# Comparison of Test Methods for the Determination of Delamination in Glued Laminated Timber

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Engineered wood products are becoming more prevalent in the residential and commercial construction industries and need to be regulated by standards that ensure their classification and performance requirements. The applicable standard in Australia for the qualification of glued laminated timber is AS/NZS 1328.1:1998 (2011), last revised in 2011. Confusion exists with the specific interpretation of the testing procedures and subsequent methods used for the delamination process. Two methods currently used for product qualification were compared: one using a drying chamber and the other using a standard laboratory dehydrating oven. The trials conducted in accordance with the standard showed a significant difference in glue line delamination between the two testing methods. This was attributed to the lack of humidity and airflow control within the laboratory dehydrating oven and an incomplete drying of the test samples, resulting in different stresses on the glue line. It is evident that the current standard procedure requires clarification to ensure consistency in the test methods and comparable test results.

*Keywords: Engineered wood products; Glued laminated timber; Glue line delamination; Australian standard; Drying oven; Dehydrating oven*

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## INTRODUCTION

Engineered wood products (EWPs) are rapidly finding favour in the construction and furniture-manufacturing sectors on a global level, with the main driving factor behind this transition being an increase in timber demand compared to supply capacity. In Queensland, Australia, demand is projected to increase by 33% by 2020, with production capacity predicted to supply only 65% of the domestic market requirement (Timber Queensland 2011). Products such as plywood, glued laminated timber (glulam), and cross-laminated timber (CLT) use previously underutilized material for purpose-made products, which are dimensionally accurate and stable with superior mechanical properties in comparison to raw timber equivalents. Structurally rated formaldehyde-based adhesives such as resorcinol formaldehyde are used in the manufacture of EWPs and remain an industry standard. Isocyanate-based adhesives (IBAs), including polyurethanes (PUR), are a relatively recent adhesive technology and are also finding use in EWP production. These rapid-cure adhesives have gained approval for load-bearing applications in external conditions in both Europe and the United States (Aicher *et al*. 2015).

For EWPs such as glulam and CLT to replace solid timber as structural elements, they need to conform to the minimum mechanical property requirements of their intended applications. These are dictated by a series of manufacturing and performance standards, either global or country specific, that establish specifications and procedures to ensure that

products, services, and systems are safe, reliable, and consistently performing as intended. They establish the minimum requirements defining the quality and safety criteria, and they are usually adopted into legislation. Some standards that regulate the production of glued laminated timber include the international standard ISO 12580 (2007), the American standard ASTM D2559-12a (2012), the European standard BS EN 14080 (2014), and the Australian / New Zealand standard AS/NZS 1328.1:1998 (2011).

All of these standards outline the timber and adhesive requirements for glulam element production, product verification processes, qualification, and routine test procedures. Whenever a new product, a new process, or a process change, such as a new adhesive or species, is to be introduced into the market, preliminary qualification tests have to be conducted to ensure compliance. Routine tests are a means of monitoring production and are conducted as a means of quality assurance.

Both qualification and routine procedures test the bond integrity of the glulam element by the introduction of a moisture gradient within the element. This induces an associated stress gradient with high tensile stresses perpendicular to the glue line, which will either result in the fracture of the timber lamella or a delamination of glue lines if the bond strength is inadequate. Delamination is assessed as part of the individual glue line as well as the total glue line of the element. All standards involve a procedure that fully impregnates test samples with water followed by a drying cycle. While the technique for the water impregnation cycle is shared among standards, there are differences in how the drying cycles are conducted. All have similar requirements for temperature and humidity within the drying chamber, but determination of the circulating airflow varies among the standards. AS/NZS 1328.1:1998 (2011) requires test specimens to be dried for a period of 21 h to 22 h at 60 °C to 70 °C with a relative humidity (RH) not greater than 15% and a circulating air velocity over the samples of 2 m/s to 3 m/s. ASTM D2559-12a (2012) also stipulates a drying temperature of 65.5 °C ± 2 °C for a period of 21 h to 22 h, but the air circulation is defined as that which is sufficient to reduce the sample weight to within 15% of the original test specimen mass. The European standard was updated in 2004 to reflect the drying cycle of the American standard, but prior to this it was similar to the Australian standard in that it specified a required air velocity based on a time.

While maintaining the correct temperature and humidity levels within the drying chamber can be digitally monitored and controlled, measuring the air velocity (specifically, how and where to measure the air velocity within the drying chamber) has proven to be a point of confusion when testing to the AS/NZS 1328.1:1998 (2011) standard. The ambiguity on this matter has resulted in several different procedures being used to measure and set airflow within the chamber. These include determination of air velocity in an empty chamber prior to loading the samples, velocity measured in front of the samples, velocity measured between the samples, and velocity measured behind the samples. One testing body uses a laboratory dehydrating oven and has suggested that the air velocity inside the chamber is not a critical factor in the drying process but is more a means of venting excess moisture from the chamber, with velocity measured to standard requirements at the exhaust vent.

While the dehydrating oven method and drying chamber method meet the requirements of the standard through temperature control, minimised humidity, and airflow control, they do so in different ways, depending on the interpretation of the standard. This study compared the method using a standard laboratory dehydrating oven with that of a fully controlled drying chamber to determine whether there are differences in the delamination outcomes as outlined in AS/NZS 1328.1:1998 (2011).

