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IN-GRADE CLT FROM UNGRADED PINUS RADIATA BOARDS.

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ABSTRACT: Within the feasibility analysis for a Cross Laminated Timber (CLT) plant, the possibility to produce in-grade panels from boards that were not strength-graded according to the applicable standard was demonstrated by tests on panels produced in industrial conditions. The "cross-lamination effect" that explains this result was observed, and an innovative CLT lay-up with inner boards at 45deg angles was tested for the first time on Pinus Radiata. A set of scans and sorting feedback information, executed by Microtec on a sub-sample of the boards, provided a very useful insight and allowed significant resource optimization, particularly in the case of knotty boards. The comparison with a benchmark of C24 Spruce CLT, produced and tested in identical conditions, showed that higher in-plane shear resistance and modulus were achievable with ungraded Radiata Pine; this is a desirable performance for mid-rise construction (buildings of at least 4-storey high), which is a growing market trend, able to generate more value for the fraction of this fast-grown plantation timber which is currently not meeting the stud framing market specifications.

KEYWORDS: Ungraded boards, CLT, Radiata Pine, supply chain resilience

1 INTRODUCTION

Cross Laminated Timber (CLT) is changing the way architects and engineers look at wood construction systems as a viable alternative to concrete and steel in mid-rise construction, and beyond. Different countries have different definitions and regulations, and in Australia "mid-rise" means buildings with 25m maximum effective height (i.e. 4-9 storeys), but some projects have already successfully been built that exceed this height limit, through a specific "Performance Solution" addressing all the design specifications. Therefore, CLT is increasingly being selected by specifiers for several reasons including safer and quicker installation, lighter weight resulting in lower requirement for foundations (and/or consolidation of existing structures in vertical extensions of buildings), excellent sustainability credentials, wellness and comfort and, last but not least, cost-efficiency when the projects are well optimized for timber construction. Consistently with its mandate, Forest and Wood Products Australia (FWPA) has coordinated a number of initiatives in this field, including some R&D projects with industry stakeholders, one of which is described here.

Radiata Pine plantations are the major source of Australian structural products and therefore, when a local Company started considering the possibility to invest in a CLT plant, it was decided to run a feasibility analysis which included a research on the mechanical properties that might be obtained from their wood resources. Information is disclosed in this paper with some restrictions, consistently with the confidentiality agreements that the authors signed with the Company.

Machine-Graded Pine (MGP) was introduced in 1996 by Pine Australia (now Plantation Timber Association Australia), following an extensive, nationwide in-grade testing program of Australian Pine (radiata pine, pinaster pine, slash pine and Caribbean pine), undertaken by CSIRO and State Forests of NSW. The MGP grades are the result of a substantial research and development program by the pine industry to ensure that accurate and reliable design properties are available for structural pine timber in Australia, through standardized test methods [1]. The benefits of increased reliability for MGP products are not only based on MGP having more accurate information on the grade proper-ties, but also on the fact that all mills producing MGP are subject to stringent third-party auditing. This assesses appropriate machine grading and monitors property and other quality control procedures to ensure the validity and consistency of the MGP design properties. Therefore, MGP10 and MGP12 grades are currently the market standard for structural timber, and ungraded boards are not used by the frame & truss manufacturing industry that supplies the largest part of the low-rise construction market (detached houses, townhouses and multi-residential apartment blocks up to 3-storey). As a consequence, at the state of the art it was difficult to imagine that a structural product like CLT, which targets the mid-rise market, would not use MGP graded boards.

