national or international industry-accepted standard test methods. However, one of the challenges that has occasionally been highlighted by researchers is that most of the available standard methods are general and usually not relevant to all types of products (e.g., Sikora et al. 2016), even though many wood adhesives nowadays are produced to be used in a specific product or application. Accordingly, the selected test method may not necessarily be the most suitable method for the specific application, although it may fulfill the basic requirements. Parameters such as bond line thickness, adhesive spread rate, press pressure, and grain orientation, influence the bond strength of wood adhesives (Rowell 2012). The influencing parameters can vary within and between applications and products, which affects the reliability of a selected standard test method. In addition, some of the common standards are quite sensitive to minor technical errors in the sample preparation or testing (Karlsson and Wong 2004). Although for research purposes in a well-controlled laboratory environment the minor technical errors could be avoided, such imperfections are usually expected to happen in the industrial use. Therefore, it is important to properly evaluate the parameters that might influence the accuracy of bond strength measurement and the extent to which common standards are sensitive to these parameters.

In this paper, a brief discussion is presented on the fundamental of the bonding mechanism and failure of wood adhesives. This is followed by a review of various technical parameters and imperfections that might influence the accuracy and reliability of key European and American standard test methods on shear strength measurement of wood adhesive bonds. The gaps and research needs in this area are also discussed in order to evaluate the importance of the effects of such imperfections on the accuracy of the standard test methods in the future research.

## Adhesive bonding of wood materials

Apart from its chemistry, the bonding performance of a wood adhesive is largely governed by its depth of penetration into the wood cells (Kamke and Lee 2007). Part of an adhesive applied between wood elements will penetrate the lumens of the wood cells through hydrodynamic flow and capillary action and a smaller amount will penetrate the wood cell-walls through diffusion (Kamke and Lee 2007, Gavrilović-Grmuša et al. 2016). A good bonding performance could be expected when the adhesive penetrates the wood cells to a sufficient degree. This will provide a good interaction and mechanical interlocking between the wood and the adhesive (Rowell 2012). Under similar conditions, the level of hydrodynamic flow and capillary action may vary between various wood species depending on their cellular structures. Due to this, the depth of penetration and therefore the bonding performance of a single adhesive will be generally influenced by the type of wood materials in addition to the viscosity of the adhesive itself.

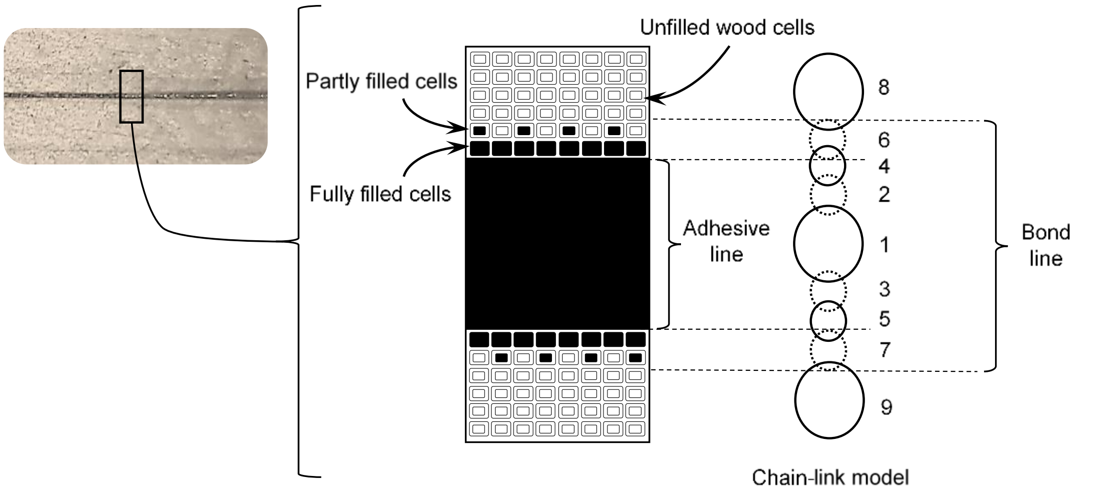


Figure 1. Illustration of the chain-link model in a wood-wood glued element.

This is usually addressed during the formulation of the adhesive and can be adjusted for different wood species and products. However, a uniform bonding performance will be challenging to achieve in manufacturing a product that is to be made of mixed wood species (Rowell 2012). A poor bonding performance in such products may result from the over-penetration of the adhesive into the more porous species or its under-penetration into the less porous one.

