

# Adhesive Groups and How They Relate to the Durability of Bonded Wood

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## Abstract

There is a need to develop models that evaluate the interaction of wood adhesives at the macroscopic level to explain observations on the durability of bonded wood laminate products with changing moisture conditions. This paper emphasizes a model that relates durability to strain on the bondline caused by wood swelling. The effect of this strain is discussed in relation to two groups of adhesives with different chemistry, structure–property and adhesive–wood interaction relationship models. The *in situ* polymerized adhesive group involves highly cross-linked polymers with a rigid backbone that need to limit the swelling of the wood surface to provide a durable bond. The pre-polymerized adhesive group includes polymers with backbone flexibility and limited cross-linking so that they can thus distribute the swelling strain within the adhesive. These models emphasize the importance of the adhesive–wood interactions and end-use application for establishing the performance criteria.

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## Keywords

Adhesives, wood bonding, moisture durability, internal stress, groups

## 1. Introduction

Wood products have long service lives; thus, adhesive bonds in wood need to have good durability for the particular use condition. Even though the demands that adhesives need to meet depend upon the end use of the product, all these adhesive bonds are expected to pass some type of moisture exposure test. These tests have been successful in helping to empirically develop adhesives that function well in end-use applications. However, development of improved products is limited by the need for each adhesive formulation to be tested in a specific end product test and with the wood species used in that application. Although the literature documents many individual studies of one or a few adhesives used with one or, in a few cases, several wood species, simple models to help understand this information have not been developed. This paper covers first a model that emphasizes the effect

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of stresses at the interface because of the wood-swelling strain. My examination of structure–property relationships and the adhesive interaction with wood led to additional models that divided wood adhesives into two general groups. One group, the rigid, highly cross-linked *in situ* polymerized adhesives, need to stabilize the wood surface to distribute this strain through the wood, whereas the second group, the flexible, lightly cross-linked pre-polymerized adhesives, distribute this strain in the adhesive. This paper discusses the basis for the swelling strain model and for establishing these two groups. Understanding the behavior of these adhesives helps in establishing the best performance standards for particular applications.

## 2. Background

Although measuring performance of wood adhesives is relatively straightforward, understanding this performance is more difficult because of three main sources of complexity. The first is the complexity of wood structure and the wide variety of bonding surfaces within and between species. Wood, in general, is a high-strength porous material. In addition, wood has a multifaceted cellular hierarchy, ranging from the cellular ultrastructure to the different cells providing either good fluid transport or high strength, to alterations of the cell structure needed to keep a tree vertical and support branches [1–4]. All these wood variations influence adhesive interaction with wood [5].

The second source of complexity is that wood consists of three polymer types (cellulose, hemicellulose and lignin) and many other minor components. Bonding surfaces including lumen walls, longitudinal fractured wall surfaces, intercellular surfaces, and transverse surfaces of ray cells [5] lead to very diverse chemical and structural interfaces [6]. Thus, localized adhesive–wood interactions vary considerably from one area to another.

The third complexity that makes wood different from most other substrates is that the adhesives can penetrate below the visible wood surface. Filling the cellular lumina provides mechanical interlocking and increases the area for adhesive contact [5–8]. Another mode of interaction is infiltration of some adhesives into cell walls and middle lamella [7, 8]. Adhesives in the cell wall may react with cell wall polymers or form interpenetrating networks [9, 10]. Consequently, proper bonding conditions are needed to avoid under- or overpenetration that lead to decreased bond strengths. Given these complexities, it has been difficult to develop a simple model to explain bondline quality.

Durability of bonded assemblies when exposed to moisture changes is of equal importance to bondline quality. Swelling and shrinking of wood are dependent upon the temperature and humidity to which the wood is exposed, as well as the wood itself [11–13]. Dimensional changes of wood under these different conditions place large additional stresses on the bondline [5, 14]. The importance of measuring moisture-related durability of wood products in most countries is evident by examining the number of standards testing this type of performance. For example,

in the United States, the ASTM adhesive standards [15] that test a wet bond are D 905-03, 1151-00, 3535-00, 4688-99 (2005), 4689-99 (2005), 4690-99 (2005), 5572-95 (2005), 5751-99 (2005). The ASTM standards that involve cycle(s) of wetting and drying are D 1183-03, 2559-04, 3434-00, 3930-93a (2005), 4502-92 (2004), 4688-99 (2005), 5572-95 (2005), 5824-98 (2003).