But to explore this possibility, which was considered potentially very significant for the optimization of the

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project's feasibility, we suggested to perform research with the aim to understand and quantify the potential benefits of innovative grading and/or layup strategies, possibly by using ungraded boards and deriving the characteristic values for structural engineering only from tests performed on the CLT panels. There are a few basic reasons why this scope of works was relevant for the Company:

- Even using only a fraction of their MGP10 and MGP12 boards for a new product, which is also potentially competing with frame & truss elements, would distract them from the established client base, therefore creating a major commercial risk;
- The MGP grading system is finalized to selecting boards for use as slender elements where buckling plays a significant role. Therefore, a single and isolated defect such as a knots or wane can already downgrade a whole board which, only a few centimetres away from that defect, may have very good mechanical qualities. The state-of-the-art solution to this problem (finger-jointing) is costly and may create a bottleneck in a CLT production;
- The effect of lamination, and even more of cross lamination, is known to "dilute" the influence of defects and therefore provide better performances than those measured on the single boards [2]. Bringing it within the grading and testing procedures may allow to optimize the yield from a fiber resource where knots and wane are relatively large (especially with respect to the board widths) like the fast-growing Radiata Pine plantation logs, which are currently considered having lower quality with respect to competing slow-growth logs.

In solid timber grading, the "reverse engineering" concept is sometimes used for in-grade testing to check production or to obtain the values representing the strength/stiffness distribution of available products as the basis for design, e.g. when a batch of ungraded timber needs to be used for a structural purpose. But so far, to our knowledge, this approach has not been applied to obtaining proprietary design values directly from product testing of CLT, instead of calculating them from the grades of the boards that are used to manufacture it. This is particularly strange because CLT is very similar to plywood in its mechanical behaviour: a few decades ago, before veneer grading machines were developed, plywood factories were testing samples from the pro-duction to derive the product's design strengths and stiffness values, as this was the only possibility. But when CLT was developed, producers and researchers were considering it more like solid timber or glulam, than a product with its own logic. Also, testing large amounts of panel samples being quite expensive, the use of available sawn timber grades to calculate the performances of CLT panels was preferred, and embedded into the Euro-pean Technical Approval Guidelines to become a market standard for many years. But this approach has proven to be particularly non-efficient for CLT, where the boards are used mostly in just two dominant stress modes (tensile bending or rolling shear), and cross lamination has a well demonstrated effect on the reduction of both fracture initiation and growth [3, 4].

The recent EN standard for CLT [5], whose drafting and approval took a very long time, has finally introduced the additional possibility to "recalculate" the mechanical properties of the timber layers from full-scale tests on panel samples. This acknowledgement of the applicability of the reverse engineering approach validates the scope and the methodology of this research.

2 MATERIALS AND METHODS

A container of Radiata Pine boards (Table 1), randomly sampled from the production at a sawmill in Australia, was shipped to XlamDolomiti's CLT factory in Italy. A narrow board width, also with respect to board thickness, was purposely chosen to maximize the influence of knots and wane, in a "worst case scenario" approach. The board cross section dimensions shown are net values, as used in the CLT after dressing before bonding.

Table 1: *Grades, sizes and quantities of the Radiata Pine boards used. The letter "U" means "Ungraded", while the letters "A" and "B" refer to two alternative sawing patterns.*

Grade	Width (mm)	Thickness (mm)	Length (mm)	Quantity (pcs)
MGP12	90	30	3300	128
MGP12	90	30	2400	128
MGP10	90	30	3300	256
MGP10	90	30	2400	256
U-A	90	30	3300	384
U-A	90	30	2400	384
U-B	90	30	3300	768
U-B	90	30	2400	768

As a first step, a random subsample of the rough sawn boards (4 packs = 512 boards) was sent to Microtec for a full non-destructive scanning, coding and grading with their GoldenEye 706 and Viscan equipment (which has a well-established correlation with MGP grades for plantation-grown Radiata Pine from the same area), in order to collect data enabling a subsequent, targeted panel layup optimization and the interpretation of failure modes (if needed). Then the boards were sent back to XlamDolomiti, for processing in their standard mill conditions, following the cycle described in the European Technical Approval (1-component PU adhesive, no edge bonding, top and side pressure).

A preliminary batch of 4x 90mm/3-layers panels was produced to test all the settings and perform the routine controls of bonding quality, then 14x 150mm/5-layers panels were produced for the mechanical testing, all in a 3300x2400mm size (LxW). A higher amount of rather small panels was preferred to a lower number of bigger panels to keep the boards' positions and alignment more easily under control. Table 2 describes the panel types and the tests which were planned on the resulting CLT samples.

