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# VIABILITY OF HYBRID POPLAR IN ANSI APPROVED CROSS-LAMINATED TIMBER APPLICATIONS

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## ABSTRACT

The development of cross-laminated timber (CLT) technology has opened up new perspectives for low-density hardwood species, which have traditionally not been rated as construction-grade materials for structural engineering applications. Several characteristics of the CLT, namely thermal performance, seismic behavior, and speed of construction, have raised interest among designers. The CLT technology has recently been used for residential and non-residential multi-story buildings and it has been identified as one of the ways for achieving tall timber building construction. As CLT gains acceptance in the industry, low-density wood species, not specified in current American National Standards Institute (ANSI) standards, need to be investigated for potentially successful use in CLT panels. This paper presents a study that demonstrates the viability of a Forest Stewardship Council (FSC) certified sustainable plantation grown low-density species, hybrid poplar (marketed as Pacific Albus), for use in performance-rated CLT panels by following the ANSI/APA PRG-320-2012: Standard for Performance-Rated Cross-Laminated Timber shear and bending test guidelines to determine the structural viability of the CLT panels.

**KEYWORDS:** Construction Materials, Cross-Laminated Timber, Engineered Wood Products, Green Building Materials, Hybrid Poplar, Wood, Wood Composites



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## INTRODUCTION

Cross-laminated timber (CLT) is an engineered structural composite panel usually consisting of three to nine layers of dimensioned lumber arranged perpendicular to each other. CLT has been successfully used as prefabricated walls, floor and roofing elements and is being proposed as a new solution for tall wood building construction (Mohammad et al. 2012). In 2011 a standard for performance-rated CLT panels (ANSI/APA PRG-320) was published and later updated in 2012. This standard provided an impetus towards acceptance of CLT in the U.S. construction industry as recently the International Code Council approved the inclusion of ANSI approved CLT panels as a building material in the 2015 International Building Code (AWC 2012).

The raw material most commonly used for construction of CLT in Europe is structural C24-grade spruce or pine, which has densities ranging from 420 kg/m$^3$ to 500 kg/m$^3$ at 12% moisture content (MC). In the US, the ANSI standard provides the requirements for the use of visually graded, machine stress rated, and structural composite lumber (SCL), in CLT panels. The standard further limits the density of lumber material to 350 kg/m$^3$ and above for use in CLT. As CLT gains acceptance in the industry, alternative and other low-density species of wood (not specified in ANSI/APA PRG-320), need to be investigated for potentially successful use in CLT panels.

The need for researching alternate uses for low-density species is increasing from oversupply of typically non-structural grade hardwoods. Hybrid poplar is an example of low-density hardwood (density between 300-350 kg/m$^3$) grown in the Pacific Northwest (PNW) region. The hybrid poplar plantations are Forest Steward Council (FSC) certified sustainable timber plantations. A value-added use for the wood is needed preferably as a sustainable building material. Therefore, the objective of this study is to demonstrate the viability of FSC certified plantation grown low-density species, like hybrid poplar, for building structurally graded CLT panels. The viability of the low-density wood for use in CLT is based on a series of tests according to ANSI/APA PRG-320-2011, namely by following shear and bending test guidelines to determine the characteristic strengths and stiffness of the panels.

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## MATERIALS AND METHODS

### Manufacturing of Cross-Laminated Timber

Hybrid poplar (marketed as Pacific Albus) was procured from Boardman, Oregon. The individual boards were No. 2 or better. The initial dimensions of the lumber were 36 x 140 x 3048 mm. The lumber was conditioned prior to CLT manufacturing in a standard room maintained at 20ºC and 65% relative humidity. The boards were planed prior to lamination. Additionally, each board was sized using a joiner in order to minimize gaps between boards created by minor warping. All of the CLT panels in these tests were three layered, each board averaging 32 mm in thickness, with each panel having a three board thickness totaling a panel thickness of approximately 96 mm. The width of each board after sizing was approximately 137 mm, with each panel having three boards in width with an average full panel width of 412 mm after pressing. The lengths of the boards were cut to 2794 mm, in order to meet the necessary span-to-depth ratio of 27 required by the subsequent bending test method ASTM D4761.

