Evaluation of Adhesive Performance at Elevated Temperatures for Engineered Wood Products

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Summary

Adhesives used in engineered wood products, such as I-joists and laminated veneer lumber (LVL), manufactured in North America are required to meet specific requirements of adhesive standards, such as ASTM D2559 in the U.S. and CSA Standards for Wood Adhesives O112 Series in Canada. However, these standards do not address the adhesive performance at temperatures above 180°C (356°F) even though the general expectation has been that the adhesives used in engineered wood products will not lose the bond strength more than wood does when exposed to elevated temperatures in unprotected assemblies, such as in most residential construction in North America. However, there is no existing standard in the world that addresses the performance of structural adhesives at an elevated temperature near unpiloted wood ignition.

In lack of an international standard, a task committee was formed in 2004 by the engineered products industry in North America to develop an industry standard for the evaluation of adhesive performance at elevated temperatures with input from many key adhesive suppliers to the industry. Through coordinated efforts, an industry standard was 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. The test method given in the industry standard was submitted to the ASTM D14 Committee on Adhesives for adoption in July 2005 and was approved for publication in April 2006 as ASTM D7247, *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures*. This paper presents the background information used to support the test method and the next step for implementation.

1. Introduction

In recent years, the engineered wood products industry has experienced a significant influx of non-phenolic-based adhesive systems, such as polyurethane-based and isocynate-based adhesives, which have unique, discrete properties relative to the phenolic-based adhesives used in North America since 1930's. Unlike phenolic-based adhesives, which are specifically recognized in some national product standards in the U.S., such as ANSI A190.1, *American National Standard for Structural Glued Laminated Timber* (ANSI 2002), and PS2, *Performance Standard for Wood-Based Structural-Use Panels* (NIST 2004), the performance of new non-phenolic-based adhesives is usually encountered some skepticism due primarily to the wide spectrum of the adhesive properties and performance.

While these relatively new adhesives have demonstrated their compliance with most existing adhesive standards, general concerns on the evaluation criteria for adhesive performance have driven the adhesive and engineered wood products industries in North America to jointly reevaluate the adequacy of existing adhesive standards for product acceptance. One of the major concerns by the engineered wood products industry is the lack of information regarding the adhesive bond strength at elevated temperatures, which is an issue that has been raised by fire services in North America.

It is recognized that full-scale fire assembly tests, such as ASTM E119 (ASTM 2000a), CAN/ULC S101 (ULC 2004), and ISO 834 (ISO 1999), or heavy timber construction address the fire resistance of wood 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 crawl space without any fire-protective membranes.

With the intent to address the adhesive performance at elevated temperatures, an industry task committee was formed in June 2004. After several 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.

The test method given in the industry standard was submitted to the ASTM D14 Committee on Adhesives for adoption in April 2005 and was approved for publication in April 2006 as ASTM D7247, *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures* (ASTM 2006a). This paper presents the background information used to support the test method and the next step for implementation.

2. The Industry Standard

2.1 Development of the Industry Standard

The test method given in APA/WIJMA AC1000-05 was intended to evaluate the condition above the hot press temperatures typically used in production of wood composites (149° to 204°C or 300° to 400°F), yet below the unpiloted 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. As a result, the test methods, targeted temperatures, and durations of the heat exposure are critical factors that needed to be considered for the development of an acceptable standard in evaluating the adhesive performance at elevated temperatures.

2.1.1 Test method

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)* (CSA 2005), was about to be finalized. Within CSA O112.9, Test Method B2 (Creep Resistance Tests) requires the ASTM D3535 (ASTM 2000b) 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 by the industry task committee 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* (ASTM 2003), which was also used in CSA O112.9 for shear strength evaluation. Through preliminary tests conducted at a Weyerhaeuser Company facility, the industry was in favor of a relatively simple specimen configuration and the test method in accordance with ASTM D905.