The CLT panel layup is kept confidential, being part of the Company's intellectual property, but the "Purpose"

column in Table 2 clearly describes the logic that was followed in selecting the ungraded boards, based on the data provided by Microtec. The 45deg crossbands layup was inspired by the positive experiences reported for slow-growth Nordic Pine [6], therefore it was decided to replicate them with a fast-growth pine species. MGP12 boards were not used in the CLT manufacturing.
The samples in Table 2 were cut at XlamDolomiti and sent for testing at Universita' degli Studi di Trento, after the routine controls on bonding quality.

Table 2: *Grades, sizes and quantities of the Radiata Pine boards used. The letter "U" means "Ungraded", while the letters "A" and "B" refer to two alternative sawing patterns.*

Type	Purpose of the type's lay-up	BL	BG	DC	GT
Spruce	European benchmark	4	2	-	4
MGP10	Structural grade reference	4	2	4	4
U-A	Use the best ungraded boards	4	2	4	4
U-B_a	Understand the lower limit	4	2	4	4
U-B_b	Improve with respect to U-B_a	4	2	-	4
U-B_{45}	Try the 45deg crossbands	2	2	-	4

Table 3: *Explanation of the test codes used in Table 2.*

Code	Test type
BL	Four-point **Bending** tests perpendicular to the plan to failure on 450x3150x150mm CLT panels, according to EN 16351 Annex C2.1 for bending MOR and MOE (**Local**)
BG	Four-point **Bending** tests perpendicular to the plan to failure on 450x1950x150mm CLT panels, according to EN 16351 Annex C2.3 for rolling shear strength, rolling shear modulus and **Global** bending modulus
DC	In-plane shear tests with **Diagonal Compression** for in-plane shear strength and in-plane shear modulus, according to [7]
GT	Rolling shear tests, according to EN 16351 Annex C2.2 (**Guillotine Test**)

The test series is very similar to what is required for product development and/or approval of CLT panels, with just a reduced number of samples because the aim of the research was not obtaining statistically significant characteristic values for design, but just a proof of concept. Moreover, the test panels and then the samples were accurately assembled, based on the data provided by Microtec, to reflect the purposes described in Table 2 and to allow for the interpretation of any possible unclear fracture patterns.
In all the tests, the load was applied by means of an MTS 244.51 actuator with 1000kN capacity and 500mm stoke. For the bending tests an MTS FT60 controller was used, endowed with 16 +/- 10V acquisition channels: two couples of AEP strain gage displacement transducers were installed and ac-quired directly by the controller. Two 10 mm instruments acquired the relative displacement of the central joke, whilst two 100 mm jokes acquired the global displacements in the central position. Instruments were applied at both sides of the panel, in the central point, thus allowing to correct effects of any unwanted torsion deriving by alignment errors and/or specimen asymmetry.
In-plane shear tests were carried out according to [7]. This method induces shear failure by axially loading a square CLT panel at two opposite corners, like shear tests carried out on masonry, and it is a good alternative to a four-point bending test with in-plane oriented panels, where unwanted bending failure often arises. This test can single out the actual type of shear failure, either torsional on the glued surfaces or perpendicular to the grain. The set-up was adapted to the reduced size of the specimens, therefore the size of the plates on which the loads were applied were reduced proportionally to the expected, reduced failure load, to 150mm length. The same MTS 244.51 hydraulic actuator was controlled by an MTS Test Star 2 system. The actuator was clamped at the top and hinged at the bottom edge, and the panel was resting on the 150mm long steel plates, leaving a "free" core failure area a*a equal to 240*240mm wide. To acquire the panel deformation, two couples of jokes, each supporting a displacement transducer, were hinged at the corners of the core. As for previous tests, AEP 10 mm stroke, strain gage linear displacement transducers were used. For panels with 45deg crossbands this in-plane shear test was not performed because it is meaningless: with 5-layer panels, there's always at least one layer with internal boards parallel to the load direction, therefore a very high load is reached, with local crushing in correspondence to the load and rest plates. Moreover, the boards loaded parallel to the grain are present only on one side, so there is a geometrical asymmetry leading to a lateral bending during test, which is evident and dangerous (during testing) since the specimen instability can be reached.
Rolling shear tests were carried out according to EN 16351 by removing two external layers from the original 5 layers, leaving a 90 mm thick, 3 layers panel. The 361 mm length of the panel was chosen in order to obtain the necessary inclination of the acting force resultant: arctan(90/361) = 14deg. The outer layers are aligned to the direction of the load, which was applied by two stiff steel plates 30 mm wide, i.e. as wide as the outer layers. The upper plate was centred above the lower hinge of the actuator. The controller, acquisition cards and transducers were the same used in the bending tests. The transducers were aligned in the load direction and acquired the relative displacement of the mid-planes of the outer layers.
Figures 1-3 show some of the panels and test setups:

