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**ADHESIVE PERFORMANCE AT ELEVATED TEMPERATURES  
FOR ENGINEERED WOOD PRODUCTS**

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# **Adhesive Performance at Elevated Temperatures for Engineered Wood Products**

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## **Abstract**

Engineered wood products, such as I-joists and laminated veneer lumber (LVL), have traditionally been manufactured with phenolic-based adhesives in North America. In the last few years, however, an unprecedented number of non-phenolic-based adhesive systems, such as polyurethane-based and isocyanate-based adhesives, have been introduced to the engineered wood products industry. While these relatively new adhesives have demonstrated their compliance with most international adhesive standards, concerns have been raised by the fire services and others on the performance of these adhesives at an elevated temperature, such as just below the ignition temperature of wood.

It is recognized that full-scale fire assembly tests, such as ASTM E119, CAN/ULC S101, or ISO 834, address the fire performance of wood assemblies. However, it is arguable that the adhesive, as a critical component of glued engineered wood products, needs to be evaluated to ensure that the adhesive will not degrade below the wood substrates being adhered when exposed to extreme heat prior to wood ignition. Unfortunately, no international adhesive standards exist in testing the adhesive to such an elevated temperature.

A task committee, as chaired by the first author, was formed in June 2004 by the engineered products industry in North America to address this issue with input from key adhesive suppliers to the industry. Through coordinated efforts, an industry standard was developed and adopted by the engineered wood products industry in March 2005. Test data suggests that this standard can be used to screen out those adhesives that significantly lose adhesive bond strength at the temperature near the wood ignition temperature. This standard has been submitted to the International Code Council (ICC), the U.S. code evaluation agency, and the ASTM Committee on Adhesives (D14.30) for adoption. This paper presents the background information and test data used to develop the industry standard.

## **1. Introduction**

Engineered wood products have traditionally been manufactured with phenolic-based adhesives in North America. Although first commercially developed in the early 1900's, phenolic resins did not attain full-scale commercial significance until being introduced into the plywood industry in the U.S. around 1934. Because of such advantages as good creep resistance, durability, fire performance, and dimensional stability at elevated temperatures, phenolic-based adhesive systems soon became the dominant systems used for such products as softwood and hardwood plywood, oriented strand board, structural glued

laminated timber (glulam) laminated veneer lumber (LVL), parallel strand lumber (PSL), and prefabricated wood I-joists.

In the last few years, however, an unprecedented number of non-phenolic-based adhesive systems, such as polyurethane-based and isocyanate-based adhesives, have been introduced to the engineered wood products industry. While these relatively new adhesives have demonstrated their compliance with most international adhesive standards, concerns have been raised regarding the performance of these adhesives at an elevated temperature.

It is recognized that full-scale fire assembly tests address the fire resistance of wood assemblies. These standard test methods for evaluating fire resistance include ASTM E119 [1], CAN/ULC S101 [2], and ISO 834 [3]. Ratings of assemblies are determined by a standard heating curve approximating assumed structural fire conditions. A fire-rated assembly, which is typically composed of fire-protective membranes, such as fire-rated gypsum boards and insulation, and structural elements, is generally required for selected types of buildings, such as multi-family dwellings and commercial buildings, in accordance with the governing fire code. Heavy timber, such as structural glued laminated timber of a significant dimension can also be used for fire-rated assemblies. However, most residential houses in North America are required to be built with neither fire-rated assemblies nor heavy timber. In fact, a vast amount of single-family dwellings in North America are built with an open-frame basement or craw space without any fire-protective membranes.

The fire services in North America have expressed concerns about the light-frame construction built with lightweight materials, such as wood trusses and prefabricated wood I-joists. There have been reported sporadic bans on these engineered wood products in some local jurisdictions around the U.S. and Canada due mainly to the perception that the fire performance of these lightweight engineered wood products is different from that of conventional solid-sawn lumber in unprotected buildings. A frequently asked question by the fire services to the engineered wood products industry has been “does your adhesive melt before wood burns?” By the context of the question, the word “melt” does not mean the glass transition temperature of the adhesive, but the degradation of the adhesive bond strength as a result of heat exposure at a temperature below the wood ignition temperature.