2.1.2 Temperature

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 unpiloted 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 elevated temperatures and time, the performance of the adhesive under actual in-service high temperature conditions could be predicted with a reasonable degree of confidence. The committee felt that testing an oven-dried, small-scale, block-shear specimen at an elevated temperature over an extended time period, until both the adherend and adhesive are uniformly heated, isolates the adhesive component and does not require testing various shapes and sizes of assembled products such as I-joists, LVL and finger joints. The rationale for isolating the adhesive is to first measure adhesive performance, then assume equal or better performance within an assembled component (such as I-joists) in real fire condition due to the insulating effect that wetter, moisture-equilibrated wood offers.

For example, the APA/WIJMA AC1000-05 test protocol measures adhesive performance at a severe temperature condition of 232°C (450°F) for 60 minutes, and lets the user of the standard determine if the adhesive is applicable to the product application, assuming the adhesive behaves similar to wood. This approach applies adhesive behavior to the product application, not visa-versa. Alternatively, others prefer quantification of the wood insulation effect for each product application solved backwards to determine a less-severe time and temperature protocol that the adhesive is exposed to in a real fire. The latter approach assumes a strong correlation between small- and full-scale testing, along similar wood behavior with and without radiant heat, respectively. Such a correlation has yet to be quantified in a published literature.

2.1.3 Exposure duration

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 and the Weyerhaeuser Company conducted a study in October 2004 in accordance with ASTM D905 using solid Douglas fir specimens. Figures 1 and 2 show the results.

As shown in Figure 1, 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. Weyerhaeuser data shown in Figure 2 also show a similar trend.

An engineering analysis has shown that for a structural member to carry the design load at extreme circumstances, the mean shear strength at an elevated temperature should be about 20% of the mean shear strength tested at the referenced temperature of 21°C (70°F). As a result, the exposure temperature of 232°C (450°F) with a 1-hour duration was chosen as the standard by the industry task committee. It is expected that the exposure duration may be required to extend beyond 1 hour to reach the targeted strength ratio of 20% if a lower temperature is selected.

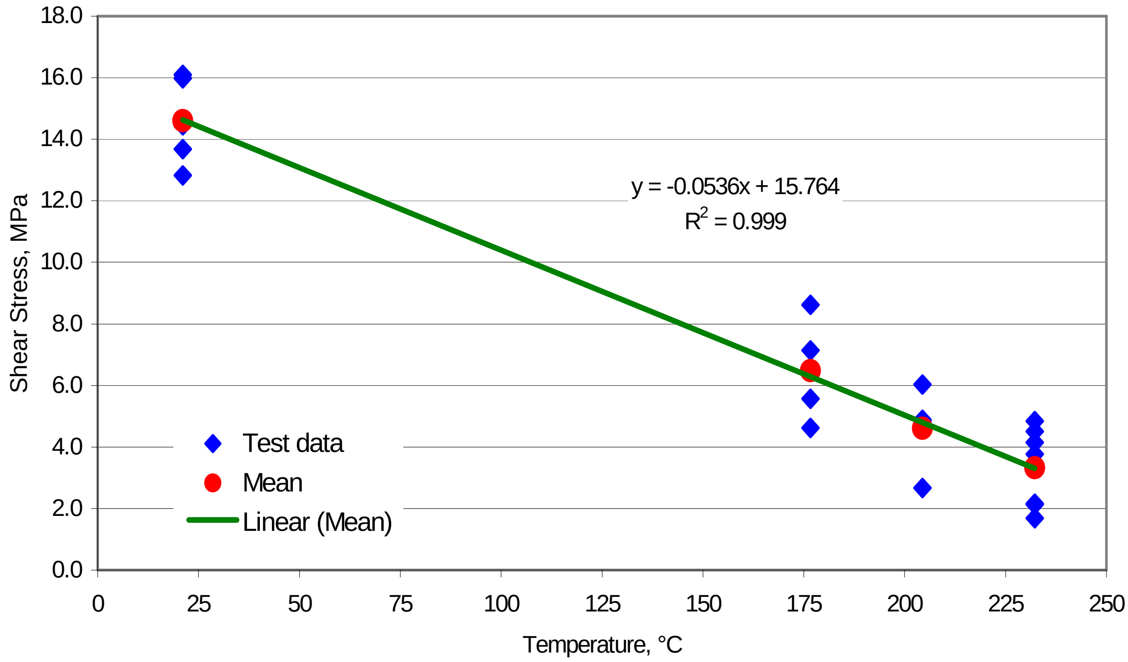

Figure 1. Shear strength of solid wood (Douglas fir) specimens at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration (APA data)

