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Advancing Timber for the Future Built Environment

AUSTRALIAN NATIONAL 2023 IN-GRADE SAWN TIMBER STUDY

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ABSTRACT: Mills producing machine stress graded softwood sawn timber in Australia are responsible for the compliance of their products. Stress grading is covered in the AS/NZS 1748 performance standards with ongoing verification covered in AS/NZS 4490. Mills operate custom configurations of stress grading equipment with tailored grading and verification processes to suit their incoming timber resource and output product stress grade mix. This paper presents the outcomes of a comprehensive national study completed in 2023 (*2023 In-Grade Study*) with 13 mills participating, accounting for ~90% of production across Australia. The *2023 In-Grade Study* comprised >16,500 tests and provided key insights into the relative performance of the structural properties tested to AS/NZS 4063.1 and characterized to AS/NZS 4063.2. Structural property distributions are discussed with discussions on the relative performance between properties used in verification (indicator) and other properties (inferred). The study reports characteristic densities and proposes a relationship between characteristic density and modulus of elasticity (MOE) for use with developing connection design models. The *2023 In-Grade Study* led to follow-on projects further investigating compression and shear test methods to AS/NZS 4063.1.

KEYWORDS: in-grade testing, characteristic values, machine stress grading, Australia, structural softwood sawn timber

1 – INTRODUCTION

Timber design in Australia references "MGP" stress grades developed as the output of machine stress grading of Australian plantation pine species (predominantly radiata pine and Queensland hybrid pine) to AS/NZS 1748 series [1, 2] including ongoing verification to AS/NZS 4490 [3]. Some mills also produce boards machine stress graded as "F5". The stress grade properties include those indicator properties tested by mills for verification in production (e.g. bending strength, MOE), and properties 'inferred' from the indicator properties (e.g. tension, compression, shear etc). The relative property relationships were developed in 1988 [4], 1993 [5], 1998 [6] and refined in 2010 [7] and are presented as design characteristic values by stress grade in AS 1720.1 *Timber structures Part:1 Design methods* [8]. The MGP stress grades in Australia are developed such that production is typically stiffness-limited. Since the previous in-grade study work in 2010 [7] several factors have changed that may impact in-grade properties including species modification, plantation generation methods and silviculture, mill grading and optimisation, design standards, test standards and construction practices. Such changes mean there is potential value to be realised in completing national in-grade studies in a contemporary context.

2 – BACKGROUND

A national in-grade study commenced in 2019 with funding from the National Institute for Forest Products Innovation, Mt Gambier Centre. The study was completed by University of South Australia at its timber testing laboratory, Mawson Lakes with technical support from TimberED Services. As well as the 13 contributing mills, significant support was provided by Australian Forest Products Association, Engineered Wood Products Association of Australasia, and Forest & Wood Products Australia (FWPA). The study is referred to as the *2023 In-Grade Study* [9]. This paper presents a summary. Results from all products tested can be found in *2023 In-Grade Study* [9].

2.1 SAMPLING

Each of the contributing mills produces stress graded sawn timber for sale into a national construction market across Australia under a national stress grading system. It was appropriate therefore that supplied product be combined into a single national product population per size, per stress grade including the species mix covered nationally. The sampling period to capture a representative reference population for such a study should occur over a 'typical' period of production. For many mills this would be an annual cycle to capture a range of plantation timber resources accessible at different times of year. The sampling period for this *2023 In-Grade Study* [9] was 2020 to

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2022 in total, and coincided with major bushfires through south east Australia, the Covid19 pandemic, and flooding events, followed by a volatile construction market. Despite these challenges timber sampling was completed for each of the contributing mills over a period that captured all seasons of production in the reference population.

The *2023 In-Grade Study* [9] sampled boards from 90x35 mm and 190x45 mm sizes at 4.8 m and greater in length. The sizes capture both the ‘narrows’ (less than or equal to 140 mm wide) and ‘wides’ (greater than140 mm wide) groupings of machine stress graded boards. (The ‘narrow’ and ‘wide’ terms relate to the board in flatwise, plank orientation as is common in the terminology adopted in production.) Boards of 4.8 m and greater in length allowed direct comparison with previous in-grade projects used to develop the stress grade design characteristic values (DVs) [4, 5, 6, 7]. Sampling included the range of stress grades produced covering F5, MGP10, MGP12 and MGP15 in 90x35 mm, and MGP10 and MGP12 in 190x45 mm. The sample also included material from below the lowest stress grade produced (non-structural material) to enable characterisation of the whole distribution of material entering the dry mill, referred to as ‘NS’ in this paper.