The adhesive used between the layers was Hexion CASCOPHEN® LT-5210J resin and CASCOSET® FM-6210 hardener. The adhesive was combined using a resin-hardener mixture ratio of 2.5:1 (by weight). The resin is a liquid, phenol-resorcinol, timber laminating resin. The glue mixture for each panel used was 60 pounds per 1000 square foot, which was within the recommended spread rate of 55 to 100 pounds of mixed glue per 1,000 square feet of glue joint. This adhesive system is recommended for wet-use or dry-use exposure and meets the requirements of ANSI/AITC A190.1 and also conforms to AITC 405.

Developing a pressing process required some ingenuity. The recommended pressure for the adhesive was 700 to 1000 kPa. With a panel area of 1.15 $m^2$ (412 mm x 2794 mm), the minimum force required to reach the target pressure was 805 kN. This was accomplished through a system of 8 threaded rods (38 mm) and nuts, which carried the load through a configuration of multiple 6.4 mm thick steel c-channel (see Fig. 1). The applied wrench torque $T$ in each nut was 700 N-m, which produced a preload

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force of 123 kN per rod. The maximum calculated force on the panel is approximately 984 kN, which meets the pressing requirement for the adhesive being used.

The panel layup was random with regard to the consideration of the placement and orientation of individual boards. The adhesive mixture was applied using a paint roller. The total assembly time of each test specimen was less than 60 min, measured from initial mixture to total pressure applied to final layup. The required pressing time for the adhesive was approximately 8 h, which was always met or exceeded (average pressing time was 24 hours). Due to irregularities in individual boards, dimensions of the final panels varied slightly, and these were re-cut to ensure straight edges. This was accomplished using a large band saw. The average value for panel width after cutting was 400 mm.

## Testing Methods

### *Non-Destructive Bending Tests*

There were 10 individual boards that made up each CLT panel, and each board was tested for dynamic modulus using a Metriguard Model 340 E-Computer, which utilizes a transverse vibration method to obtain the dynamic modulus of elasticity reported as Average Board Modulus of Elasticity (ABMOE) in Table 1. The results from the CLT panels were compared to their constituents to verify a correlation between individual board stiffness and panel stiffness. These tests were completed on all of the boards, except for the boards used to manufacture the first panel, since a correlation between individual board strength and panel strength was not considered until the results from the first panel were compared with published hybrid poplar properties.

### *Bending Tests*

Bending properties of the panels were assessed by conducting flat-wise, third-point bending tests as per ASTM D4761 and as recommended in ANSI/APA PRG-320. The testing apparatus used is shown in Fig. 2. Specimen dimensions were 400 mm wide by 96 mm thick, and the on-center span was 2.54 m, which resulted in a span-to-depth ratio of 27. The specimens were loaded to failure using a displacement based loading rate of 12.7 mm/min using a 178 kN (40 kips) capacity MTS actuator.  An LVDT sensor was

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used at the center-line to obtain deflection. A load-deflection curve was hence obtained and used for calculating the measured modulus of elasticity (MOE) and Modulus of Rupture (MOR) using relationships presented in Fig. 2. Because CLT is not homogeneous, these calculated MOE and MOR values were also adjusted for composite section using k-method of composite theory (Blass and Fellmoser 2004). For a three layer section, the equation is:

$$k = 1 - \left(1 - \frac{E_{90}}{E_0}\right)\left(\frac{a_{m-2}^2}{a_m^2}\right) \tag{1}$$

where, $k$ is the composite factor, $E_0$ is the MOE in the longitudinal direction, $E_{90}$ is the MOE in the transverse direction, $a_{m-2}$ is the thickness of the inner layer, and $a_m$ is the outside (total thickness) of the section. CLT handbook presents a general assumption that $E_{90} = E_0/30$, this further simplifies the equation. Since all specimens in this test are approximately of the same size and configuration, the composite factor $k$ of 0.964 is computed using Eq. 1 (with $a_{m-2}$ = 32mm and $a_m$ = 96mm) for all panels.

During the bending tests, an optical measurement instrument based on the principles of digital image correlation (DIC) was used to measure the strain that developed on the x-z plane along the edge of the panels. DIC is a full-field, non-contact technique for measurement of displacements and strains. The principle behind DIC is well understood and explained in Sinha and Gupta (2009), where the reader is directed for more background. The DIC setup consisted of a pair of cameras arranged at an angle to take stereoscopic images of the area of interest. The area of interest was adjacent to the loading point, where the largest combination of shear and bending moment were expected. Once the cameras were set up for each test, a calibration of the DIC system was done to reduce error in the measurements. The cameras were externally triggered to capture images at a rate of one picture every ten seconds during the tests and were connected to a computer where the images are stored. Using Vic 3D (Correlated Solutions Inc., 2010), the images were analyzed to obtain strain values for the areas of interest.