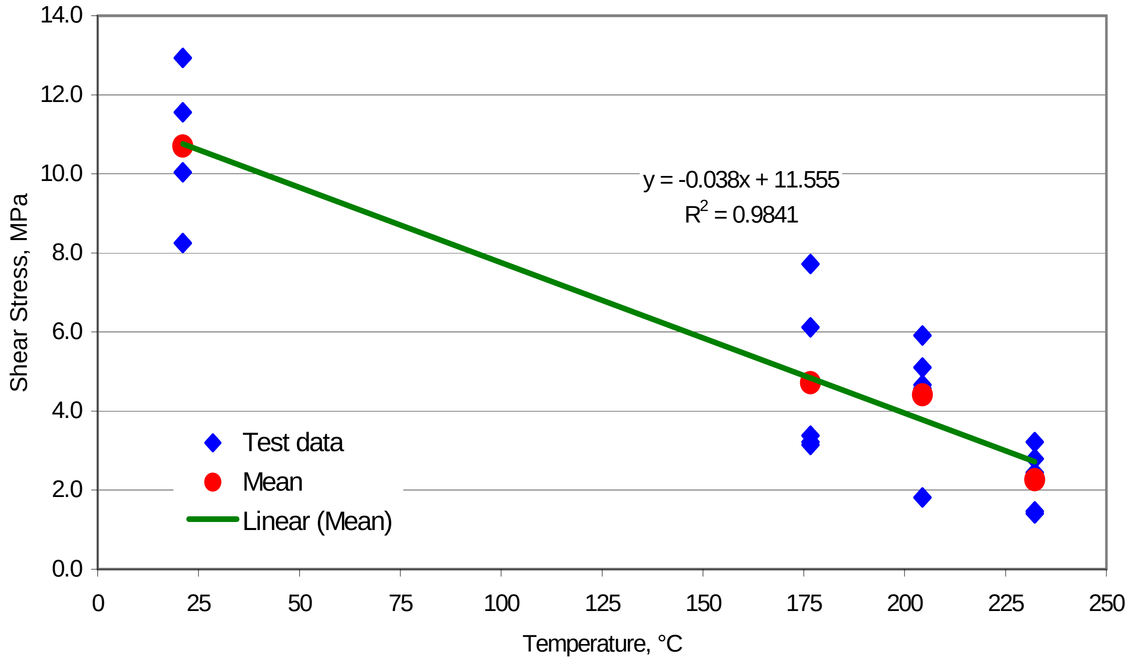

Figure 2. Shear strength of solid wood (Douglas fir) specimens at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration (Weyerhaeuser data)

2.2 Sensitivity Studies

A series of tests were conducted by APA and Weyerhaeuser to evaluate the sensitivity of the industry standard using 6 commercially available non-phenolic adhesives with 5 replicates per adhesive, as shown in Table 1. All specimens were fabricated by the Weyerhaeuser, and tested at

APA and Weyerhaeuser 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.

Table 1. Adhesives tested in sensitivity studies

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)

Results from the APA tests are shown in Figure 3. Weyerhaeuser results are shown in Figure 4. For comparison purposes, the results from control (solid wood) specimens, as previously mentioned in Figures 1 and 2, are superimposed in Figures 3 and 4. Similar trends were observed.