In addition, there are ASTM moisture-related standards for bonded wood assemblies. Many other organizations, such as the American Institute of Timber Construction (AITC), American Plywood Association (APA), and American National Standard Institute (ANSI) in the United States, either have standards or help in development of standards for moisture-related durability of wood products, such as laminated wood beams, plywood, oriented strandboard, particleboard and medium-density fiberboard. There are many similar standards in other countries. For our testing, we have generally used ASTM D 905 and D 2559 because of their wide acceptance as important measures for exterior durability and because they provide a reasonable rapid assessment of durability.

These standardized tests can be useful for assessing in-use performance of adhesives in bonded assemblies; however, the lack of detailed models of the bonding process and of durability testing hinders the design of improved adhesives and bonded products. Any development of a new adhesive is hampered by the need to always assess its utility using empirical tests with the wood species specified for the end application. This means that only a few formulations can be evaluated because of the long time commitment to performance testing, and the empirical nature of testing means that established criteria will be very conservative, especially in structural applications.

Can models be developed that help us understand what is happening in moisture-related durability tests? The wood bonding process and durability testing are very complicated processes, given the complexities described previously. However, simplified models can help us understand why we observe what we do in empirical test data and can lead to more effective adhesive solutions. The interest in developing these models was driven by the lack of models that can explain literature data. For example, the literature does not explain why epoxies, in most cases, do not provide durable bonded assemblies with wood, whereas in some cases, they do. These models help explain the observed failure of epoxies in the adhesive layer near the wood surface [16] and that better epoxy adhesive performance is actually obtained by bonding to less polar acetylated wood [17].

### 3. Terminology

Because of the complex structure of wood and its absorptive as well as adsorptive properties, a clear definition of the terminology used in this paper is important for understanding the models presented here. Two main areas of terminology refer to penetration into the wood and interphase and other regions of the bondline.

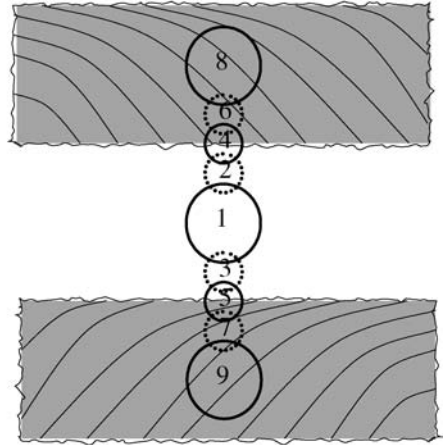
Wood bonding is more than a visible surface bond because of adhesives' ability to penetrate into wood. Penetration is a good term for generally describing adhesive soaking into wood. However, two fundamentally different phenomena are covered by this overall process, and they have different effects upon wood. Flow is used to describe movement of bulk adhesive, whether it is flow across the surface as in wetting or flow into the wood to fill empty lumina of wood cells. This flow is described by normal capillary phenomena. On the other hand, many chemicals can move into the wood cell walls provided that they are fairly low in molecular weight. This infiltration of the cell wall is controlled by a molecule's hydrodynamic volume and solubility parameter. The infiltration process can influence the wood's physical and mechanical properties, whereas flow into the lumina improves mechanical interlocking but has little effect on the wood's swelling properties.

The second area of terminology involves the interphase. Given the adhesive's penetration into wood, thickness of the interphase generally exceeds thickness of the bulk adhesive. Thus, to understand the bond properties and failure mechanisms, interphase as defined by the ASTM D 907 as "a region of finite dimension extending from a point in the adherend where the local properties (chemical, physical, mechanical and morphological) begin to change from the bulk properties of the adherend to a point in the adhesive where the local properties equal the bulk properties of the adhesive" [15] can be further divided into three regions. Wood interphase is the region from the wood surface to the maximum penetration depth of the adhesive. The interface is the boundary between the wood and adhesive phases. The adhesive interphase is the region from the wood surface to where the adhesive begins to exhibit its bulk properties. Adding in the bulk wood and bulk adhesive regions and the same three layers on the other side of the bond results in a bondline with nine regions defined here, as previously described by Marra [18, 19] with somewhat different terminology (Fig. 1). These regions may be better visualized using an epoxy-bonded yellow poplar (*Liriodendron tulipifera*), as shown in Fig. 2. The adhesive layer is usually thinner than that in Fig. 2, in which case the bulk adhesive region may be very small.