The engineered wood products industry in North America is sensitive to the question raised by the fire services and has a strong desire to ensure the adhesive bonds in engineered wood products will not degrade more than solid wood when exposed to any temperatures up to wood ignition. In April 2004, the industry was made aware of a situation that an adhesive might have been dissociated at a temperature near wood ignition. With the intent to address this issue, an industry task committee, as chaired by the first author, was formed in June 2004. After several intensive meetings and conference calls, and with the input from key adhesive suppliers to the industry, an industry standard, APA/WIJMA AC1000-05, *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds on Glued Wood Products at Elevated Temperatures*, was approved by the industry in March 2005 (available from APA - The Engineered Wood Association, <http://www.apawood.org>, and Wood I-Joist Manufacturers Association, <http://www.i-joist.org>). This paper describes the background information and test data used to develop the standard. Like any new standard, AC1000 is by no means a perfect standard. Since its release, there have been some comments that will be addressed by the task committee in the coming months.

## 2. Development of the Industry Standard

Based on the Wood Handbook [4], the thermal degradation of wood occurs in three phases: a) dehydration or loss of water vapor (up to 150°C or 302°F), b) non-combustible degradation where gaseous vapors are slowly given off and char begins to form (100 to 250°C or 212° to 482°F) and c) combustible degradation where volatile organic compounds are emitted, which may or may not flame, depending on oven conditions (280° to 500°C or 536° to 932°F). The test method given in APA/WIJMA AC1000-05 is intended to evaluate the condition at the upper end of the second phase of wood degradation, above the hot press temperatures typically used in production of wood composites (149° to 204°C or 300° to 400°F), yet below the ignition temperature of the wood. It is understood that wood ignition is the decomposition (pyrolysis) of material into volatiles and a char residue. The temperature at which the wood ignites is a function of the wood moisture content and species, the temperature and heat flow in the surrounding environment, and the time of exposure at an elevated temperature.

There is no existing standard in the world that addresses the performance of structural adhesives at an elevated temperature near wood ignition. With the understanding that wood will degrade at such a high temperature and the desire of the industry was to ensure the adhesive bond would not degrade more than wood (i.e., the performance of solid wood is the benchmark), the targeted temperatures, test methods, and durations of the heat exposure were identified as critical factors that needed to be considered for the development of the industry standard. A series of coordinated but independent tests were conducted by organizations representing the engineered wood products industry to gather relevant data in October and November 2004.

### 2.1 Targeted Temperatures

As the objective of the industry standard was to evaluate the adhesive performance at an elevated temperature near wood ignition, a series of tests was conducted at a bond line temperature (not the air temperature) of 177, 204, and 232°C (350, 400, and 450°F). The upper temperature of 232°C (450°F) was selected based on the understanding that the wood ignition temperature is near that temperature and the objective of the industry standard was to evaluate the adhesive performance up to the temperature just before wood ignition. It was understood by the industry that the correlation between these elevated temperatures and the bond line temperatures in end-use applications might be difficult. However, it was believed that if the adhesive bonds meet the performance of solid wood at these temperatures, the performance of the adhesive under actual in-service high temperature conditions could be ensured with a high degree of confidence.

### 2.2 Test Methods

At the time when the industry effort was initiated in June 2004, a Canadian adhesive standard, CSA O112.9, *Evaluation of Adhesives for Structural Wood Products (Exterior Exposure)* [5], was about to be finalized. Within CSA O112.9, Test Method B2 (Creep Resistance Tests) requires the ASTM D3535 [6] specimens be compression loaded at a constant stress of 2.1 MPa (305 psi) for 2 hours at an air temperature of 180°C (356°F). While the constant-load method at a constant temperature was considered attractive, an