Sample size for each grade and size from each mill varied with anticipated bending strength coefficient of variation (CoV) to target a consistent level of statistical confidence for the sample from each mill. Equation 1 is based on Appendix F in AS/NZS 4490 [3] where n is the sample size, and V_b is the MOR CoV.

$$n = \left(\frac{1.15V_b}{0.073}\right)^2 \qquad (1)$$

The relationship is plotted in Figure 1 for a single mill. In this case the orange dots represent the sample size required to achieve a consistent level of confidence per grade based on the 'typical’ bending strength CoV by grade. The black crosses are the sample size-to-CoV relationship from the *2023 In-Grade Study* [9] data for an example mill. All crosses are above the blue line that describes the relationship, and therefore all sample sizes by grade satisfied the required level of confidence. This approach was taken mill-by-mill. The nationally combined data included many more boards in the samples per grade, per size, per tested property. The sample sizes selected in this project are compatible with the methodology outlined in ISO 12122-1:2014 [10] and enabled characterisation of each mill’s production separately.

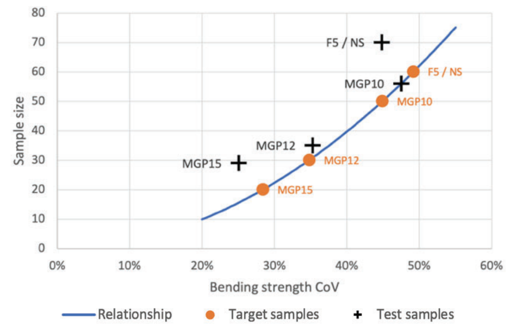

Figure 1 – Sample size (n) by bending strength CoV (V_b)

2.2 SPECIMEN DATA AND PREPARATION

AS/NZS 1748 series is made up of *Part 1: General requirements* [1], and *Part 2: Qualification of grading method* [2]. *AS/NZS 4490*, which covers *Verification of properties* [3], is referenced by AS/NZS 1748 series. Together these standards cover the production of timber sampled for this *2023 In-Grade Study* [9].

Machine stress grading data was captured for each of the ~ 15,000 sampled boards. Each mill uses a unique combination of grading equipment with custom threshold settings and verification processes tailored to suit their input resource, processes, and output products. The grading data from each mill was therefore unique. In response, an ‘agnostic’ grading profile was developed to unify presentation of the grading information from each mill. These agnostic grading profiles were a key part of the quality control procedures in the testing to verify the correct identity and position of each test specimen (Figure 2). The agnostic grading profiles also create valuable legacy data, allowing future reinterrogation of the data generated through this study in future studies or industry driven initiatives. Test specimens were prepared from each graded piece and were taken to represent the grade of the whole piece. However, the grading data enabled an estimation of the grade of a length cut from within a board that could be used to simulate properties associated with optimised trimming in production.

The focus of the *2023 In-Grade Study* [9] was random position testing in accordance with AS/NZS 4063.2 [11]. Biased position bending testing was also conducted on viable 90x35 mm specimens for an associated FWPA funded project *Developing a technical basis for a biased testing structural property verification method for Australian sawn softwood* [12], and to generate test data to support Phase II qualification of participating mills to AS/NZS 1748.2 [2].

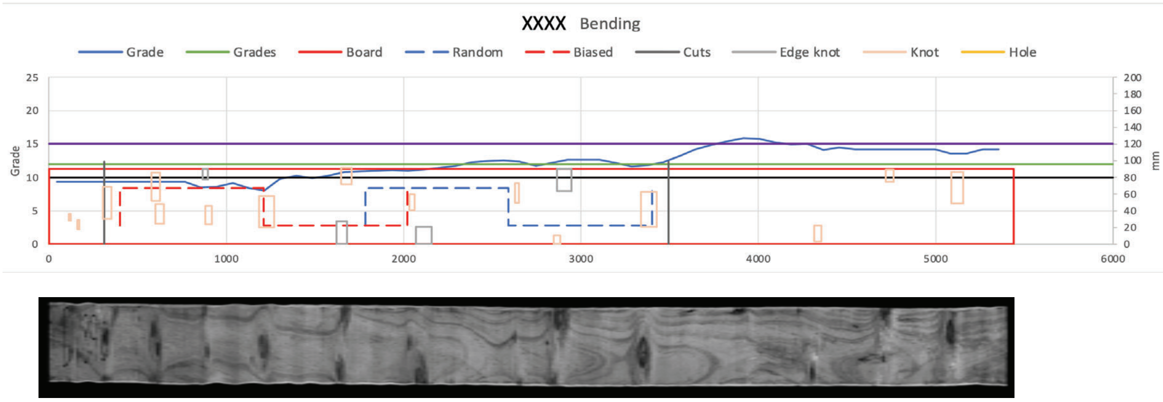

Figure 2 – 'Agnostic' grading profile and specimen data

3 – TESTING

Testing was completed through 2021 and 2022 at the University of South Australia's timber testing laboratory. Bending strength and apparent modulus of elasticity, beam shear strength, compression parallel to grain, and tension parallel to grain were tested in accordance to test methods and under standard conditions presented in AS/NZS 4063.1 [13] with density and moisture content also measured [14, 15].