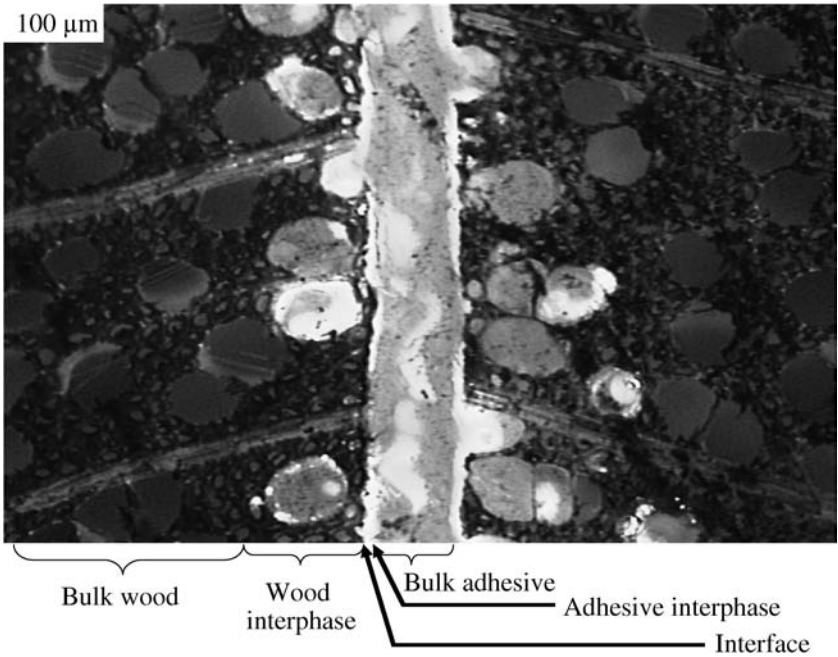
#### 4. Importance of Swelling Strain

Moisture-related durability tests for wood adhesive bonds fall into two main groups. The first are those that involve wet/dry cycles to check for bond delamination. This type of test is used in interior plywood testing [20] and structural beams (D 2559 and D 3434) [15]. The shrinking and swelling of the wood alone provides sufficient force on the bond to cause some adhesives to fail. The second type of test involves testing either the strength of the adhesive under wet conditions (ASTM D 905 portion of D 2559, or D 906 for exterior plywood) [21] or the resistance to wood swelling in composites such as oriented strandboard [22], particleboard [23], or medium-density fiberboard [24].

- Link 1 — bulk adhesive
- Links 2 and 3 — adhesive interphase
- Links 4 and 5 — adhesive–wood interface
- Links 6 and 7 — wood interphase
- Links 8 and 9 — bulk wood



**Figure 1.** Marra’s description of bondline failure zones using the terminology described in this paper rather than Marra’s original terms [19].

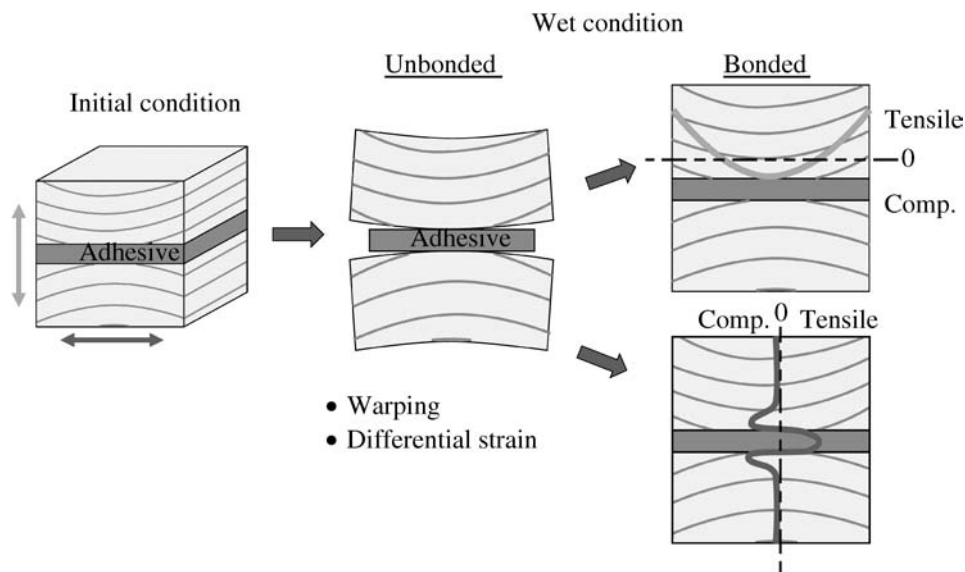


**Figure 2.** Epoxy/yellow-poplar bondline cross-sectional view using fluorescence spectroscopy showing the different regions of the bondline.