important consideration for the new industry standard was the ability of the engineered wood products plant to conduct in-plant testing. In addition, the ASTM D3535-type specimens are relatively difficult to prepare, as compared to the shear block specimen in accordance with ASTM D905, *Standard test methods for strength properties of adhesive bonds in shear by compression loading* [7], which was also used in CSA O112.9 for shear strength evaluation. Through preliminary tests conducted at a Weyerhaeuser/Trus Joist plant, the industry was in favor of a relatively simple specimen configuration, as shown in Figure 1, and the test method in accordance with ASTM D905. It should be noted that the 3.2-mm (1/8-inch) gap that is typically used in the block shear test jig for evaluation of the block shear strength of wood is not permitted in ASTM D905.

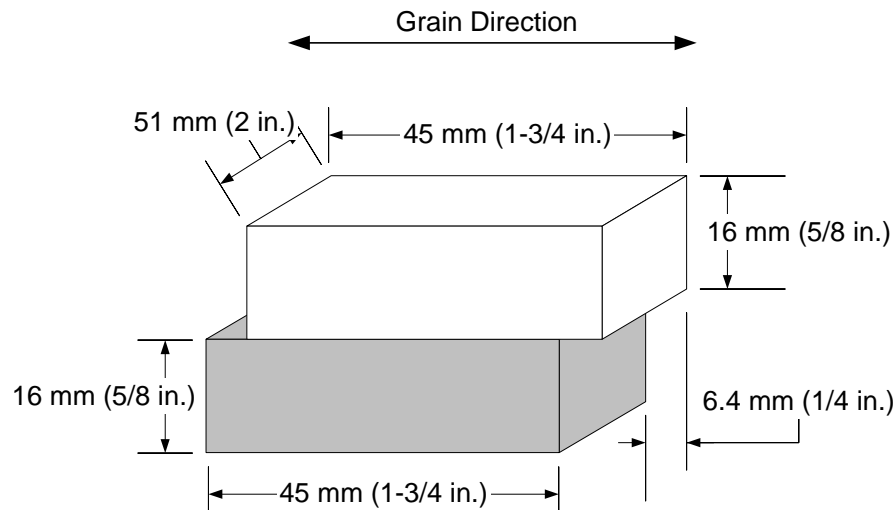


Figure 1. Form and dimensions of a bonded specimen

### 2.3 Heat Exposure Durations

For the purpose of providing data in determining the shear strength degradation of solid wood when exposed to a constant heat at various temperatures for a 1-hour duration, as measured at the middle of the shear block specimen with a thermocouple, APA - The Engineered Wood Association conducted a study in October 2004 in accordance with ASTM D905 using solid Douglas fir (*Pseudotsuga menziesii*) specimens. Table 1 and Figure 2 show the results.

Table 1. Solid wood (Douglas fir) test results

Adhesive	Temperature, °C (°F)	Mean shear strength, MPa (psi)	COV, %	Residual shear strength	Mean wood failure, %
Control	Ambient <sup>(a)</sup>	14.6 (2118)	9.8	1.00	100
	177 (350)	6.5 (940)	23.5	0.44	
	204 (400)	4.6 (668)	26.4	0.32	
	232 (450)	3.3 (482)	35.9	0.23	

<sup>(a)</sup> Approximately 21°C (70°F).