### *Short Span Bending Tests*

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Short span bending tests were conducted according to ANSI/APA PRG-320, which refers back to the center point tests described in ASTM D4761. These tests were used to determine the maximum shear stress ($f_v$) and the interlaminar shear capacity ($f_s$). The testing equipment was the same as used in the third point bending tests. These short span tests had a span of 508 mm, which is approximately 5 to 6 times the depth (96 mm). The overhang to either side of the supports was minimal. The loading rate of 1.27 mm/min ensured that the tests met the minimum requirement of 4 min to reach failure.

### *Block Shear Tests*

Block shear tests were conducted according to ASTM D905, at a loading rate of 5 mm/min in a universal testing machine with 100 kN (22.5 kips) capacity. Specimens were prepared according to the ANSI standard. Load was applied to the side of the sample that had a parallel grain direction, leaving the bearing side to the perpendicular grain section. The results from this test are considered to provide only an approximation of the shear strength, since there is not enough data to support a precise method to obtain the shear capacity of the given configuration.

## RESULTS AND DISCUSSION

### Bending Tests, Strain Progression, and Failure Mechanisms

The values obtained from the non-destructive bending tests represent the dynamic MOE. The mean value for these tests was 8446 MPa, which is slightly higher than a similar hybrid specimen static bending MOE value of 7540 MPa (Hernandez et al., 1998). Transverse vibration is known to overestimate the static bending MOE by 4-5% in Douglas-Fir samples (Ross et al., 2005), which may explain the higher values obtained. Our results estimates the dynamic modulus as approximately 10.7% higher after adjusting for composite section values in both, the static CLT panel tests and individual board tests. This is reasonable considering the relatively small sample size, which affects the precision of this study.

The results from the third point bending tests are presented in Table 1, which includes MOR, apparent MOE, failure load, and deflection. All seven panels were tested for MOE, with panels 04 and 05 not tested to failure, in order to obtain short span test specimens. The mean MOR was 26 MPa with a

COV of 25%, which is relatively high for a wood composite. Smaller sample size (5 panels) and laboratory manufacturing procedures might have led to larger variability. The mean apparent MOE was 7359 MPa, with a COV of 5.9%. Higher variation is observed in strip shaped specimens such as the ones in this study compared to full sized panels (Steiger and Gulzow, 2009) due to the heterogeneous nature of the material. Comparing the adjusted MOE values for the panel to another hybrid poplar specimen, the mean result was only 2% lower than Hernandez et al. (1998).

The values calculated for this study were a ranked percentile with linear interpolation between closest ranks, which gives a 5$^{th}$ percentile value using the range of values within a sample set. These values were calculated only for comparison purposes with the ANSI standard. No attempt was made to establish design parameters for CLT manufactured with hybrid poplar. The 5$^{th}$ percentile MOE was 7100 MPa while MOR was 18.2 MPa. Comparison of these values to the characteristic values in ANSI/APA PRG-320 shows that the MOE obtained experimentally is lower than the MOE of the lowest CLT Grade E3 (MOE = 8300 MPa). On the other hand, characteristic MOR values observed were higher than the listed values for Grade E3 (17.4 MPa). This indicates a potential for hybrid poplar to meet the bending strength requirements of CLT Grade E3, but not meet the current ANSI/APA PRG-320 MOE requirements, which is expected since hybrid poplar is a low-density wood species with a lower MOE.