Much of the emphasis on bond failure has been on the stresses due to shrinkage as wood dries because cracks are more visible when wood dries [5]. However, the wood swelling process is the first condition the wood bond encounters in an accelerated durability test (standard tests, such as ASTM D 2559 or D 3434, use a vacuum

to remove air entrapped in the wood, followed by pressure to force the liquid into the voids to accelerate the swelling of the wood. This swelling may not be relieved by wood fracture such as that often observed in the drying portion. Weakening of the bond under the swelling condition is clearly demonstrated by the often-observed decrease in the percentage failure within wood relative to that in the adhesive under wet conditions. Wood swelling imposes considerable internal strain at the interface between wood and the adhesive, and if strain is not distributed, a large stress occurs at the interface. Figure 3 illustrates complex forces at the interface. The left drawing is a normal wood bond. The center drawing shows the tendency of wood to swell laterally and bow if the adhesive is placed between wood blocks but not bonded to them. The two right drawings show tensile and compressive forces in the perpendicular and lateral directions (see Fig. 3). Wood bowing creates a compression in the middle and tension at the outer edges in the normal (perpendicular) direction in the upper right figure. The lower right part of the figure illustrates lateral strains of compression on the wood surface as the adhesive restricts wood swelling and tension on the adhesive surface as the wood tries to swell.

Is the swelling strain large enough to rupture wood–adhesive bonds? Swelling varies with the orientation, type of wood specimen, and difference in moisture levels, but it can be up to 5–10% [25, 26]. A wood swelling force as high as 8 MPa for beech has been claimed [27], although a more recent study reported a much lower value (1.2 MPa) for spruce [28]. Even when the swelling force is not large enough to fracture the bond, this internal force is large enough to weaken the bond. Therefore,



**Figure 3.** The difference in behavior of unbonded (adhesive is placed between the wood blocks but is not bonded to the wood) and bonded wood when the wood swells and an illustration of the forces both parallel and perpendicular to the bondline from the swelling of the wood.

the bond fails at lower applied loads than it would if this force did not exist and this leads to lower percentage of wood failure. The influence of this swelling strain on lowering the percentage wood failure has been illustrated using an epoxy adhesive with five wood species [10]. For high-swelling wood, the percentage wood failure decreased for wet shear tests compared with dry shear tests; in addition, the percentage wood failure returned to close to initial values when shearing redried samples. However, the percentage wood failure did not decrease for wet wood bonds that were made with wood with lower swelling capacity. A different example was in development of new soy adhesives. It was observed that any slippage of the bond in the first swelling step would lead to unacceptable performance in the three cycle soak/dry procedure for interior or decorative plywood (unpublished research). These and other examples show that wood swelling often initiates bond failure.

This is not meant to imply that the only factor in bond durability is the degree of wood swelling. The better the bond quality, the more swelling strain the bond can endure without failure. It is also important to consider how swelling strain can be distributed away from the interface to limit stress concentration. The better the strain is distributed, the more likely a bond would be able to withstand moisture-related changes in wood dimensions. Examination of wood adhesives' structure–property relationships and adhesives' interactions with wood led to grouping these adhesives as described in the next two sections.

## 5. Adhesive Chemistry and Polymer Properties

Considering not only the chemistry of the bonding process but also the chemical and mechanical responses of the bondline to the moisture-related durability testing helps to understand durability of adhesively bonded wood. While evaluating all the common wood adhesives, it became clear that they fell into two distinct groups. This grouping was originally based on the ability of an adhesive to interact with wood, but it became apparent that the same grouping applies to the adhesive's polymer morphology and the ability of the bondline to respond to moisture changes in the wood, which is a main factor of durability. Consequently, it is proposed that adhesives for bonding wood should be examined on the basis of two main groups (*in situ* polymerized and pre-polymerized) based upon their chemistry and structure–property relationships. The *in situ* polymerized group is made up of small molecules, generally less than 2,000 g/mol average molecular weight (MW), and cross-linked to form relatively rigid polymers, while adhesives that are pre-polymerized prior to application mainly consist of higher MW molecules and the cured adhesives have sufficient flexibility.

### 5.1. Group 1: In Situ Polymerized Adhesives

Most wood-bonding adhesives by volume belong to the *in situ* polymerized group; these adhesives often infiltrate into cell walls prior to curing and are relatively rigid polymers and highly cross-linked after curing. They are composed of oligomers or

monomers or both that form polymer chains and cross-links between chains after application to the wood surface. The oligomers' average molecular weight and their ratio to monomers often depend upon the specific bonding application. All these adhesives contain some portion that is low enough in molecular weight to infiltrate into cell walls. The largest volume adhesives for wood bonding are molecules of amino resins made from urea or melamine or both and linked by condensation reactions with formaldehyde. These cured adhesives are quite rigid [29] because of the aromatic structure of melamine, the resonance forms of urea, and the short methylene bridges in the backbone and cross-links [30].