- The panels with diagonal crossbands
- The 4-point bending setup, and
- The planar shear tests setup.

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3 RESULTS

The results from the board scanning are summarized in Table 4, and those from the tests on CLT panels are summarized in Table 5.

From the data in Table 4, it is quite clear that also the ungraded boards have rather good strength and stiffness properties, and in particular:

- "A" has a predicted MOR/MOE profile which falls in between MGP10 and MGP12,
- "B" is lower in density and predicted MOR/MOE, while it is higher in knottiness.

Table 4: *Values of density, knottiness, MOR and MOE of the board types. Each value is the average of 128 boards, the number between brackets is its Coefficient of Variation. The knottiness is an index developed by Microtec for their grading algorithms, the MOR is the predicted lowest 5th percentile bending strength of the board, and the 3 different MOEs are, respectively: measured by a dynamic tool (Viscan), predicted from knottiness and density, and the average of the previous two. The table is split in 2 parts, with the same left column.*

Board Type	**Density** kg/m3	**Knottiness** -	**MOR** MPa
MGP12	547 (8%)	1,930 (50%)	39.9 (16%)
MGP10	499 (10%)	2,965 (46%)	29.6 (33%)
A	504 (8%)	2,402 (50%)	34.7 (24%)
B	483 (7%)	3,484 (34%)	24.6 (33%)

Board Type	$\mathbf{MOE_{dyn}}$ MPa	$\mathbf{MOE_{pred}}$ MPa	$\mathbf{MOE_{avg}}$ MPa
MGP12	14,251 (14%)	11,036 (13%)	13,538 (14%)
MGP10	10,852 (26%)	8,552 (25%)	10,309 (26%)
A	12,788 (17%)	9,967 (16%)	12,149 (17%)
B	9,488 (18%)	7,555 (17%)	9,014 (18%)

The main result of the tests on CLT is that with ungraded Radiata Pine boards randomly selected from the current sawmill production output (which is additional to the MGP grades output) it was possible to obtain panels whose mechanical performances matched, and in some case even exceeded, those of both the reference Radiata Pine panels made with MGP10 boards, and of the Spruce panel (which provided a significant bench-mark because it was made of boards with a very good quality).

Moreover, the effect of the two different sawing patterns ("A" and "B") was clearly visible from the tests, as was the result of using crossbands layered at 45deg, consistently with previous findings [6]. The improvement sought from the U-Bb sample by optimizing the cost-effective layup adopted in U-Ba was indeed obtained, validating the underlying hypothesis and the use of the scanning results to inform the selection of the boards with criteria that differ from the MGP grading rules. The U-B boards being very knotty, they would have a low yield if graded according to MGP10 rules, therefore discouraging the use of this sawing pattern for the frame & truss market, but they can become a valuable resource when used correctly for CLT, where an optimized layup results in good panel performances.