## EXPERIMENTAL

### Materials

Material supplied for the study was a randomized mix of two exotic pine plantation species, slash pine (*Pinus elliottii*) and Caribbean pine (*Pinus caribaea*). The test material comprised strength-graded Machine graded pine (MGP) 15 backsawn boards sized at 90 mm × 35 mm × 5400 mm with an average timber moisture content of 12%. Boards that presented a high frequency of high-density late wood on the face and had minimal defects were selected for the trial. These were reduced to 400-mm lengths and allowed to condition at 20 °C and 65% RH (12% equilibrium moisture content, EMC) in a constant environment chamber until constant mass was achieved.

### Sample Manufacture

Eight glulam elements of six lamellae were manufactured for the study as follows. Forty-eight 400-mm-long boards were passed through a rotary planer fitted with newly sharpened blades to remove 2 mm from all contact surfaces in 0.5 mm increments. The boards were randomly presented for adhesion within 60 min of planing and adhered using a structural rated, single-component polyurethane adhesive (1C-PUR, Jowat Jowapur 686.70, Jowat Klebstoffe, Detmold, Germany). This was applied at a spread rate of 200 g/m$^2$, applied to one contact surface in each glue line and pressed on a dual-axis gluing bench at 1.2 MPa, ensuring that the whole process did not exceed the specified open time of the adhesive. The total press time was 180 min at 20 °C and 50% ambient RH. The glulam elements had a final size of 400 mm x 190 mm x 90 mm. All samples were stored at ambient conditions for 7 d to ensure that the adhesive had achieved full cure.

The centrepoint of each glulam element was determined and marked. One side of each of the eight elements was labelled from 1 to 8, and the other side was labelled from 9 to 16. The elements were cut along the centreline to yield 16 separate test samples (Fig.3).

### Testing Procedure

Each test sample was treated according to the requirements of AS/NZS 1328.1:1998 (2011), Appendix C, test cycle A, as follows. A 75 mm test sub-sample was obtained from the centre of each 200 mm test sample. Each glue line was labelled from 1 to 10, and the length of each individual glue line across the grain was determined using digital calipers under a magnifying lens and recorded. Water impregnation was performed in a treatment cylinder by total immersion of the test samples in water at 20 °C and application of a vacuum at -78 kPa held for 5 min, followed by a pressure cycle of 550 kPa for 1 h. While still immersed, the vacuum/pressure cycle was repeated, resulting in a two-cycle impregnation period.

Samples 1 to 8 were placed in a computer-controlled laboratory drying chamber, arranged approximately 60 mm apart, and oriented so that the end grain was perpendicular to the flow of air. The chamber was baffled to ensure that all airflow was directed over the samples. An initial airflow of 2.4 m/s was set in the centre of the sealed chamber and 50 mm in front of the samples using a vane anemometer calibrated by the National Association of Testing Authorities (NATA) (Fig. 1). Initial airflow measurements were recorded in front of each sample before starting the drying cycle. All samples were dried under constantly monitored and controlled conditions for 21 h at 65 °C and less than 15% RH, with an air velocity of 2.4 m/s. Both temperature and RH were monitored over the duration of the run with two HOBO MX1101 temperature/RH data loggers (Onset Computer

Corporation, Bourne, MA, USA). These were placed in the centre of the chamber at two locations within the airflow, 100 mm in front of the samples, and 100 mm behind the samples, and set to log at 5-min intervals. The water impregnation and drying cycles were performed twice before the samples were inspected for delamination, as outlined in AS/NZS 1328.1:1998 (2011).


**Fig. 1.** Airflow measured in dehydrating oven with flow controlled through exhaust vent

Samples 9 to 16 were dried in a Thermoline Scientific TO-235F laboratory dehydrating oven (Thermoline Scientific, Wetherill Park, NSW, Australia) with the temperature control set at 65 °C. Four rack shelves were evenly placed in the oven chamber, and two samples were placed on each shelf approximately 300 mm apart. Air velocity was measured at the exhaust vent of the kiln until a final exhaust velocity of 2.64 m/s was achieved. Adjustment was *via* an adjustable flap on the air inlet fixture. Initial airflow measurements were recorded at three locations (left, centre, and right) on each shelf before starting the drying cycle (Fig. 2).

**Fig. 2.** Airflow measured in dehydrating oven with flow controlled through exhaust vent

All samples were dried for 21 h at 65 °C, with no control of RH. Both temperature and relative humidity were monitored with three HOBO MX1101 temperature/RH data loggers (Onset Computer Corporation, Bourne, MA, USA). These were placed in the centre of the top, middle, and lower shelves and set to log at 5-min intervals. The water impregnation and drying sequence was repeated twice before the samples were inspected for delamination as outlined in AS/NZS 1328.1:1998 (2011). A schematic representation of the sample manufacture and testing process is shown in Fig. 3.