The next largest adhesive type is phenolics made from phenol and/or resorcinol molecules linked by condensation reactions with formaldehyde; biobased tannin and lignin adhesives also fall into the phenolics category, based upon chemistry and polymer properties. Aromatic phenol groups linked by methylene groups along the chain and between chains provide a very rigid structure [31].

Polymeric diphenylmethane diisocyanate (pMDI) is an important binder adhesive for making wood composites. However, the term 'polymeric' is misleading because the main components are oligomeric and monomeric [32]; thus, pMDI clearly belongs in the *in situ* polymerized group. Isocyanate groups react with water to produce urea; after decarboxylation an amine is formed that reacts with other pMDI molecules to produce polyurea-type products. Linking these aromatic units together in the backbone and with numerous cross-links does not allow for much flexibility in these adhesives.

Another adhesive type is epoxies based on the diglycidylethers of bisphenol A and a polyamine cross-linker to form their polymer chains and cross-links. These epoxies are used in repair and low-bonding pressure applications. The simple epoxies are known for their stiffness, but may have their impact resistance improved by adding rubbery domains [33].

All *in situ* adhesives generate polymers with a high degree of chain cross-linking and the backbones have a high content of aromatic or resonance-stabilized structures with very limited flexibility. This rigidity in the backbone as well as cross-links serve well in providing adhesive bonds with non-detectable creep required for structural wood bonds [5, 6]. However, the downside is that rigidity in the adhesive limits its ability to respond to dimensional changes in wood.

## 5.2. Group 2: Pre-polymerized Adhesives

The second group of wood adhesives comprises preformed polymers with higher molecular weights than those of *in situ* adhesives and with suitable retention of flexibility after cross-linking. Most pre-polymerized adhesives have backbones that are mainly non-aromatic and non-cyclic, allowing for rotation along chains. In addition, some of the water-borne adhesives in this group may be dispersions that do not fully coalesce, allowing for inter-particle movement. Often, limited cross-links are introduced to provide additional creep and moisture resistance. This group includes poly(vinyl acetate), one-component polyurethanes, emulsion polymer isocyanates,



proteins and mastics [5]. The poly(vinyl acetate) group has a flexible aliphatic backbone with some formulations having limited cross-linking. Polyurethanes and emulsion polymer isocyanates have flexible polyether or polyester segments. Proteins are rigid when dry but become more flexible as the water content increases because the internal hydrogen bonds plasticize.

In actuality, most adhesives are more complex in nature than shown by the simple groups above. Actual adhesive products are formulated to have specific properties for particular applications. They often range broadly in molecular weight, may consist of different domains on the nanoscale, may be particles with limited coalescence, have additives, such as fillers, extenders, tackifiers, etc., or even be blends of polymers. However, for understanding moisture durability of wood bonds, the *in situ* and pre-polymerized adhesive groups provide a useful way to evaluate general chemistry and structure–property relationships.

## 6. Models for the Effect of Moisture Changes on Adhesive Bonds

In the prior sections, the emphasis was on the importance of understanding the concentration and distribution of interfacial strain upon moisture level changes in wood and the two adhesive groups, the *in situ* polymerized and pre-polymerized adhesives, based upon their chemistry and structure–property relationships. These two groups are also different based upon how they interact with wood and how their respective bondlines respond to the strain imposed by dimensional changes in wood. Dissipation of the strain either through wood or the adhesive interphase would decrease localized stress imposed upon the bondline.

### 6.1. Group 1: In Situ Polymerized

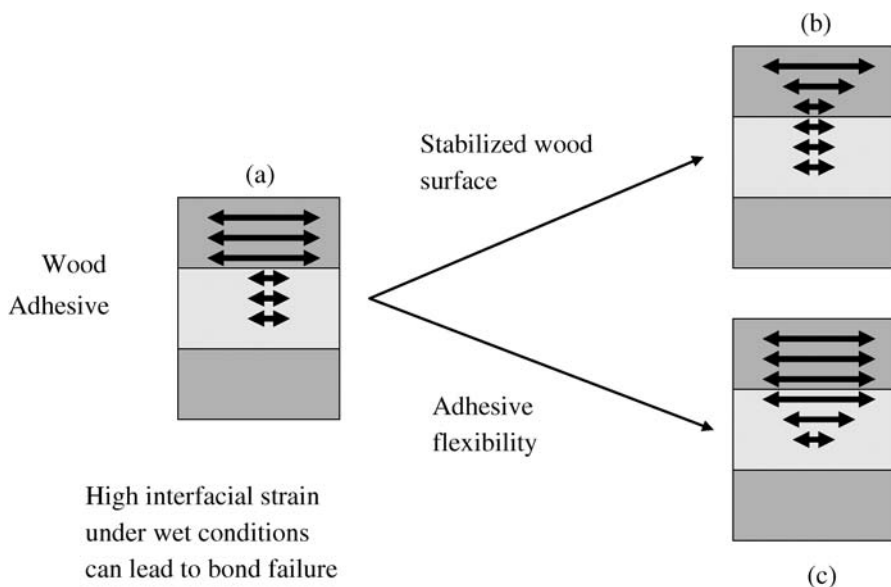
The *in situ* polymerized adhesives, being rigid because of the generally aromatic nature of the backbone and the high degree of cross-linking, have limited ability to change dimensionally as wood swells, potentially creating large stresses at the interface. However, the rigid phenol-formaldehyde (PF) and phenol-resorcinol-formaldehyde adhesives are still considered the most moisture-durable wood adhesives. The ability of these adhesives to form strong, water-resistant bonds is surprising given the brittleness of cured adhesive films. In contrast, the generally tougher epoxy adhesives often give poor results in wood durability tests. Trying to address the difference in performance of these two adhesives led to development of models for how the bond might deal with the strain differential between the adhesive and wood.