According to Marra (1992), the adhesive bond in wood materials can generally be modeled using a chain-link analogy comprised of five links (Fig. 1). Despite its detailed structure, the chain-link analogy is effective in describing and studying the bond performance of wood adhesives. As shown in Figure 1, Link 1 in the chain-link analogy is bulk adhesive; Links 2 and 3 are the adhesive interphase (or the adhesive boundary layer); Links 4 and 5 are the wood-adhesive interface; Links 6 and 7 are the interphase of the wood; and Links 8 and 9 are bulk wood (clear wood unaffected by the adhesive). According to this model, the bond is as strong as the weakest link in the chain.

The best-case scenario for a wood adhesive is when Links 8 or 9 are the weakest in the chain, resulting in pure wood failure. Most adhesives usually achieve this when tested in dry conditions. However, certain wood adhesives fail in the interphase region when tested in wet conditions (Frihart 2005). The interphase region is quite critical as it has to accommodate the possible swelling and shrinkage of the wood and volume reduction of the adhesive while it cures. Swelling and shrinkage strains in either components at service will also result in increased internal stresses that can negatively influence the bond performance in the interphase region (Frihart 2009). Due to this phenomenon, the performance of wood adhesives needs to be studied at various dry and wet states to mimic the actual conditions at service.

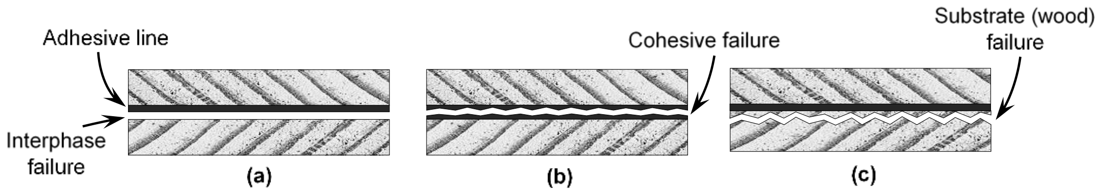


Figure 2. Three general macroscopic failure modes of wood adhesive bonds under shear force.

The chain-link analogy is quite detailed and therefore sometimes challenging to use especially for predicting failures in the bond line. This is because the induced stresses are usually not uniformly distributed across the bond line and therefore the failures do not always happen in only one single link in the chain (Hass 2012). Most standard test methods examine the bond performance of wood adhesives under shear loads, either in compression or in tension. Under shear stress, three macroscopic failure modes can be observed in general with the assumption of a uniform stress distribution: interphase failure, cohesive failure, and substrate or wood failure (Fig. 2).

a. Interphase failure refers to a type of shear failure that occurs within the interphase region of the bond line. Interphase failure occurs within Links 2 to 7 in the chain-link analogy. This includes failure in the adhesive interphase region (Links 2 and 3), interfacial failure (Links 4 and 5), and failure in the wood interphase region (Links 6 and 7). The interfacial failure (i.e., failure at the wood-adhesive interface) leaves clear wood on one surface and adhesive on the other. A true interfacial failure is not common for strong wood adhesive bonds but it can result from the poor adhesive penetration that may happen due to high density of wood, inadequate surface preparation, or high viscosity of the adhesive itself. Sometimes failure in the adhesive interphase region (Links 2 and 3) or the wood itself (Links 6 and 7) may be mistaken for the interfacial failure (Links 4 and 5). The differences are difficult to detect at the macroscopic level.

b. Cohesive failure is the pure shear failure of the bulk adhesive within Link 1. In wood materials, a cohesive failure may indicate that the shear strength of the adhesive line is less than that of the wood itself. This type of failure may also be observed when the adhesive line is too thick.

c. Substrate (wood) failure is characterized by the shear failure of the wood fibers within Links 8 and 9. This type of failure occurs when the shear strength of the bond line is higher than that of the wood.

In practice, other types of shear failure can also occur as a combination of the three general failure modes. Nevertheless, most standard test methods on shear strength measurement of wood adhesive bonds do not account for this effect and only require the percentage of wood failure to be assessed visually to the nearest 10%. However, to properly understand the wood adhesive bonding mechanism, the relevant experiments are better to be associated with both macroscopic and microscopic evaluations of the failure modes of the bond line as well.