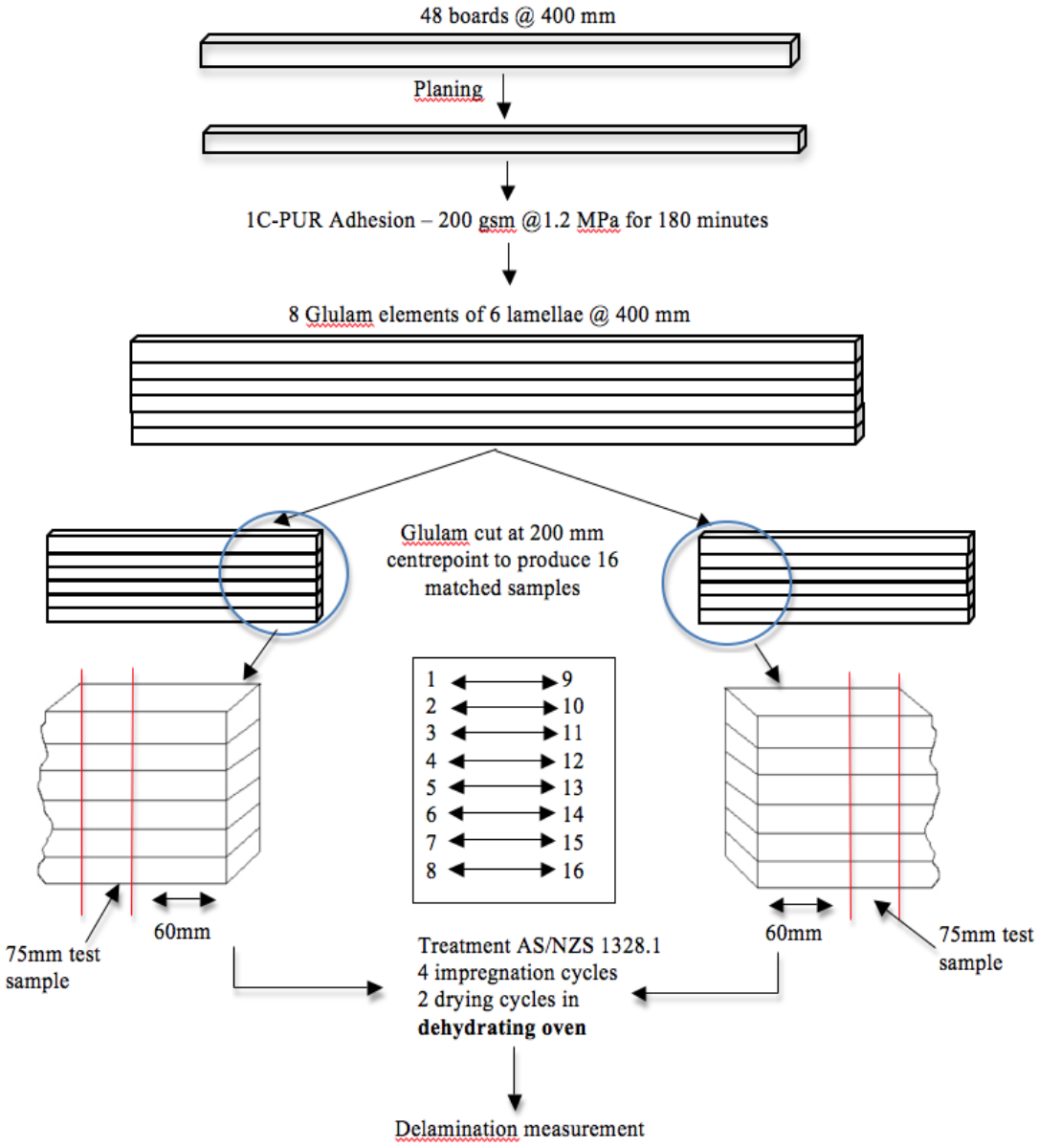


**Fig. 3.** Sample manufacture and testing process

Delamination of gluelines was measured within 1 hour of completion of the drying cycle using digital calipers and an illuminated desk stand magnifier. Delamination was considered to be areas with an open glueline that was as a result of adhesive failure. Delamination on areas of defects, such as knots and knotty areas, were not measured and

were excluded from the assessment. Delamination as a result of timber fiber failure, checking, or other causes was also not included in the measurements of calculations.

The acceptance criteria established in the standard for a Type 1 adhesive delamination test allow a maximum delamination of 40% for each individual glue line and no more than 5% total delamination of the sum of all glue lines. An extra test cycle should be performed if the total delamination is greater than 5% but less than 10%. The total delamination percentage should not exceed 10% after this final cycle for the sample to pass.

## Moisture Content Determination

After delamination measurements were completed, moisture content determination samples were removed from two positions within each of the 16 glulam elements. A 15-mm cube was cut 15 mm from the bottom edge of the bottom lamella at a position 35 mm in towards the centre, along the grain. A second 15-mm cube was obtained from the centre of the glulam element, also 35 mm in, along the grain (Fig. 4). After initial weights for each block were recorded, all samples were placed in a dehydrating oven at 103 °C overnight.

The samples were allowed to cool in a desiccator before obtaining an oven-dry mass. All samples were then returned to the dehydrating oven at 103 °C and dried for a further 2 h. After cooling in a desiccator, the samples were weighed, ensuring constant mass and comparing to the previous oven-dry weight (in accordance with AS/NZS 1080.1:2012 (2012).