The answer why these rigid phenolic resins exhibit such great durability appears to lie in the ability of phenolic adhesives to infiltrate cell walls and decrease their ability to swell. Nearn originally proposed that penetration of adhesive into the wood cell walls was important for durability of wood bonds [34]. He later claimed that as the infiltration of phenol-formaldehyde adhesive into the cell wall decreased with increasing molecular weight of the adhesive, Douglas-fir plywood bond durability decreased [35]. The infiltration of phenol-formaldehyde resins into wood has

been demonstrated by a number of methods: fluorescence microscopy [36], autoradiography [37], transmission electron microscopy [34, 35], scanning electron microscopy with spectroscopy [38], dynamic mechanical analysis [39, 40] and anti-shrink efficiency [41]. An interesting study used dynamic mechanical analysis to show that low and high molecular weight PF resins had differing effects on cell wall mechanical properties, most likely because of variations in the amount of PF entering the cell wall [39, 40]. PF resin's alterations of the wood swelling properties has been known for many years [41]. Thus, data for PF support the concept that PF entering the cell wall to decrease its swelling plays a role in the durability of these bonds. A study on a melamine-formaldehyde resin showed that it can also decrease the swelling of the wood and improve its mechanical properties [42–45]. Thus, many of the *in situ* polymerized adhesives can alter the wood interphase to allow the swelling strain to be distributed away from the interface between the adhesive and the wood and to provide water-durable bonds.

On the other hand, not all the *in situ* polymerized adhesives can provide moisture-durable bonds; epoxies, in particular, have in many cases not provided 'durable' bonds. Although they are not major adhesives for wood bonding, the extensive literature on epoxies helps to explain their poor performance. Is the failure of epoxy adhesives simply a matter of incorrect formulation? Whereas some formulations are better than others, data using many experimental formulations [46, 47] and commercial formulations [48] have not shown any highly durable formulations. Poor wetting is also not likely to be the answer because epoxies are certainly less polar than normal wood adhesives, considering that the latter are mainly waterborne. Although penetration can be a factor with many wood adhesives leading to poor durability, this is not likely the answer for epoxies. Some of the lower viscosity adhesives can penetrate too deeply into wood, but epoxies do not overpenetrate. From our research, we have observed reasonable penetration into wood and we have not observed failure at the wood–adhesive interface [16]; thus, underpenetration is not likely the answer. Consequently, poor bond quality is not likely the reason for poor epoxy performance. These results led to the model of interfacial strain being critical to understanding performance of the epoxy resins [16]. Dry and wet tests for an epoxy adhesive using five different wood species (white oak, hard maple, aspen, southern yellow pine and Sitka spruce) supported the concept that the greater the swelling strain, the less durable was the epoxy bond [49].

A primer was developed that helped epoxies and other adhesives pass the standard moisture durability tests. This primer, hydroxymethylated resorcinol (HMR) is a mixture of monomers and oligomers from the reaction of resorcinol with formaldehyde, and it greatly improves the durability of wood bonded with an epoxy [50]. Vick's theory [50] stated that the primer was a coupling agent that served as a bridge between wood polymers and epoxy resin by forming covalent chemical bonds. However, more recent data have supported the theory that the primer modifies the wood interphase (similar to PF described earlier) to stabilize it [51, 52]. Thus, extensive studies on the HMR primer lend support to the



**Figure 4.** Ways interfacial strain can be dissipated by either (a) stabilization of the wood surface by an *in situ* polymerized adhesive or (b) adhesive flexibility for a pre-polymerized adhesive. Arrows are for easy visualization and do not reflect the absolute amplitude of the strain.

importance of stabilization of wood surfaces for enhanced performance of epoxy bonds.