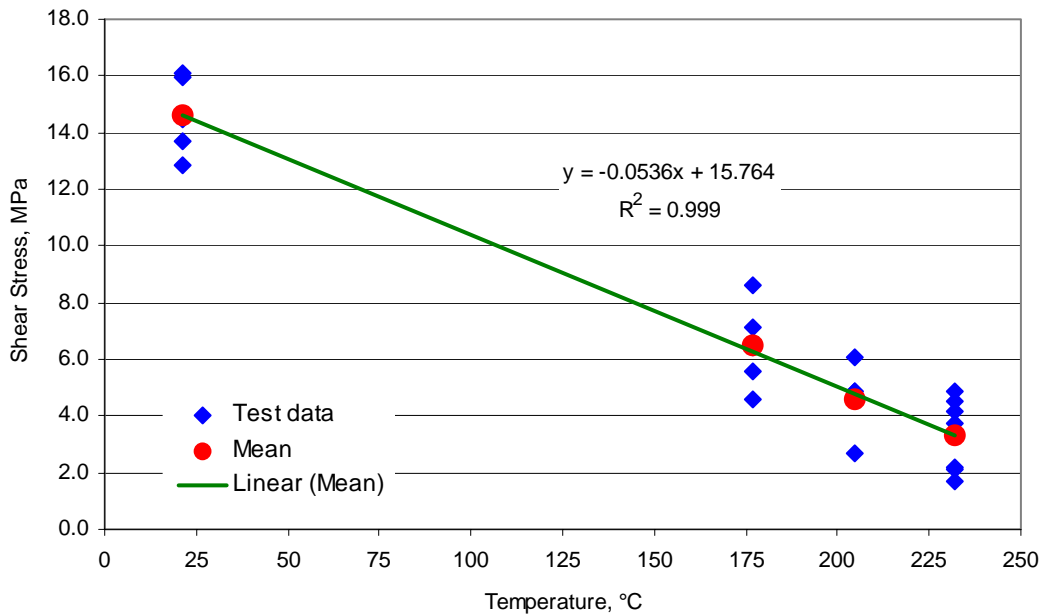


Figure 2. Shear strength of solid wood (Douglas fir) specimens at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration

As shown in Table 1 and Figure 2, the mean shear strength of the solid wood Douglas fir specimens with a 1-hour constant heat exposure (at the middle of the specimen) at 177°C (350°F), 204°C (400°F), and 232°C (450°F) is 44%, 32%, and 23% of the mean shear strength at the ambient temperature of 21°C (70°F), respectively. From the perspective of engineering design for fire, the mean shear strength at an elevated temperature is expected to remain capable of carrying the design shear. As a result, for LVL products used in the U.S., the allowable shear stress with a typical coefficient of variation of 25% from block shear tests may be expressed as a percentage of the mean shear strength of the same materials tested at the referenced temperature of 21°C (70°F):

$$f_{v,m,te} = F_{v,ts} = \frac{f_{v,k,ts}}{C_a} = \frac{f_{v,m,ts}(1-1.645v)}{C_a} \quad [\text{Eq. 1}]$$

- where
- $f_{v,m,te}$  = mean shear strength at an elevated temperature
  - $F_{v,ts}$  = allowable shear stress at the referenced temperature (21°C)
  - $f_{v,k,ts}$  = characteristic shear strength at the referenced temperature (21°C)
  - $C_a$  = a factor that accounts for factor of safety and load duration
  - $f_{v,m,ts}$  = mean shear strength at the referenced temperature (21°C)
  - $v$  = coefficient of variation

The  $C_a$  factor is codified as 3.15 in ASTM D5456, *Standard Specification for Evaluation of Structural Composite Lumber Products* [8]. Therefore,

$$f_{v,m,te} = 0.19 \times f_{v,m,ts} \quad [\text{Eq. 2}]$$

In other words, the mean shear strength at an elevated temperature is expected to be about 20% of the mean shear strength tested at the referenced temperature of 21°C (70°F). Since the objective of the industry standard was to ensure that the strength of engineered wood products, including the adhesive bond strength, is capable of carrying the design loads even at an elevated temperature, it appears that a 1-hour heat exposure is approaching the 20% shear strength at the referenced temperature of 21°C (70°F) if the target exposure temperature is 232°C (450°F). If a lower temperature is selected, the exposure duration may be required to be extended beyond 1 hour to reach the targeted strength ratio of 20%. Therefore, the duration of heat exposure of 1 hour was chosen by the industry with the understanding that it is intended to “protect” the design stress of engineered wood products in an extreme condition of 232°C (450°F), which may or may not exist in end-use applications.

### 3. Adhesive Tests

Based on the considerations given above, a study was conducted by the industry to evaluate the performance of 6 commercially available adhesives at elevated temperatures, as shown in Table 2.