Fig. 2 illustrates the commonly observed failure mechanism. Most of the panels (Tests 02, 03, 06, 07) failed in combined bending and shear in the region located next to the loading points in the section closest to the supports. DIC measurements were taken in several specimens tested in bending and an example of strain distribution (Test #06) throughout the composite section is presented in Fig. 3. The DIC images (Fig. 3) are taken at 50% of maximum load and immediately before failure of the specimen. As expected, the maximum longitudinal strains are seen at the top and bottom of the section due to bending. It should be noted that the boards were not edge glued, which may have contributed to the large amount of strain in the middle section shown in $e_1$ (major principle strain) immediately before failure. The shear strain ($e_{xy}$) contour plot in Fig. 3 provided an indication of the typical failure path, which can be seen in Fig. 2. The strain progression is assumed to be nearly symmetric across the centerline up to failure. It is further observed that the strain in the section tends to concentrate both in the laminations between the layers and the edges of the center layer boards. Strain is greatest between the loading point and the support, following a diagonal path along the top lamination, through a center layer board edge, and along the bottom lamination. The strain observed showed that the maximum strains occurred along the typical failure path, which is a diagonal cracking that develops near the loading point at the top to a point closer to the support at the bottom.

## Short Span Bending Tests and Failure Mechanisms

Short span bending tests provided maximum shear stress ($f_v$). This in turn was used to estimate the interlaminar shear capacity ($f_s$) based on one third of the calculated $f_v$. The COV associated with shear stress was 15.1% (Table 2), which is comparable to other similar wood products. Failure during short span tests was similar to failure observed in the long span bending tests. Typical failure was in shear adjacent to the loading point, carried from the bottom layer near the supports, to the top layer near the loading point. Additionally, few tests exhibited small tension cracks that developed in the bottom layer directly below the loading point. Shear throughout the section was the primary failure mechanism in the short span bending tests. The ranked 5$^{th}$ percentile values, which were calculated for comparison purposes only, were $f_v$ = 1.6 MPa, with a corresponding $f_s$ = 0.53 MPa. The characteristic test values from ANSI/APA PRG-320 for CLT Grade E3 are $f_v$ = 1.3 MPa, and $f_s$ = 0.43 MPa. Therefore, hybrid poplar potentially exceeds the ANSI/APA PRG-320 shear strength requirements.

## Block Shear Tests

The shear strength values obtained from the block shear tests (Table 2) were greater than the shear strength values obtained from the short span bending tests. Additionally, a relatively low COV of 8.2% was observed (Table 2). Shear strength values from ASTM shear block tests tends to overestimate the failure shear stress from bending tests in structural composite lumber (Lam and Craig 2000). Wood failure in excess of 85% was observed in all samples, which suggests good adhesive bonding (AITC T107). During testing, some squashing occurred in the bearing side of the block that had a grain

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orientation perpendicular to the loading plane. This may have affected some of the test values of the shear strength. Since there are no active standards that address the orthogonal layering configuration of CLT, this method is an approximation due to possible variation from rolling shear, which is the shear through the wood rather than the adhesive. The orientation of CLT should be considered when looking at strength results and evaluating adhesives. Block shear methods could be useful in the future to estimate shear strength without having to perform full panel testing.

## CONCLUSION AND RECOMMENDATIONS

The practical implication of the testing program performed was to determine whether hybrid poplar is a viable option for use in structural design of CLT. The results from the long and short span bending tests are promising since the experimental results show that the low-density (hybrid poplar) CLT will potentially meet and exceed the shear and bending strength requirements for ANSI/APA PRG-320 CLT Grade E3. However, hybrid poplar did not meet the stiffness requirements (MOE). These strength and stiffness testing results show that hybrid poplar CLT panels have a high structural efficiency (ratio between mechanical performance and wood density) and indicate that structural design using low-density CLT panels would be deflection governed. It is worth noting that hybrid poplar has not traditionally been used for structural applications, and emphasis should be placed upon accurate grading of boards and attention given to their location during panel layup.

Design of wooden structures is largely dictated by serviceability requirements. Although there are many current applications where CLT panels are used effectively, the use of hybrid poplar in CLT may not meet serviceability conditions on its own. However, like other engineered wood products, hybrid poplar could be utilized in conjunction with higher density species to achieve more efficient panels. More research is needed on CLT panels comprised of multi-species layers including low-density species such as hybrid poplar.

The work presented herein is a first step that provides encouraging results in what concerns the use of hybrid poplar for structural applications. Nonetheless, in future, a testing campaign that includes a larger number of samples can be undertaken to optimize the layering scheme of the hybrid poplar CLT panels. Furthermore, development of design guidelines and analysis verification tools can be developed to improve dissemination of the proposed CLT panel solution.

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## REFERENCES

AITC 405-2008. Standard for adhesives for use in structural glued laminated timber. American Institute of Timber Construction.