Table 5: *Average values (MPa) of the mechanical parameters measured on the CLT panels. The table is split in 2 parts, with the same left column. Note 1 - Timber boards on the single panel used as benchmark were of very good quality, with no significant defects, much better than an average C24 grade. Note 2 - Grs is computed based on the reduced area Ars. Note 3 - Average published data, from [7].*

Test	**Spruce**	**MGP10**	**U-A**
Bending strength (MOR)	38.40 (1)	29.29	33.51
Bending modulus (MOE)	11,070	8,359	10,565
Global bending modulus (E_{global})	9,055	7,392	9,133
Rolling shear strength (bending)	1.48	2.40	2.48
Rolling shear modulus (bending) (2)	-	65.4	65.5
In-plane shear strength	4.67 (3)	8.22	8.13
In-plane shear modulus	543 (3)	944	730
Rolling shear strength (guillotine)	1.36	2.18	2.26
Rolling shear modulus (guillotine)	72.7	170	208

Test	$\mathbf{U\text{-}B_a}$	$\mathbf{U\text{-}B_b}$	$\mathbf{U\text{-}B_{45}}$
Bending strength (MOR)	24.65	31.28	33.31
Bending modulus (MOE)	7,169	8,813	9,379
Global bending modulus (E_{global})	6,594	8,419	8,128
Rolling shear strength (bending)	2.15	1.95	2.33
Rolling shear modulus (bending) (2)	7.4	-	65.9
In-plane shear strength	7.99	-	-
In-plane shear modulus	688	-	-
Rolling shear strength (guillotine)	2.34	2.40	3.16
Rolling shear modulus (guillotine)	198	164	277

The confidentiality agreements in place do not allow for further disclosure on the results.

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4 DISCUSSION

When CLT panels are used as floor slabs, the bending stiffness is typically more important than the shear stiffness in reducing the structural deformability that often governs design; indeed, higher shear resistance is important for short span slabs with heavy loads, but this is rarely the case in residential design.

It is interesting to compare the estimate of the rolling shear parameters using bending or guillotine tests: the resistance is similar in both tests, but the guillotine test offers a simpler way to measure shear stiffness, and it can be easily carried out also to evaluate the bonding quality during production, therefore leading to higher number of measurements and providing a statistically more reliable information. Modelling of Radiata Pine CLT [4] have shown a 40% reduction of the critical load (associated with rolling shear failure) when edge-gluing is not considered in the manufacturing process, like in the present case. Therefore (and from some of the author's unpublished experiences), we can certainly expect that this would apply also to the use of the U-A and U-B panel types described here. Similar results were found by [8] for Pinus Taeda from Brazil and [9] for Southern Pine from the USA.

Other factors which were not addressed by this research, but will provide further optimization opportunities, are the variation of the lamella thickness and, if edge bonding is not considered, the aspect ratio of the boards (thickness divided by width). Specimens with 35mm and 20mm thick laminations were studied in [10] to evaluate the influence of this parameter on the rolling shear strength. The test results indicated that the recommended characteristic rolling shear strength values of CLT products in Europe and Canada might be over-conservative and it might be more efficient to specify different rolling shear strength values for CLT with different lamination thickness.

Lower grade lumber with a higher percentage of knots was recommended in [11] for the crossbands, which are mainly responsible for resisting shear stresses. The authors found that using the shear analogy method to interpret their results led to underestimations of rolling shear strength, especially in the case of CLT specimens containing knots. Clearly, also within this research, knottiness has proven to be a positive factor for the stiffness of crossbands, which mostly govern panel shear performances in bending, but close attention should be paid in the panel manufacturing to avoid excessive knots (and especially excessive wane) at the upper and lower layers of the panel, since the efficiency of some types of mechanical connections could be negatively affected; this certainly re-quires further research.

It is also worthwhile to mention the increased bending resistance of U-B45 panels with respect to their counterparts: simply changing the internal board inclination the rolling shear resistance increases by 50 % and – more importantly – the bending resistance and stiffness increase by 30%, thus deserving further research for a proper evaluation of the industrial feasibility.