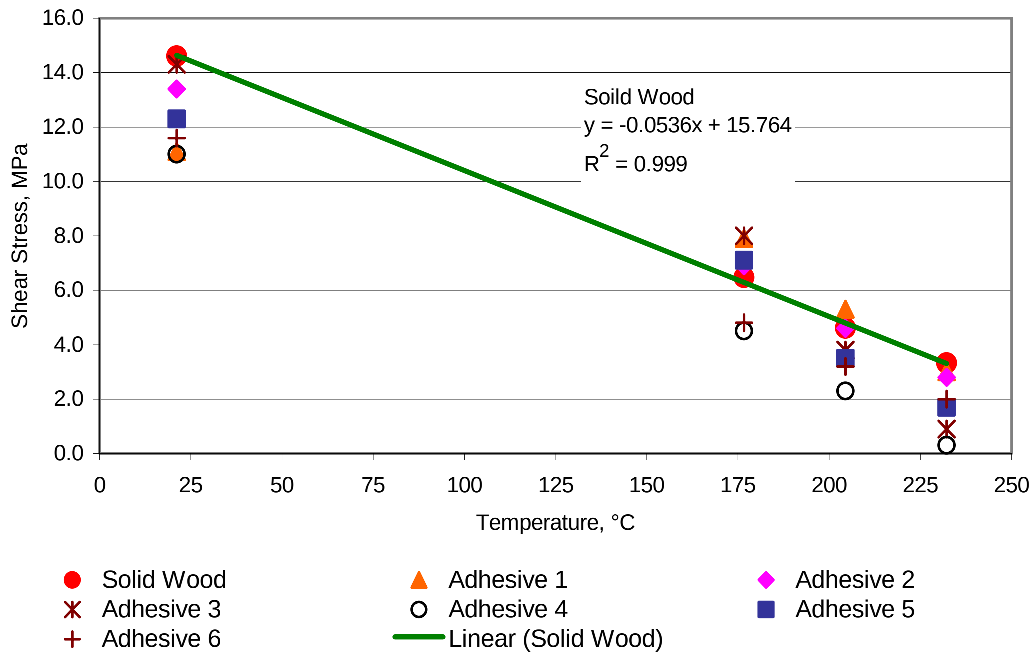

Figure 3. APA test results for shear strength of solid wood (Douglas fir) specimens and 6 adhesives at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration

As noted from Figures 3 and 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). These results suggest that the test method developed by the industry appears to be capable of segregating adhesive performance at an elevated temperature.

Note that the above test data were derived following the ASTM D7247 test method, with the only exception that the specimens were not oven-dried for 24 hours and cooled in a desiccator. The committee decided to specify oven-drying after reviewing the test data to further remove any shear strength effect due to moisture and to ensure that the specimen weight reduction during the test was primarily due to thermal degradation.