American National Standard ANSI/AITC A190.1-1992, Structural Glued Laminated Timber. American Institute of Timber Construction, 7012 South Revere Parkway, Suite 140, Englewood, CO 80112.

APA – The Engineered Wood Association. *Standard for Performance-Rated Cross Laminated Timber.* ANSI/APA PRG-320. Tacoma, WA. 2012.

ASTM (2012). Standard Test Method for Strength Properties of Adhesive Bonds in Shear by Compression Loading. ASTM 905-08. Annual Book of ASTM Standards, Vol. 15.06. ASTM, West Conshohoken, PA.

ASTM (2012). Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Material ASTM D4761-05. Annual Book of ASTM Standards, Vol. 04.10. ASTM, West Conshohoken, PA.

Blass, H. J., and Fellmoser, P. (2004). "Design of Solid Wood Panels with Cross Layers." *In 8th World Conference on Timber Engineering*, 14:2004.

Hernández, R. E., Koubaa, A., Beaudoin, M., and Fortin, Y. (1998). "Selected Mechanical Properties of Fast-growing Poplar Hybrid Clones." *Wood and Fiber Science* 30 (2): 138–147.

Lam, F. and Craig, B.A. (2000). "Shear Strength in Structural Composite Lumber." *Journal of Materials in Civil Engineering* 12 (3): 196–204.

Mohammad, M., Gagnon, S., Douglas, B.K., and Podesto, L. (2012). "Introduction to Cross-Laminated Timber." *Wood Design Focus*, 22(2): 3-12.

Ross, R. J., Zerbe, J. I., Wang, X., Green, D. W., and Pellerin, R. F. (2005). "Stress Wave Nondestructive Evaluation of Douglas-fir Peeler Cores." *Forest Products Journal*. 55 (3): 90–94.

Sinha, A. and Gupta, R. (2009). "Strain Distribution in OSB and GWB in Wood-Frame Shear Walls." J. Struct. Eng., 135(6), 666–675.

Steiger, R., and Gülzow, A. (2009). "Validity of Bending Tests on Strip-shaped Specimens to Derive Bending Strength and Stiffness Properties of Cross-laminated Solid Timber (X-lam)." *Proceedings of CIBW18 Timber Engineering*, University of Karlsruhe, Karlsruhe, Germany. Paper: 42–12.

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Figure1

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Figure 1: Fixture for pressing CLT panels

Figure2

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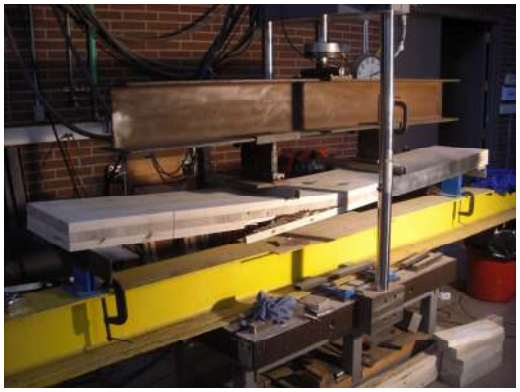

$$MOR = \frac{P_{max}L}{bh^2} \qquad MOE = \frac{23PL^2}{108bh^2\Delta}$$

Figure 2: Test set up and a panel (06) at failure and equations for calculating Modulus of Elasticity and Modulus of Rupture. Here, $P$ is the applied load (N); $L$ is the span of the CLT (mm); $b$ is the width (mm); $h$ is the depth of CLT (mm); $\Delta$ is center-span deflection measured from the LVDT (mm); and $P_{max}$ is the maximum applied load.