To understand the PF *versus* epoxy data, a schematic is helpful. The stresses in Fig. 3 are shown as the strains that generate these stresses in Fig. 4. The model for highly moisture-durable *in situ* polymerized wood adhesives involves some of the adhesive infiltrating the cell wall to decrease swelling at the interface. Adhesive concentration in the cell wall should decrease away from the adhesive layer creating a gradient of decreasing wood swelling near the interface, as illustrated in Fig. 4b. However, if adhesive does not stabilize the cell wall, then most of the swelling force transfers to the adhesive layer, as in Fig. 4a. Generally, this internal stress can lead to failure at lower applied loads in a shear test, such as ASTM D 905 (compressive) or D 906 (tensile), and is even sufficient to cause delamination of glulam beams in D 2559, especially if the wood warps, creating a normal force.

## 6.2. Group 2: Pre-polymerized Adhesives

The other group of adhesives, the pre-polymerized, can enter the cell lumens, but they are generally too high in molecular weight to infiltrate the cell wall to the extent previously described for *in situ* polymerized adhesives. Thus, the cell wall stabilization mechanism is not available to these adhesives. On the other hand, these adhesives have more flexibility in the backbone than *in situ* polymerized adhesives, thus allowing for deformation of the adhesive to decrease strain at the interface, as illustrated in Fig. 4c. Adhesives that fall into this group are the polyurethane,

poly(vinyl acetate), emulsion polymer isocyanates and proteins. These adhesives are linear polymers with few aromatic or cyclic groups in the backbone, allowing for localized deformation in the adhesive that distributes the swelling strain through the adhesive interphase. Emulsion polymer isocyanates and proteins are discussed in another publication [53].

Polyurethanes are good wood adhesives and show good strength even under wet conditions. Polyurethanes consist of polyether or polyester segments joined together by reaction with diisocyanates. These polyethers and polyesters are called soft segments and provide polyurethanes with their ability to deform and contribute to polyurethane toughness in tensile tests. These adhesives can exhibit a range of properties by using different soft segments and other formulation changes. Many of polyurethane wood adhesives are one component by having an excess of isocyanate in their formulations. Unreacted isocyanate combines with water to yield a carbamic acid that decomposes to an amine and carbon dioxide. This amine then reacts with another isocyanate group to form a urea group linking together soft segments. Carbon dioxide forms gas bubbles within the adhesive layer and the foamed structure provides another mode of deformation of polyurethane. The ability of polyurethanes to absorb additional energy by deformation is likely to be the reason that some polyurethanes possess higher strengths than phenolics under wet conditions even with lower percentage of wood failure.

Flexible poly(vinyl acetate) is another widely used wood-bonding adhesive. Polymerization of vinyl acetate leads to a linear chain that has flexibility, and the absence of any strong inter-chain bonding or crystallization leads to polymer that can deform. Even the cross-linked versions of poly(vinyl acetate) retains good flexibility. Thus, interfacial strain due to wood swelling can readily be distributed through the adhesive.

Obviously, a balance is needed between the localized deformation necessary for handling swelling strains and excessive deformation that leads to unacceptable creep for structural applications. This balance is often accomplished by lightly cross-linking polymers. Cross-links limit macroscopic creep, but adhesive can still deform to distribute the swelling strain if long segments exist between cross-links.

## **7. Service Life Literature for Bonded Wood**

Mechanisms of bond failure in accelerated tests help clarify whether accelerated tests measure the same phenomenon as exists with in-service use. For the most part, bonded wood products have been functioning well in service for many years, including in structural applications. Glulam beams using a casein (protein) adhesive have been supporting the roof of a Forest Products Laboratory building since 1934, with the only repair being made after a fire charred a few of the beams. However, accelerated tests are needed to make sure that there is an acceptable match of adhesive and wood for the designed product and to facilitate the approval of new

adhesives, as adhesive users typically do not have the luxury of waiting 75 years to assess new adhesives.

Only a few reported studies relate accelerated test data to actual exterior test results. The effectiveness of standard phenol–resorcinol–formaldehyde (PRF) and PF adhesives in bonded beams for bridges and buildings that have endured in service may have discouraged additional studies. In the most complete study to date, Caster tested 11 adhesives by using both exterior exposure at four locations for up to 16 years, and by using a severe automated boil-accelerated test for up to 800 cycles for Douglas-fir plywood [54]. This study predicted the service-life for wood bonds by showing a good correlation between accelerated test data and exterior exposure data. These results seem to be in good agreement with general observations on wood bond durability, except for the epoxy performance discussed below.