Table 2. Adhesives tested in this study

Adhesive ID	Adhesive Type
1	2-part Polyurethane Emulsion Polymer (PEP)
2	2-part Emulsion Polymer Isocyanate (EPI)
3	1-part Polyurethane (PUR)
4	1-part Polyurethane (PUR)
5	1-part Polyurethane (PUR)
6	2-part Emulsion Polymer Isocyanate (EPI)

The data reported herein were based on the tests conducted at the APA Research Center in Tacoma, Washington, which is accredited under ISO 17025 by the International Accreditation Service (IAS) in the U.S. and Standards Council of Canada (SCC). All specimens were fabricated by Weyerhaeuser/Trus Joist in accordance with Figure 1 and tested at APA in October and November 2004 in accordance with ASTM D905 after being subjected to three temperatures of 177°C (350°F), 204°C (400°F), and 232°C (450°F) for a 1-hour duration. The bond line temperature was monitored with a thermocouple, as shown in Figure 3. For each adhesive and temperature combination, 5 replicates were tested. Since the industry standard was at the development stage when the tests were conducted, the purpose of the testing was not necessarily to identify any deficient adhesives, but to assess such factors as ease of testing, suitability of prescribed temperatures levels and time durations, and repeatability from one testing facility to another.

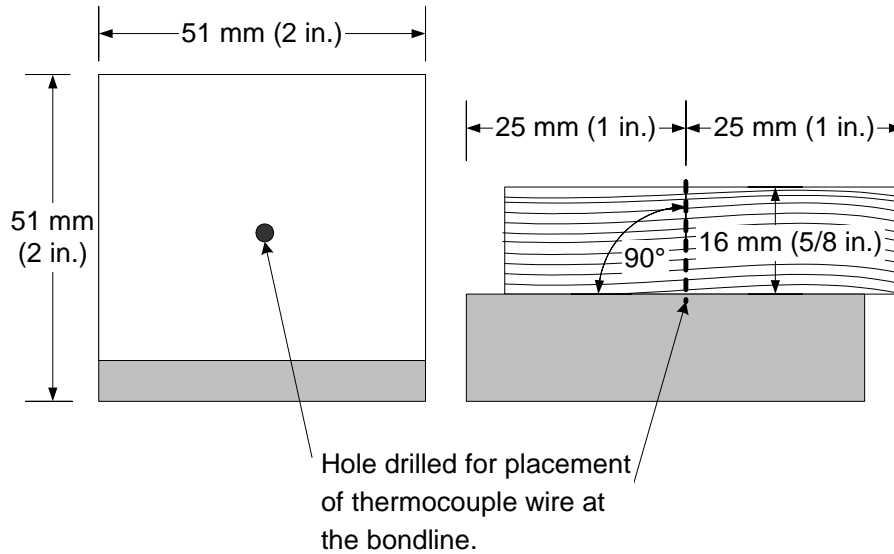


Figure 3. Top view (left) and side view (right) of drilled hole for thermocouple placement

Results from the APA tests are shown in Table 3 and Figure 4. For comparison purposes, the results from control (solid wood) specimens, as previously mentioned in Figure 2, are superimposed in Figure 4. Similar trends were observed from tests conducted by Weyerhaeuser/Trus Joist and other engineered wood product manufacturers.