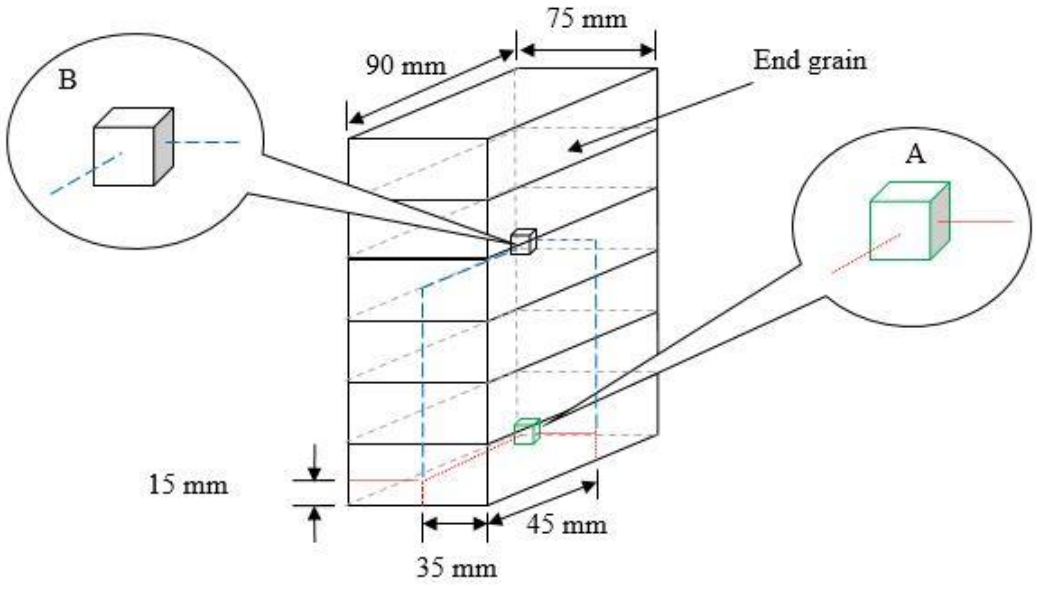


**Fig. 4.** Moisture content samples (A) from the middle outer edge and (B) from the centre of the glulam block

## RESULTS AND DISCUSSION

Comparison of airflow measurements within the loaded chambers revealed a distinct difference in the measured air velocities of the two drying methods. The computer-controlled drying chamber delivered a consistent airflow across all samples, ranging from 2.15 m/s to 2.56 m/s, within the parameters set out by the standard. The dehydrating oven showed a much less consistent airflow throughout the chamber. Greater velocities were measured along the left side of the chamber where the air entered the oven, while lower velocities were recorded along the right side of the chamber. The lowest velocities were recorded in the centre of the chamber, with the bottom of the oven registering no airflow (Fig. 5). None of the velocities measured in the dehydrating oven met the requirements of the standard.

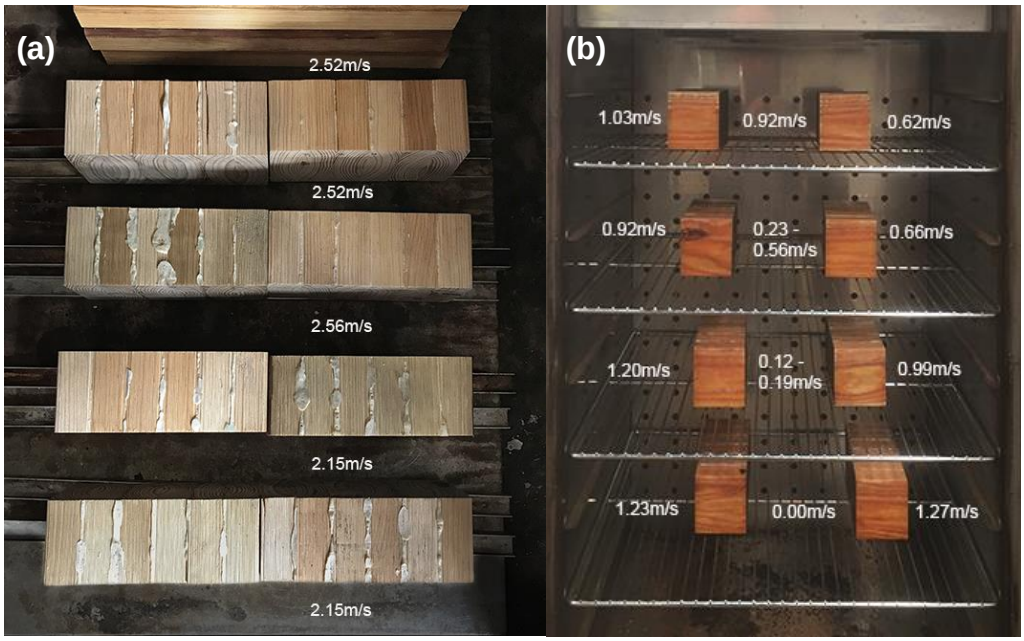


**Fig. 5.** Measured air velocities in (a) drying chamber and (b) dehydrating oven

Although the temperatures of the drying chamber and the dehydrating oven were well controlled within the parameters of the standard (Fig. 6), the RH recorded over the treatment period showed a marked difference in the regulation capacities of the two methods, as displayed in Fig. 7. The drying chamber accurately controlled the temperature and humidity within the standard's specifications. As expected, the dehydrating oven accurately controlled the temperature but was outside of the limits specified in the standard for the RH, which should remain less than 15% during the treatment period. Instead, the RH was at 26% when the drying cycle began and did not decrease below 15%, as required by the standard, until 12 h into the drying cycle. This indicates that the humidity was not adequately evacuated, possibly due to the high water content and high evaporation rate of the specimens.