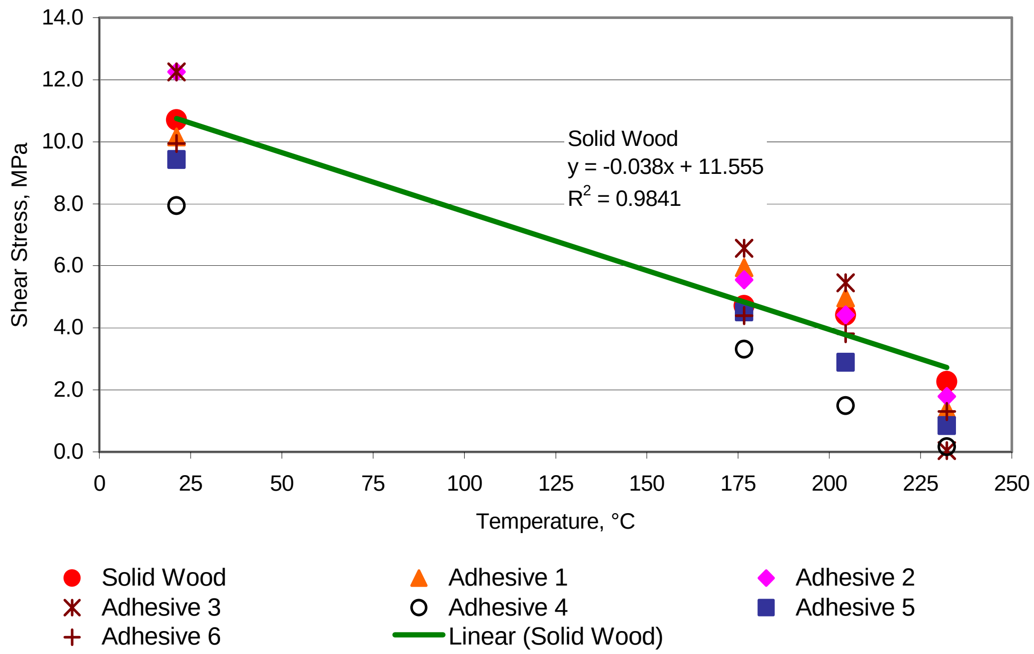

Figure 4. Weyerhaeuser test results for shear strength of solid wood (Douglas fir) specimens and 6 adhesives at various temperatures, as measured at the middle of the shear block specimens, for 1-hour duration

2.3 Acceptance Criteria

To account for test uncertainties, 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. The adhesive is 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.

3. The ASTM D7247 Standard

After its approval by the engineered wood products industry in March 2005, the industry standard, APA/WIJMA AC1000-05, was submitted in its entirety to the ASTM D14 Committee on Adhesives for adoption in July 2005. A substantial philosophical debate took place at the ASTM committee in October 2005, concerning the scope of the standard, after a D014.03 Subcommittee ballot. The majority of the committee members believed that the ASTM standard should focus on a generic test method without a specific temperature and heat exposure duration. The committee agreed that the specific test conditions should be left to the product standard committee, such as ASTM D07.02 on Lumber and Engineered Wood Products, to establish specific performance attributes in accordance with the intended applications for the engineered wood products.

With this general consensus, the test method given in the industry standard was approved by the D14 Main Committee for publication in April 2006. This new ASTM standard, designated as ASTM D7247, *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures*, contains essentially the same test method described in APA/WIJMA AC1000-05 without the specific temperature, heat exposure duration, and performance criteria.

With the approval of ASTM D7247, ASTM D07.02 Subcommittee will take on the challenge in establishing specific requirements for adhesive performance at elevated temperatures for prefabricated wood I-joists and structural composite lumber (SCL). A committee meeting has been scheduled on June 6 through 7, 2006 to develop a ballot in revising ASTM D5055, *Standard Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists* (ASTM 2005), and ASTM D5456, *Standard Specification for Evaluation of Structural Composite Lumber Products* (ASTM 2006b).

There are a few significant issues that need to be resolved by the ASTM D07.02 Subcommittee in the immediate future:

1) Heat exposure duration -- While APA/WIJMA AC1000-05 specifies 232°C (450°F) and 1 hour heat exposure duration based on the consideration previously mentioned, it may be arguable that the specified temperature and exposure duration are too severe, as compared to the performance of engineered wood products, such as I-joists, in an unprotected assembly, which typically fails in less than 10 minutes. On this basis, there seems to be a general consensus that the heat exposure duration could be limited to 10 minutes at the targeted temperature to allow time for the entire glueline surface (beyond the thermocouple) to reach a uniform temperature.

2) Targeted temperature -- This by far has been the most divisive issue. From the viewpoint that the intent of the industry is to establish a standard that demonstrates the adhesive bonds in engineered wood products are comparable to solid wood when exposed to temperatures up to unpiloted wood ignition, the targeted temperature should be as close to the wood ignition temperature as possible. This is the basis under which APA/WIJMA AC1000-05 specified 232°C (450°F), and is the current industry standard pending review by the D07.02 Committee. Other considerations currently debated are:

    a) It is arguable that the intent of the industry could be satisfied by specifying both a solid-wood shear-strength-degradation benchmark and a minimum temperature requirement. Based on the data presented in Figures 1 and 2, it appears that the targeted retention strength of 20% (i.e., the strength degradation of 80%) between the elevated temperature and ambient conditions can be used an upper bound of a performance-based criterion. ASTM D7247 contains a non-mandatory example of such a performance-based concept as follows:

        i) The targeted temperature should not be less than 204°C (400°F), and
        ii) The exposure duration should be sufficient to reduce the mean shear strength of solid wood control specimens by at least 50% but not more than 80%, or 10 minutes, whichever is longer.