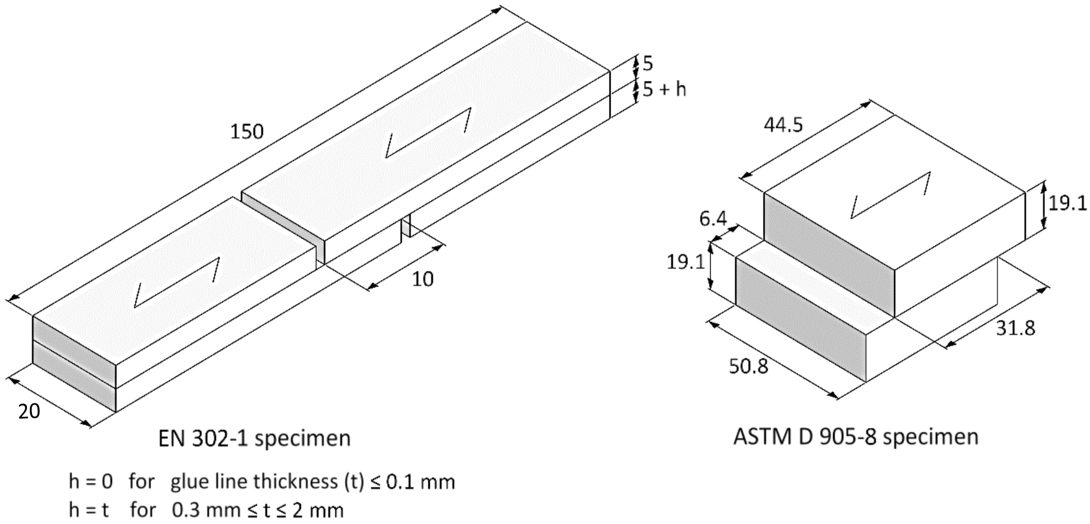


Figure 3. Configurations of EN 302-1 and ASTM D 905-8 specimens. Measurements in mm.

### Key methods for shear strength measurement of wood adhesive bonds

Standard tests methods used for evaluating the bond strength of wood adhesives usually require the strength measurements to be taken under uniaxial shear stress parallel to the grain direction. In some standards, the shear stress is created by compressive loading and in some others by tensile loading. For each category, one of the most frequently used test methods is described in the following.

EN 302-1 (2013) is a European standard used for evaluating the shear strength of wood adhesives for load-bearing timber structures with close contact and thick glue lines. This standard provides guidance on measuring the shear strength of wood adhesives parallel to the grain direction. The shear stress must be induced on the adhesive line by tensile force. The test method has been developed for evaluating the shear strength of wood adhesives using different conditionings in both dry and wet states and under low and high temperatures. It is also suitable for assessing the compliance of one-component polyurethane adhesives, phenolic and aminoplastic adhesives, and emulsion polymerized isocyanate adhesives.

ASTM D 905-8 (2013) test method from the American Society for Testing and Materials is used to evaluate the shear strength of wood adhesive bonds by compressive loading. The bond area in this standard is quite larger than that in EN 302-1 (2013). ASTM D 905-8 (2013) test method is generally used to evaluate the shear strength of adhesive bonds in wood and similar materials. This test method is quite straightforward with respect to the necessity of following its specified conditions of specimen preparation, conditioning, and testing. The shear strength of the adhesive bond in this method is measured parallel to the grain direction. The configuration and dimensions of the EN 302-1 (2013) and ASTM D 905-8 specimens are shown in Figure 3.

**Imperfections of test specimens in practical use**

The application of the standard test methods in a well-controlled laboratory environment is not usually associated with major imperfections. However, in daily industrial use of standard test methods the likelihood of errors and imperfections is quite high. The imperfections could be related to the geometry, dimensions, but also mistakes/errors related to the general procedures for preparing and testing of the specimens. A few researchers have already raised the importance of this subject in the past as well. Karlsson and Wong (2004), for example, evaluated the sensitivity of the EN 302-1 and ASTM D-905 test methods to eccentric loading, amount of adhesive, and errors in cutting grooves and steps in the specimens. The experimental design of the study was not fully factorial and therefore the interaction effect of the test variables was not evaluated. However, they concluded that both test standards are sensitive to the intentional errors in the preparation and testing of the specimens. The results obtained were significantly affected even when there was only ± 0.5 mm error in the cutting depth of grooves and steps in the specimens.

In numerous studies in the past, the effects of growth ring orientation, press pressure, glue line thickness, and adhesive spread rate on the shear strength of wood adhesives in dry conditions were proved to be significant. However, there are uncertainties on how imperfection and inconsistency in such variables may influence the accuracy of the standard test methods. In EN 302-1 (2013), for example, it is assumed that a press pressure of 0.8 ± 0.1 MPa will result in a glue line thickness of 0.1 mm or less. This is quite general and may not necessarily result in the same glue line thickness, for example, in a low-viscosity adhesive compared to an expanding adhesive with a high viscosity.

The optimum spread rate of a wood adhesive is usually recommended by the manufacturer. The adhesives spread rate has conventionally been measured in many studies as the amount of adhesive that is initially applied on the adherents' surfaces. However, this method is clearly not reliable because it does not indicate how much adhesive will actually stay between the surfaces for bonding as a large amount of the adhesive initially applied will squeeze out under press pressure. This can lead to drawing incorrect conclusions from the results of bond strength measurement especially if the adhesive spread rate is one of the test variables. To overcome this drawback, the weight of the specimens before gluing and after clamping can be measured to estimate the amount of adhesive that is left for bonding (as in Santos et al. 2019). Measuring the exact bond line thickness and correlating it to the test results of individual specimens could be another solution. By measuring the bond line thickness, the volume of the adhesive applied in unit bond area could be estimated. The actual spread rate of the adhesive can then be estimated by multiplying the volume of the adhesive by its density at any stage even without knowing the weight of the specimens before gluing. A simple statistical correlation between the actual adhesive spread rate and the results obtained from the shear test of the bond line can then be used to adjust the results and improve the accuracy and repeatability of the experiments. For this purpose, clear guidelines must be provided on how the bond line thickness and adhesive volume can be rapidly and accurately estimated at the gluing or subsequent stages in practice.