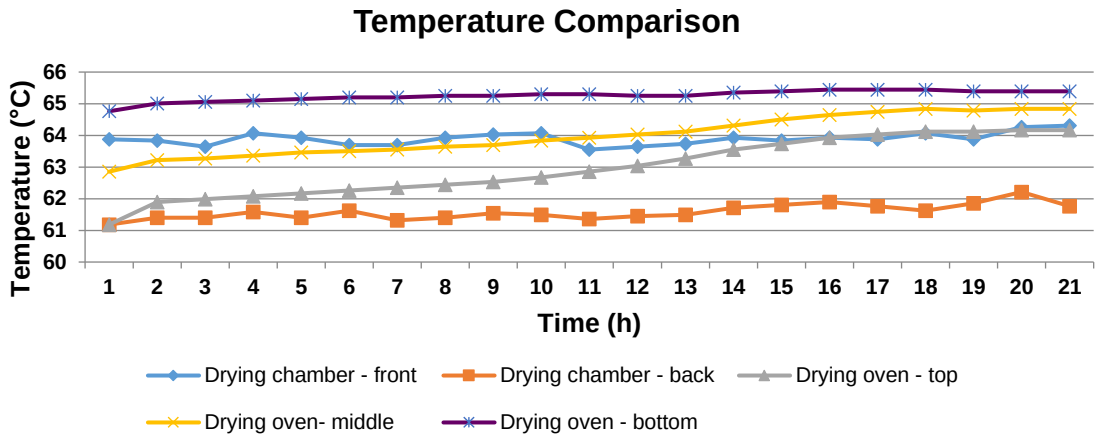


**Fig. 6.** Temperature comparison between the drying chamber and the dehydrating oven over the 21-h trial

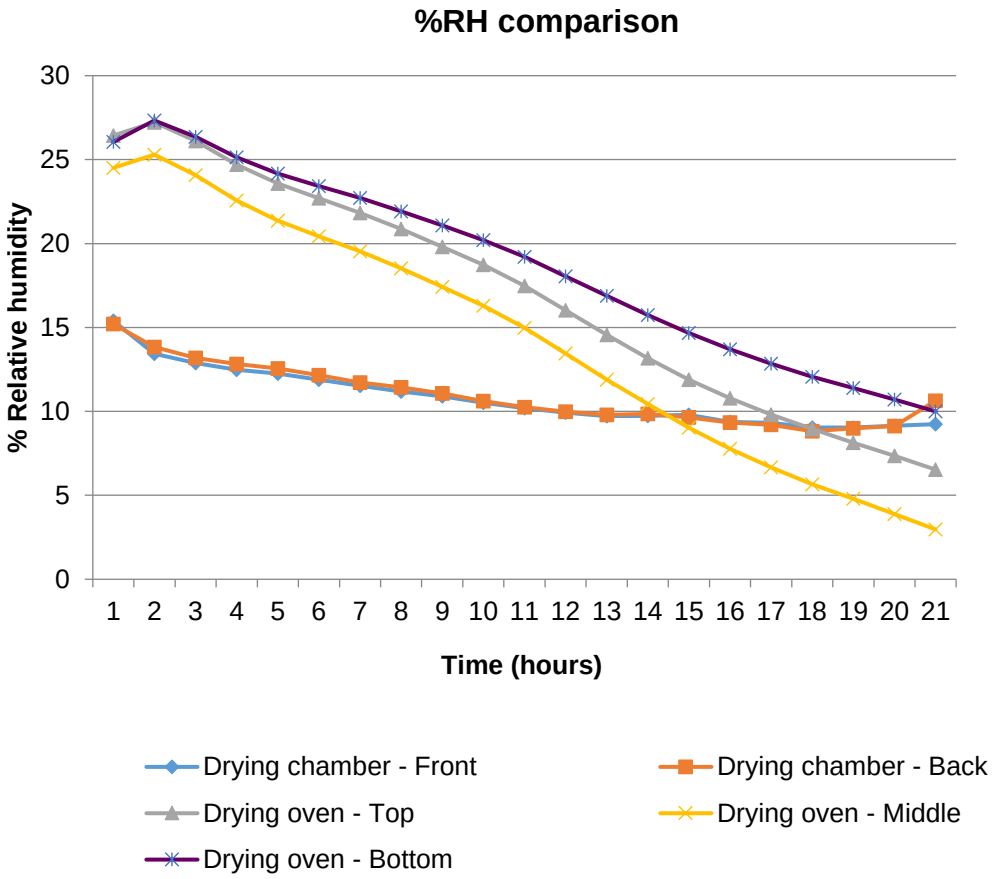


**Fig. 7.** Comparison of relative humidity (RH) recorded inside the drying chamber and the dehydrating oven, showing the variability between the two methods over the 21-h run time. Red line denotes the 15% maximum allowable RH, as specified by the standard.

The delamination results of the matched samples from the two different drying methods reveal noticeable differences, as shown in Table 1 and Fig. 8. Only one of the specimens in the drying chamber exceeded the maximum allowable delamination of 40%,

but it also exhibited a high overall level of total delamination. Overall, 50% of the glulam specimens placed in the drying chamber passed the requirements for both maximum delamination percentage and total delamination percentage. Although all the specimens dried in the dehydrating oven achieved maximum delamination percentages less than the 40% outlined in the standard, none of them passed the requirement for total delamination percentage. The average total delamination percentage was 18% for the dehydrating oven, while it was 7.4% for the drying chamber.