Table 3. Adhesive test results from APA

Adhesive	Temperature, °C (°F)	Mean shear strength, MPa (psi)	COV, %	Residual shear strength	Mean wood failure, %
1	Ambient <sup>(a)</sup>	11.1 (1608)	21.5	1.00	99
	177 (350)	7.9 (1147)	11.5	0.71	87
	204 (400)	5.3 (772)	10.4	0.48	71
	232 (450)	3.0 (440)	30.9	0.27	29
2	Ambient <sup>(a)</sup>	13.4 (1940)	10.2	1.00	89
	177 (350)	6.9 (1006)	16.2	0.52	51
	204 (400)	4.6 (667)	16.7	0.34	30
	232 (450)	2.8 (414)	26.2	0/21	15
3	Ambient <sup>(a)</sup>	14.3 (2071)	12.7	1.00	100
	177 (350)	8.0 (1167)	9.0	0.56	91
	204 (400)	3.8 (554)	21.0	0.27	38
	232 (450)	0.9 (13)	86.7	0.01	0
4	Ambient <sup>(a)</sup>	11.0 (1601)	11.3	1.00	97
	177 (350)	4.5 (650)	5.7	0.41	74
	204 (400)	2.3 (328)	17.4	0.20	46
	232 (450)	0.3 (44)	75.8	0.03	0
5	Ambient <sup>(a)</sup>	12.3 (1793)	10.1	1.00	96
	177 (350)	7.1 (1025)	17.4	0.57	78
	204 (400)	3.5 (503)	36.4	0.28	47
	232 (450)	1.7 (244)	19.4	0.14	22
6	Ambient <sup>(a)</sup>	11.6 (1678)	9.7	1.00	96
	177 (350)	4.8 (695)	28.9	0.41	27
	204 (400)	3.2 (465)	25.6	0.28	11
	232 (450)	2.0 (285)	33.3	0.17	7

<sup>(a)</sup> Approximately 21°C (70°F).



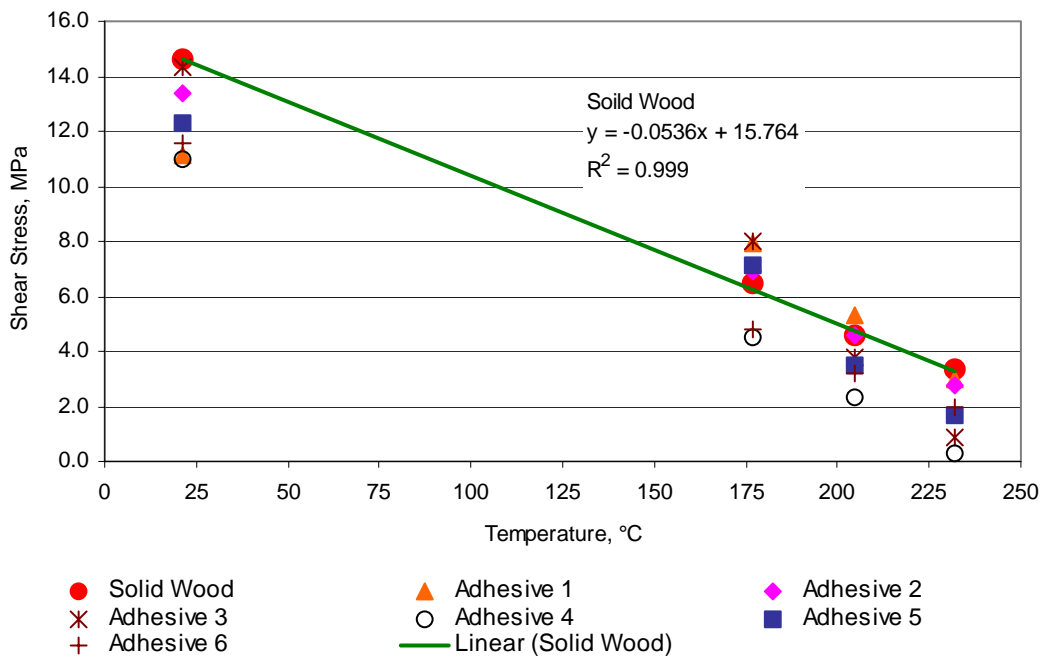


Figure 4. Shear strength of solid wood (Douglas fir) specimens and 6 adhesives at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration

As noted from Figure 4, the shear strength of some adhesives, such as Adhesives 1 and 2, and to some extent, Adhesives 5 and 6, followed the general trend of the shear strength from solid wood. On the other hand, some adhesives, such as Adhesives 3 and 4, seemed to be completely dissociated at 232°C (450°F) after 1-hour heat exposure (those bonded specimens could be broken in half at the bond line by hand pressure). This drastic loss of bond strength seems to occur for Adhesives 3 and 4 when exposed to an elevated temperature between 204°C (400°F) and 232°C (450°F) after 1-hour heat exposure, as evidenced by the residual shear strength shown in Table 3. The exposure duration could be a significant factor contributing to this behaviour. Unfortunately, no specific data are available to quantify it at this point in time.