Figure3

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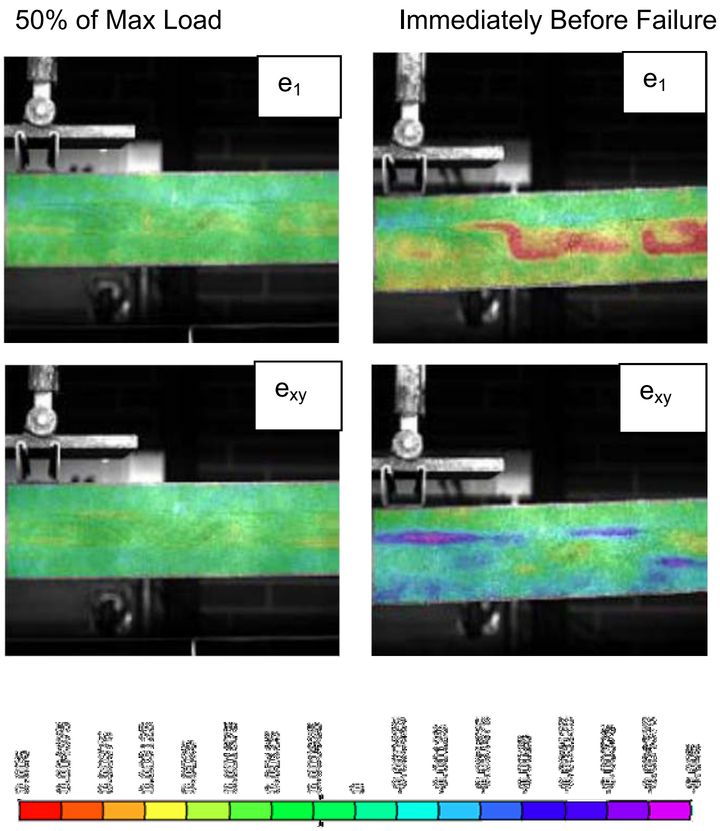


Figure 3: DIC strain measurement at 50% max load and immediately before failure along with its legend.

Figure 4

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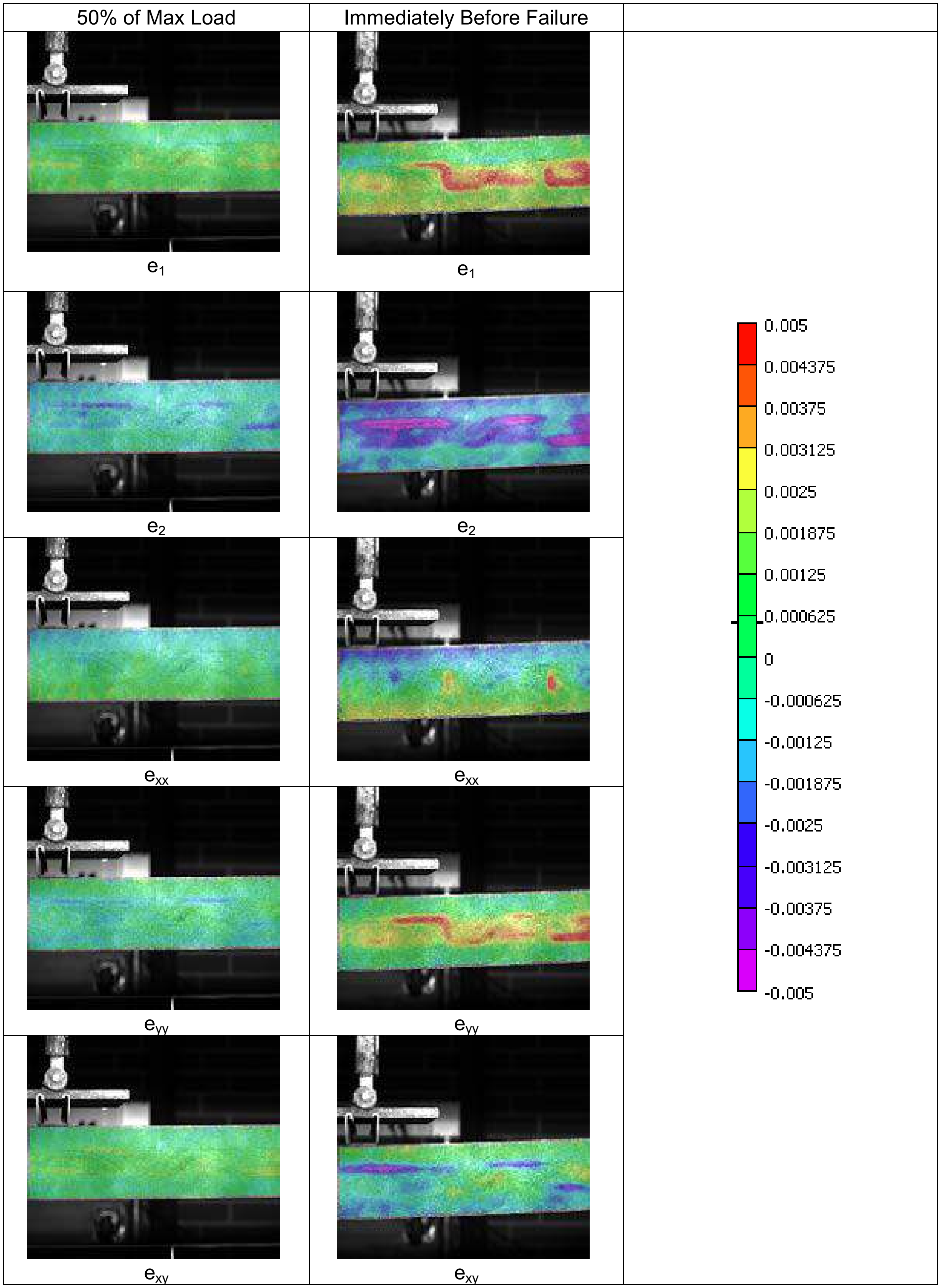