**Table 1.** Drying Chamber and Dehydrating Oven Delamination Outcomes after Treatment to AS/NZS 1328.1:1998 (2011), Appendix C

| | Drying Chamber | | | Dehydrating Oven | | |
|---|---|---|---|---|---|---|
| Sample Numbers | Maximum Delamination (%) | Total Delamination (%) | Outcome | Maximum Delamination (%) | Total Delamination (%) | Outcome |
| 1 and 9 | 7.3 | 4.1 | Pass | 16 | 18.4 | Fail |
| 2 and 10 | 9.8 | 5.2 | Fail | 15.2 | 16.2 | Fail |
| 3 and 11 | 6.9 | 3.3 | Pass | 22.4 | 14.9 | Fail |
| 4 and 12 | 19.3 | 9.2 | Fail | 19.9 | 12.3 | Fail |
| 5 and 13 | 12.5 | 4.4 | Pass | 31.1 | 18 | Fail |
| 6 and 14 | 48.8 | 12.7 | Fail | 19.1 | 11.2 | Fail |
| 7 and 15 | 10.1 | 4.6 | Pass | 19.7 | 27.7 | Fail |
| 8 and 16 | 34.1 | 15.6 | Fail | 26.4 | 24.9 | Fail |
| Average | 18.6 | 7.4 | | 21.2 | 18.0 | |

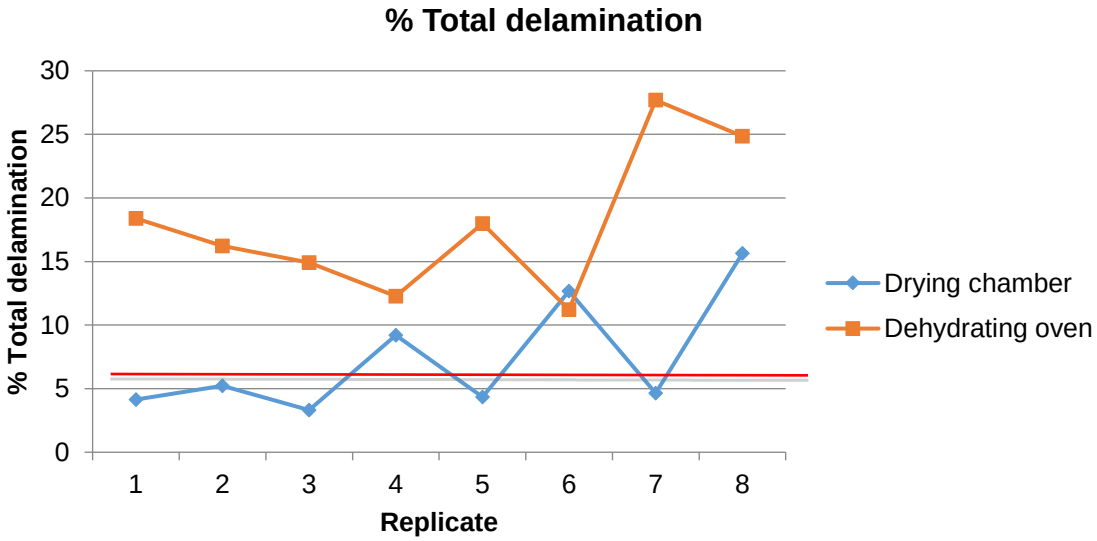


**Fig. 8.** Comparison of total delamination results for samples in the drying chamber and in the dehydrating oven. Red line denotes 5% threshold for total delamination, as defined in the standard.

A Wilcoxon signed-rank test was conducted to determine the effect of the treatment conditions within the standard specifications on the total delamination percentage. The

differences in scores were approximately symmetrically distributed, as assessed by a histogram with superimposed normal curve. Data are medians unless otherwise stated. Of the 8 glulam specimens manufactured for the study, the dehydrating oven yielded greater total delamination in 7 specimens compared to samples placed in the drying chamber. Matched samples 6 and 14 showed similar total delamination. There was a statistically significant average median decrease in the total delamination percentage when the specimens were exposed in the drying chamber (7.4%) compared to the dehydrating oven (18.0%), resulting in an 10.6% difference ($z = 0.017$, $p < .05$).

This outcome was unexpected, because the drying capacity of the drying chamber is far superior (with greater air velocity and better control of RH, adhering to the standard) to that of the dehydrating oven. The cause of the greater delamination in the dehydrating oven specimens was investigated by analysing the gradient of moisture content within the specimen. Table 2 and Fig. 9 show a marked moisture content difference on average and within the specimen gradient. The outer moisture content is that measured from the 15-mm blocks close to the edge of the glulam elements (Fig. 4, position A), while the inner moisture content is that obtained from the blocks taken at the centres of the glulam elements (Fig. 4, position B).

**Table 2.** Drying Chamber and Dehydrating Oven Specimen Moisture Content after Treatment to AS/NZS 1328.1:1998 (2011), Appendix C

| | Drying Chamber | | | Dehydrating Oven | | |
|---|---|---|---|---|---|---|
| Matched Specimens | Position A MC (%) | Position B MC (%) | Difference MC (%) | Position A MC (%) | Position B MC (%) | Difference MC (%) |
| 1 and 9 | 12.8 | 6.6 | 6.2 | 24.8 | 18.5 | 6.4 |
| 2 and 10 | 13.5 | 6.6 | 6.9 | 30.9 | 14.8 | 16.1 |
| 3 and 11 | 12.8 | 10.9 | 1.9 | 28.3 | 17.3 | 11.0 |
| 4 and 12 | 12.0 | 10.2 | 1.8 | 28.7 | 17.7 | 11.0 |
| 5 and 13 | 10.9 | 9.9 | 1.0 | 27.3 | 16.6 | 10.7 |
| 6 and 14 | 12.4 | 10.2 | 2.2 | 31.0 | 20.4 | 10.6 |
| 7 and 15 | 12.0 | 11.5 | 0.5 | 24.3 | 16.9 | 7.4 |
| 8 and 16 | 13.3 | 11.4 | 1.9 | 34.1 | 19.8 | 14.3 |
| Average | 12.5 | 9.7 | 2.8 | 28.7 | 17.7 | 10.9 |