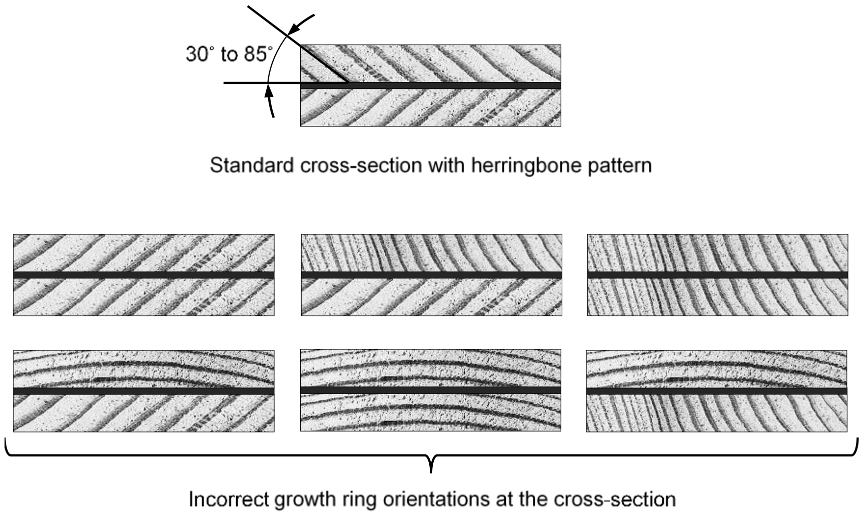


Figure 4. Some examples of incorrect growth ring orientations in EN 302-1 (2013) specimens.

The adhesive penetration depth on each side of a specimen is also likely to vary if the growth ring orientations of the adherents are different (see Figure 4 as an example). In such a case, the differences in the shear strength may not be significant for strong adhesive bonds tested in dry conditions, as most of the failure is likely to take place in the wood itself. However, cycles of wetting, boiling, and drying in the next stages of the test and increase in the test temperature required by standards can lead to increased internal stresses as a result of variable shrinkage and swelling of the specimens with different growth ring orientations. This can result in more decrease in the strength of Links 2 to 7 in the bond line of a specimen with small adhesive penetration depth. Therefore, the variation in the adhesive bond strength in the specimens with different growth ring orientations can become more notable. In such a situation, the accuracy and repeatability of a given test method will need to be addressed properly under various testing temperatures and moisture contents when exposed to such imperfections.

The subjects of growth ring orientation and fibre direction are especially important for evaluating the suitability of an adhesive that is going to be used in the production of certain types of EWPs with crossing layers—such as cross-laminated timber. In such products, the growth ring pattern and fibre direction in each layer vary significantly even within the same product type. However, the standard test methods described in this paper evaluate the shear strength of wood adhesives only in one direction—i.e., parallel to the grain. In numerous studies, researchers have been adopting their own test methods to evaluate the shear strength of adhesive bonds in products with crossing layers (e.g., Sikora et al. 2016). It is however still uncertain as to what extent the results of such tests may differ from those obtained from the available standard test methods on similar adhesives and wood species.

The existence of so many uncertainties in the basic application of the standard test methods indicates important research needs in this area. The future research should cover a range of objectives to properly understand the importance of the variables discussed in this paper and then propose reliable solutions to reduce the uncertainties associated with the imperfections and suitability of such standards for different products and applications.

## Summary and Conclusions

In this paper, a short introduction is provided on the bonding of wood materials, failure of adhesive bonds, and the key test methods used for measuring the shear strength of wood adhesives. For commonly used test methods, the uncertainties related to specimen fabrication and their influence are discussed and suggestions are made for addressing these drawbacks in the future research. Overall, it could be concluded that the standard test methods on the shear strength measurement of wood adhesives are quite general and come with important degrees of uncertainties that need to be addressed. It can be suggested to the future research to determine the importance of the influence of imperfections in specimen preparation and testing (both geometrical and technical aspects) on the reliability and accuracy of the standard test methods under various conditioning procedures. With the rapid development of EWPs, the need for establishing more detailed and reliable product-specific test methods is also paramount in evaluating the suitability of wood adhesives for different products and applications.

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