        The choice of a minimum temperature of 204°C (400°F) is open for debate. One supporting argument for this temperature has been that the actual temperature under an unpiloted fire would flash over with a very short duration. Since most glueline within a joint in I-joists and SCL is likely to be protected by wood, the actual glueline temperature experienced during an unpiloted fire would hardly reach 232°C (450°F), or, if it did reach temperature, the time differential between 204°C (400°F) and 232°C (450°F) is minimal. One opposing argument would be that permitting an adhesive that fails prior to wood at elevated temperatures, regardless of the wood insulating effect, is not incorporated into current product standards, which assumes the adhesive behaves like wood. The product standard may need to be revised to specify a minimum insulating layer of wood to protect the glueline from heat exposure. The resulting interpretation of this protective layer would be difficult for I-joist applications such as finger joints in flanges and the web/web glueline, which are directly exposed to fire.

b) A Canadian study underway has shown sensitivity to elevated temperatures using a constant load method, starting at ambient temperature and increasing oven temperature up to 220°C (428°F). Test data suggest that adhesives with poor performance at elevated temperatures tend to fail below a glue line temperature of 204°C (400°F). While test results from the Canadian constant-load method are not directly comparable to the ASTM D7247 post-temperature test, it does demonstrate a broad range of adhesive performance when the oven is set for 220°C (428°F). Similar to the United States, work is currently underway to address the elevated temperature performance issue in the CSA standards and to determine the minimum temperature requirements.

3) Performance criteria -- Based on the principle of APA/WIJMA AC1000-05, it is generally agreeable that the ratio of the mean residual shear strength between the targeted temperature and ambient temperature for the bonded specimens should be equal to or higher than the lower 95% confidence interval on the ratio of the mean residual shear strength for the solid wood specimens. Table 2 shows the results based on the APA data presented in Figures 1 and 3. It is important to note from Table 2 that the selection of the targeted temperature is critical to Adhesives 3 and 5, which performed acceptably at 204°C (400°F), but perform poorly at 232°C (450°F).

Table 2. Adhesive performance in accordance with the performance criteria

Adhesive	Temperature	Residual Strength	Criteria
Control	204°C 232°C	0.26[a] 0.13[a]	--
Adhesive 1	204°C 232°C	0.49 0.13	Pass
Adhesive 2	204°C 232°C	0.36 0.15	Pass
Adhesive 3	204°C 232°C	0.44 0.00	Pass Fail
Adhesive 4	204°C 232°C	0.19 0.02	Fail
Adhesive 5	204°C 232°C	0.31 0.09	Pass Fail
Adhesive 6	204°C 232°C	0.38 0.13	Pass

[a] The lower 95% confidence interval on the ratio of mean residual shear strength

4. Conclusion

In response to the general expectation that the adhesives used in engineered wood products will not lose the bond strength more than wood does when exposed to elevated temperatures in unprotected assemblies, the engineered wood products industry in North America has successfully developed and published a consensus-based test standard, ASTM D7247, *Standard Test Method for Evaluating the Shear Strength of Adhesive Bonds in Laminated Wood Products at Elevated Temperatures*. With this test standard in place, the industry is taking on the challenge in establishing specific requirements for adhesive performance at elevated temperatures for prefabricated wood I-joists and structural composite lumber (SCL) under ASTM D07.02 Subcommittee on Lumber and Engineered Wood Products. The heat exposure duration, targeted temperature, and performance criteria are key issues that need to be resolved by the committee in the immediate future.

5. References

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