Figure 4: DIC strain measurement at 50% max load and immediately before failure

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**Table 1: Results from bending tests**

| Test | MOR | MOE | ABMOE | Maximum Load | Deflection at Failure | SG |
|---|---|---|---|---|---|---|
| Units | MPa | MPa | MPa | kN | mm | - |
| 01 | 17 | 7202 | - | 26 | 35 | - |
| 02 | 23 | 7050 | 9239 | 34 | 48 | 0.367 |
| 03 | 29 | 8291 | 8308 | 42 | 60 | 0.348 |
| 04* | - | 7288 | 8042 | - | - | 0.345 |
| 05* | - | 7443 | 7577 | - | - | 0.344 |
| 06 | 25 | 7120 | 7776 | 37 | 54 | 0.341 |
| 07 | 34 | 7097 | 7909 | 50 | 65 | 0.338 |
| Mean | 26 | 7356 | 8142 | 38 | 52 | 0.347 |
| STDEV | 6 | 433 | 591 | 9 | 12 | 0.010 |
| COV | 24.9% | 5.9% | 7.3% | 24.2% | 22.4% | 3.0% |
| Legend | MOE - Apparent Modulus of Elasticity (adjusted with composite factor k)<br>ABMOE - Average Board Modulus of Elasticity (dynamic, adjusted with composite factor k for comparison)<br>SG - Specific Gravity (measured dynamically)<br>STDEV - Standard Deviation<br>COV - Coefficient of Variation<br>*Panels not tested to failure; cut into sections for short span tests | | | | | |

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**Table 2: Results from short span bending and block shear tests along with their standard deviations (STDEV) and coefficient of variations (COV)**

| Short Span Bending Tests | | | | | Block Shear Tests | | |
|---|---|---|---|---|---|---|---|
| Test | Modulus of Rupture | Max Shear Stress | Max Load | Failure Deflection | Test | Max Load | Shear Strength |
| Units | MPa | MPa | kN | mm | Units | kN | MPa |
| 04 - 01 | 24.0 | 2.08 | 115 | 15.3 | 01 - B2 | 6.67 | 3.50 |
| 04 - 02 | 20.1 | 1.76 | 98.0 | 13.0 | 01 - B3 | 5.75 | 2.85 |
| 04 - 03 | 17.2 | 1.50 | 83.0 | 8.70 | 02 - B1 | 5.82 | 2.93 |
| 04 - 04 | 26.0 | 2.27 | 125 | 13.9 | 02 - B2 | 5.56 | 2.81 |
| 05 - 01 | 28.2 | 2.45 | 134 | 13.5 | 02 - B3 | 6.26 | 3.16 |
| 05 - 02 | 22.9 | 1.99 | 110 | 13.2 | 03 - B1 | 6.33 | 3.14 |
| 05 - 03 | 21.2 | 1.84 | 102 | 8.40 | 03 - B2 | 6.53 | 3.28 |
| 05 - 04 | 24.6 | 2.14 | 118 | 11.2 | 03 - B3 | 5.57 | 2.80 |
| Mean | 23.0 | 2.00 | 111 | 12.1 | Mean | 6.06 | 3.06 |
| STDEV | 3.00 | 3.02 | 16.0 | 2.50 | STDEV | 0.44 | 0.25 |
| COV | 15.1% | 15.1% | 14.7% | 20.4% | COV | 7.20% | 8.20% |