Epoxy-bonded wood durability studies have produced contradictory data, and it is important to use the models in this paper for examining these data. Epoxies are often not considered to be durable enough for wet exposure and an AITC memorandum cautions on the sole use of epoxies in exterior applications [55]. Certainly ample literature data document the poor performance of a wide variety of epoxy adhesives in standard accelerated aging tests [46–48, 50, 56, 57]. Thus, it is surprising that Caster's results showed two epoxies as the best adhesives in exterior exposure and accelerated aging [54]. Although not explicitly mentioned in the study, Vick and others reported that the specimens tested were actually pretreated with polyethylenimine primer [50]. It can be assumed that this primer was responsible for the unusually good bond durability observed for epoxy adhesives used in this study. However, even this polyethylenimine primer was not nearly as effective as the HMR primer in preventing delamination in ASTM D 2559 accelerated aging cycles for Sitka spruce laminates bonded with epoxies [50]. The data are consistent with the theory that HMR stabilizes the cell wall to decrease interfacial strain. Thus, with the correct epoxy primer, bonds can be very durable in accordance with the models proposed in this paper.

Most previous durability studies used exterior exposure and accelerated aging tests with rapid and large changes in wood moisture level. However, do these exterior data correlate to data where wood is protected, as in the interior of a building? The models in this study would indicate that for less rapid and severe moisture level changes, epoxy may be sufficient, especially for the repair of wood beams. Avent and coworkers have done extensive studies to show the suitability of epoxies for beam repair [58–60]. Avent's research also shows that epoxies can make the repaired beam even stronger than the original beam. However, these tests did not use severe accelerated or outdoor tests. Raknes shows data indicating that structural bonds that are protected from the weather may perform well when using certain adhesives that are not acceptable for full exterior durability [61]. This is an important consideration because epoxy adhesives are likely to be suitable for their use in repair of existing interior beams, whereas they would not meet specifications for production of new beams. Epoxies are used even where water exposure is an issue,

such as in the repair of timber beams and bridges [58, 62], wood boat construction, wood airplane construction, and repair of decayed wood because they work better than other wood adhesives for gap filling a low bonding pressure applications. Consequently, the models can be used to help set appropriate standards for the particular application.

## 8. Conclusions and Future Research

Wood is a complex substrate for adhesive bonding. Although some adhesives provide bonds that perform well in accelerated moisture-related exposure tests and in-service use, many aspects have not been understood as well as they need to be. Important in moisture-related tests are the large differences in swelling and shrinking between wood and the adhesive, which can cause a large interfacial strain. Also important is how different adhesives can distribute the strain to limit interfacial stress concentration. In trying to understand performance differences with adhesives, it has been determined that there are two general groups of wood adhesives based upon their chemistry–structure–property relationships, adhesive–wood interactions, and responses of bonded assembly to moisture changes. *In situ* polymerized adhesives (phenolics, amino resins, isocyanates and epoxies) have a rigid backbone and are usually highly cross-linked when cured. To achieve a durable bond, the adhesive needs to distribute the swelling strain across the wood interphase region to lower interfacial stress. On the other hand, pre-polymerized adhesives (poly(vinyl acetate), polyurethanes, emulsion polymer isocyanates and proteins) have some backbone flexibility and a lower degree of cross-linking that can allow them to distribute strain in the adhesive interphase, which decreases interfacial stress. These models have been used to evaluate our data and the literature data for epoxy resins. Our data showed that failure of epoxies was in the adhesive interphase region, probably because of considerable interfacial stress, and that the use of certain species of wood or the proper primer can decrease bond failure. Knowledge presented here helps clarify why the literature has shown epoxy adhesives to be both good and poor in moisture durability.

Industry is dependent upon the accelerated tests being the methods for determining durability. Caster's work seems to give a reasonable correlation between exterior exposure and an accelerated test [54]. However, Caster's study only used one species of wood and the specimens were not under load. A critical question then follows: Does running an accelerated test with high amplitude dimensional changes and a limited number of cycles give the same response as an actual exterior exposure test with lower dimensional change and several cycles in all cases? This question is complicated especially for wood, knowing that wood stress relaxes during swelling and shrinking changes given sufficient time. Do interior beams that may not get wet need to pass the accelerated tests designed for exterior exposure? Better knowledge of the fundamentals of adhesive interaction with wood and how adhesives fail in these tests is very important for being able to design better wood

adhesives and bonded assemblies. Models discussed in this paper indicate that more work needs to be done to understand the durability of wood bonds to ensure that accelerated tests are correctly predicting end-use performance for different types of adhesives.

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