These results suggest that some polyurethane-based adhesives may be sensitive to an elevated temperature above 204°C (400°F) for an extended period of time. The test method developed by the industry appears to be capable of segregating adhesive performance at an elevated temperature if the adhesive bond is exposed to a temperature above 204°C (400°F). As previously mentioned, the North American engineered wood products industry has a desire to benchmark solid wood performance. In combination with the relationship between the mean shear strengths at an elevated temperature and the referenced temperature, as given in Equation 2, and the fact that some polyurethane-based adhesives have drastically different response at an elevated temperature above 204°C (400°F), the industry adopted the 1-hour exposure at 232°C (450°F).

It is possible that the ignition temperature of some wood species may fall below the specified temperature of 232°C (450°F). The industry standard permits the tests to be conducted at a lower temperature for such species if it is justified to the satisfaction of the

engineered wood product manufacturer, qualified third-party inspection agency, and code evaluation agency.

## 4. Acceptance Criteria

Due to test uncertainties, the residual strength at the elevated temperature, as shown in Equation 2, is not meant to be deterministic. As a result, the industry standard specifies the use of matched specimens between solid wood blocks and bonded blocks. Details of the specimen preparation are given in the industry standard. It is generally considered acceptable if the ratio of the mean residual shear strength between 232°C (450°F) and 21°C (70°F) for the bonded specimens is equal to or higher than the lower 95% confidence interval on the ratio of the mean residual shear strength for the solid wood specimens. It should be noted that the wood failure criteria were not specified in the standard because of the difficulty in estimating wood failure after the specimens are exposed to an elevated temperature for 1 hour.

## 5. Remaining Issues

Since the release of APA/WIJMA AC1000-05 in March 2005, ASTM D14.30 *Subcommittee on Wood Adhesives* has been considering the adoption of the standard. A committee ballot, which contains minor editorial and format changes, is expected to be issued in August 2005. CSA O177, *Qualification Code for Manufacturers of Structural Glued Laminated Timber* [9], is also balloting the adoption of the industry standard by reference. In addition, a proposal to adopt APA/WIJMA AC1000-05 into an acceptance criteria by the International Code Council Evaluation Service (ICC ES) was discussed at the last ICC ES hearing in June 2005.

During the last ICC ES hearing, the adoption of the industry standard was strongly supported by most adhesive suppliers. However, there were concerns raised by two adhesive suppliers on the severity of the standard in terms of the specified temperature and exposure duration. From their viewpoint, it was arguable that the specified temperature and exposure temperature are too severe, as compared to the performance of engineered wood products, such as I-joists, in an unprotected assembly. One adhesive supplier has suggested that the standard be revised to allow either 1) linear temperature rise from ambient to 204°C (400°F) at bond line over a period of 60 minutes or 2) constant air temperature of 180°C (356°F) for 2 hours in accordance with CSA O112.9. These arguments reflect the different viewpoints between some adhesive suppliers and the engineered wood product manufacturers, who tend to take a conservative approach when addressing the concerns raised by the fire services or in response to the issues driven by potential liability. The committee from the engineered wood products industry will be considering the suggestions provided by the adhesive suppliers in September 2005.

## 6. Conclusions

An industry standard developed by the engineered wood products industry in North America provides an evaluation method on adhesive bond performance at an elevated temperature near wood ignition. The test method appears to be capable of segregating adhesive performance at an elevated temperature if the adhesive bond is exposed to a temperature above 204°C (400°F) for an extended period of time. However, while this

standard is being adopted by a variety of product and test standards, concerns on the severity of the specified temperature and exposure duration remain to be addressed.

## 7. References

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