MC – moisture content

The average outer and inner moisture contents were, respectively, 28.7% and 17.7% for the dehydrating oven specimens and 12.5% and 9.7% for the drying chamber specimens. As expected, the drying chamber showed a more effective drying capacity than the dehydrating oven due to the greater air speed on the specimen surfaces. Interestingly, the difference between the inner and outer moisture content was more than three times greater in the dehydrating oven specimens than in the drying chamber specimens. As the moisture gradient within the wood is directly related to the internal stresses placed upon the timber lamellae and ultimately the glue line, any large difference in the gradient between the outer portion and the inner portion of the glulam element will increase the stresses within the timber. This was the case with the dehydrating oven samples.

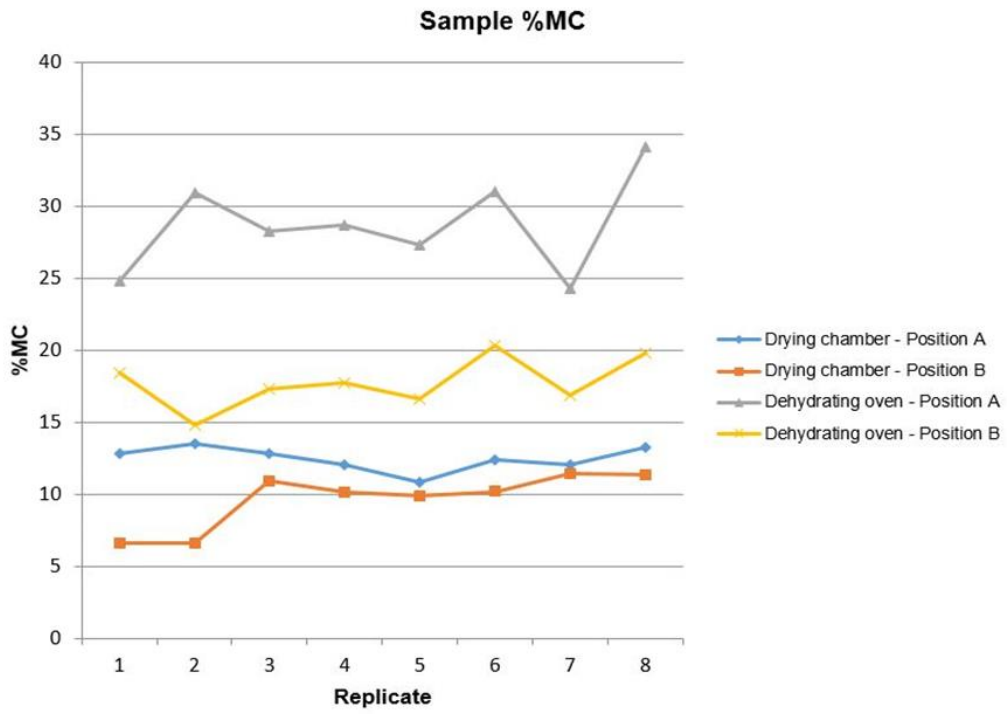


**Fig. 9.** Comparison of moisture contents determined from the outer zones of the glulam elements (position A) and the centers of the glulam elements (position B)

The lack of controlled airflow over the samples resulted in a slower drying rate of the timber. Consequently, at the end of the 21-h cycle, the samples had not dried to the same extent as those that were placed in the drying chamber. This was evident when comparing the checking patterns of the specimens exposed to the two different drying methods (Fig. 10). The specimens dried in the drying chamber exhibited checking on the fully exposed end-grain face, indicating that the timber had dried to a level below the fibre saturation point, resulting in internal stresses that caused the timber to shrink and crack. In comparison, the specimens dried in the dehydrating oven only exhibited checking on the outer perimeter, and the centre was devoid of any checking, indicating that the moisture levels in this zone were still greater than the fibre saturation point. These moisture differential stresses also became evident when the glulam elements from the two different treatments were cut from the base towards the centre. The samples from the dehydrating oven had enough stress that the timber sprang outwards when cut, in an effort to relieve the stress within the timber due to the drier external timber material. The samples from the drying chamber showed little movement at all (Fig. 11).

A Wilcoxon signed-rank test was conducted to determine the effect of the treatment conditions on the moisture content differences between the inner and outer areas of the specimens. The moisture content differences between the two treatment samples were compared for all the matched samples. Data are medians unless otherwise stated. Of the eight glulam specimens manufactured for the study, all the dehydrating oven samples showed a greater difference in moisture content between their internal and external parts compared to the drying chamber samples. There was a statistically significant decrease of the average of differences, as shown in Table 2, in the moisture content differential (on average 8.1% gap) when the specimens were exposed in the drying chamber (2.8%) compared to the dehydrating oven (10.9%) ($z = 0.012$, $p < .05$).


**Fig. 10.** (a) Specimens dried in the drying chamber exhibited a more uniform checking pattern than (b) those dried in the dehydrating oven. A central zone was easily identified where no checking had occurred.