The assessment of the mechanical properties of CLT panels based on four-point bending tests and guillotine tests, instead of the calculation based on the board grades, is a very promising opportunity for both the producers and the specifiers because it may result in getting "more from less" in terms of performances, and a higher product reliability, therefore making the whole production, design, and construction process a more sustainable one. This assessment approach, finally embedded into the European standard, can be rather easily applied in mill conditions due to the typical availability of offcuts from the CNC machining of large panels to produce the different elements in a building. Different analytical theories have been implemented and were used in [9] to estimate stiffness and strength properties under loads perpendicular or parallel to the principal plane of CLT panels from laboratory tests, predicting the associated deformation and failure mechanisms and assessing the reliability of the estimated properties with respect to the expected design values (and in terms of consistency among specimens with different layer configurations); the bending response is on average well represented in the theories currently used, for the two cases of loading, while for loads perpendicular to the plane the characteristic rolling shear strength appears to have a significant variability among the different layups, and for loads in plane a combined rolling and torsional shear failure criterion would provide more consistent results with respect to a less rigorous approach. Again, further experiences will provide better calibrations for the foreseen industrial quality control and in-grade testing routines.

5 CONCLUSIONS

The possibility to produce in-grade CLT panels from boards that were not strength-graded according to the applicable standard was demonstrated. The "cross-lamination effect" that explains this result was observed also for fast-grown Radiata Pine plantation logs, and particularly for sawing patterns that are not optimized for obtaining MGP grades and are therefore more cost efficient of MGP-specific patterns.

A set of scans and sorting feedback, executed by Microtec on a sub-sample of the boards, provided a very useful insight and suggested that significant resource optimization is possible, particularly for very knotty boards, leading to CLT panels which com-pared well also with a benchmark of C24 Spruce CLT which was produced and tested in identical conditions, showing that higher in-plane shear resistance and modulus were also achievable with ungraded Radiata Pine, a desirable performance for mid-rise which is a growing market trend.

These results will contribute to generating more value from a significant fraction of the Radiata Pine fibre resource which is currently not meeting the stud framing specifications and the MGP grading rules, therefore enhancing the resilience of the Australia supply chain.

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Figure 1 *– The U-B_{45} panels (diagonal crossbands).*

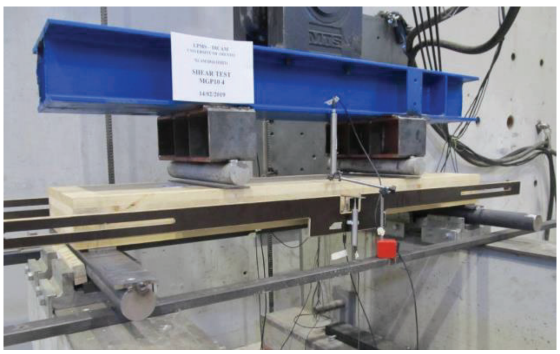

Figure 2 *– The 4-point bending tests setup.*

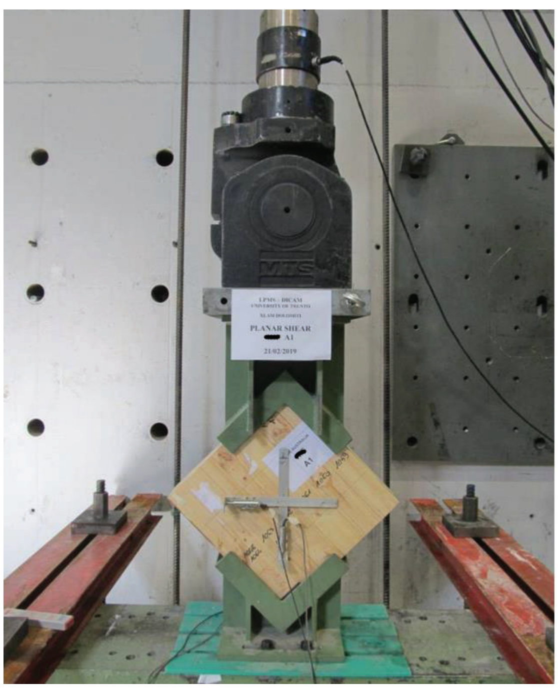

Figure 3 *– The planar shear tests setup.*

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