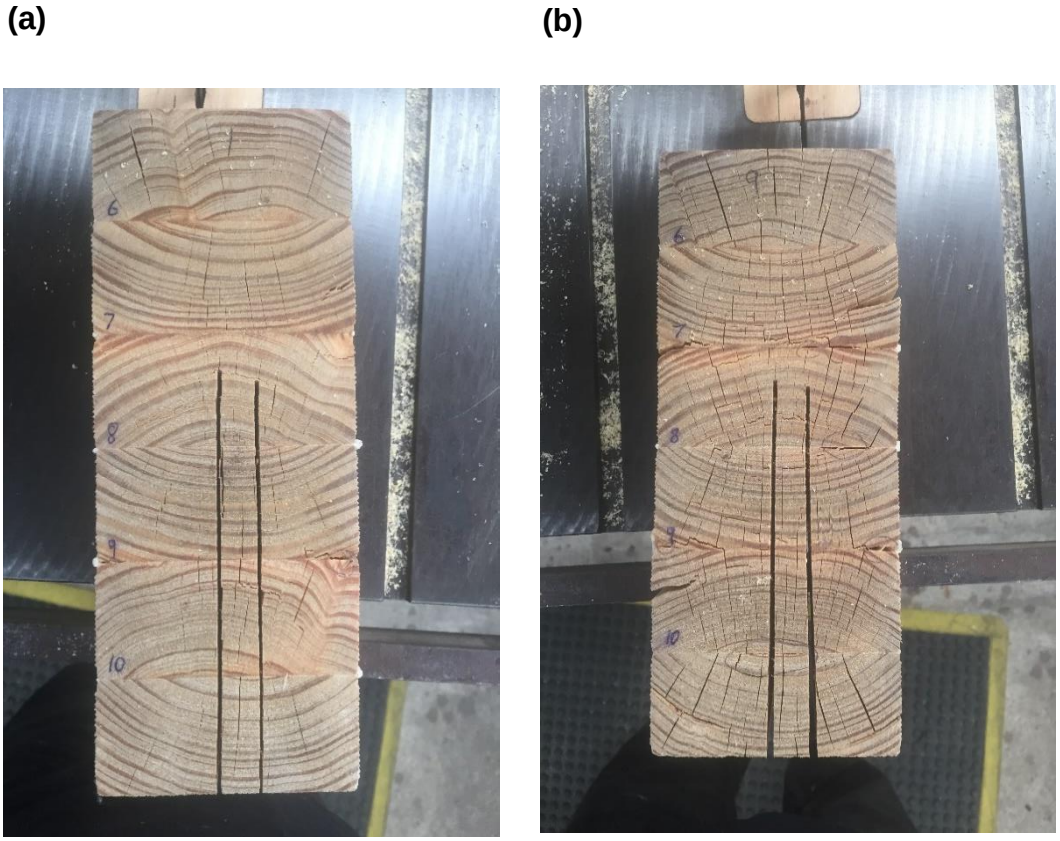


**Fig. 11.** (a) The specimen dried in the drying chamber showed little stress and movement in the cut due to the minimal moisture gradient. (b) The specimen dried in the dehydrating oven (right) had greater stresses within the timber, causing the cuts to open up.

Although it was evident that the dehydrating oven dried the samples at a slower rate, it is also possible that the drying chamber may cause an underestimation of the delamination. A moisture differential, resulting from the drying process, is what induces the great stresses within the timber, causing the delaminations. While the differential exists, the outer shell of the lamella is under tension due to shrinkage caused by the loss of moisture, while the inner core remains under compression due to the greater moisture content. This results in the lamella either bowing or cupping, which in turn causes stress on the glue line. If the adhesive has not created a strong bond, the adhesive will break within the glue line, which is classified as a delamination. A well-bonded glue line, in contrast, will cause the timber to crack, resulting in timber failure in the glue line area. As the drying step of the treatment progresses, the differential between the shell and the core diminishes, and the moisture of the lamella approaches equilibrium. The tension and compression stresses will dissipate, and the lamella will settle back to its original shape, thus reducing the stresses on the glue line. In this case, it is possible that the delaminations that were present during the periods of high stress will close up and, although still present, will no longer be evident when assessed under a magnifying lens.

## CONCLUSIONS

1. There was a significant difference between the two methods currently used for assessment of glue laminated structural elements according to AS/NZS 1328.1:1998 (2011) requirements. The drying chamber meets all the requirements of the standard with relation to temperature control, humidity control, and airflow. On the other hand, the dehydrating oven only has the ability for temperature control with no regulation of humidity or airflow over the samples. The outcome is less controlled drying and greater delamination of the samples in the dehydrating oven. The more effective drying capacity of the drying chamber gave a moisture difference that was three times less than the dehydrating oven specimens. The direct relationship between the moisture gradient within the wood and the internal stresses placed upon the timber lamellae would therefore result in decreased stresses on the glueline for samples in the dehydrating chamber. These results demonstrate the need for clarification of the standard procedure to ensure that there is reproducibility of results.

2. The two methods tested in this trial were both considered suitable given the ambiguity of the Australian standard yet resulted in significantly different levels of delamination.
3. The results showed that the current version of the standard (AS/NZS 1328.1:1998 2011) requires further research and redrafting. This will ensure that there is sufficient clarity in the methodology for better testing uniformity among testing bodies.

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