The sampled boards were visually verified prior to cutting into test pieces by comparing the appearance of the board (i.e., location of knots, mill-assigned grade, and visual character) against the associated board photo (when photos were provided) and agnostic grading information provided from the mills (as shown in Figure 2). Every test was photographed. Test pieces that failed below their anticipated 5th percentile strength or above their anticipated 99th percentile strength were retained for detailed post-failure examination.

4 – RESULTS

The following section presents results from the nationally combined test data. Results are presented by property, by size and grade. Analysis was performed using log-normal distributions for all properties and the method presented in AS/NZS 4063.2:2010 [11] Appendix B3 for MOE, and Appendix B2.2 for strength properties and density. Characteristic values (CVs) are compared against design characteristic values (DVs) from AS 1720.1 [8] to calculate design ratios (DRs). CoV values are included for each property, and average (avg) values are included where relevant. Section 5 presents discussion on the relative property performance.

4.1 DENSITY

Density data were captured on all test specimens. Characteristic values for density in this *2023 In-Grade Study* [9] are calculated using AS/NZS 4063.2 [11] Appendix B2.2, typically adopted for strength properties assuming log-normal distributions. This method differs from that presented in AS/NZS 4063.2 Appendix B6 *Characteristic Values for Density* which is based on a mean density. These values are typically used for estimating self-weight of timber elements, but the use of Appendix B2.2 for fifth percentile density characteristic values in this study is appropriate given that characteristic density values are presented to inform future development work on connection design in AS 1720.1 [8]. Table 1 and Figure 3 present density results corrected to 12% moisture content in accordance with AS/NZS 1080.3 [14]. Table 1 includes both 90x35 mm and 190x45 mm boards. Figure 3 presents 90x35 mm boards. Summary observations from the density data include:

- Joint Design (JD) groups JD4 and JD5 defined by AS 1720.2 [16] Table 3 as 'Average Minimum density at 12% moisture content' are highlighted on Figure 3.
- Log-normal distributions represent a good fit for the data (Figure 3).
- CoV is ~10%, which is as anticipated for a fibre-limited property.
- CoV decreases as grade increases which is as anticipated.
- Non-structural density CV is slightly higher than F5, but the NS will have included some high-density product deemed NS from utility (wane) in the mix. This can be seen on the CFDs (Figure 3) where the red line crossed the top of the higher graded material distributions.

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Table 1: Density results

Density *(ρ)* at 12% MC					
Size (mm)	**Grade**	**Count**	**CV (kg/m³)**	**CoV**	**Avg (kg/m³)**
90x35	**NS**	1950	397.8	11.8%	487.6
90x35	**F5**	2185	386.4	12.6%	480.6
90x35	**MGP10**	2960	426.3	9.8%	504.3
90x35	**MGP12**	1302	472.0	8.5%	546.4
90x35	**MGP15**	428	537.5	8.2%	619.8
190x45	**NS**	1891	405.1	12.2%	500.1
190x45	**F5**	-	-	-	-
190x45	**MGP10**	1715	433.4	9.3%	508.2
190x45	**MGP12**	760	483.2	8.3%	557.4
190x45	**MGP15**	-	-	-	-

Table 2: Average MOE parallel to grain results

Average MoE parallel to grain *(E)*						
Size (mm)	**Stress Grade**	**Count**	**CV (GPa)**	**CoV**	**DV (GPa)**	***DR***
90x35	**NS**	487	5.8	39.2%	N/A	*N/A*
90x35	**F5**	554	8.1	24.8%	6.9	*1.2*
90x35	**MGP10**	726	10.7	20.0%	10.0	*1.1*
90x35	**MGP12**	326	13.3	12.7%	12.7	*1.1*
90x35	**MGP15**	107	16.5	11.7%	15.2	*1.1*
190x45	**NS**	472	6.6	35.0%	N/A	*N/A*
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	427	10.7	19.2%	10.0	*1.1*
190x45	**MGP12**	187	13.7	11.9%	12.7	*1.1*
190x45	**MGP15**	-	-	-	-	-

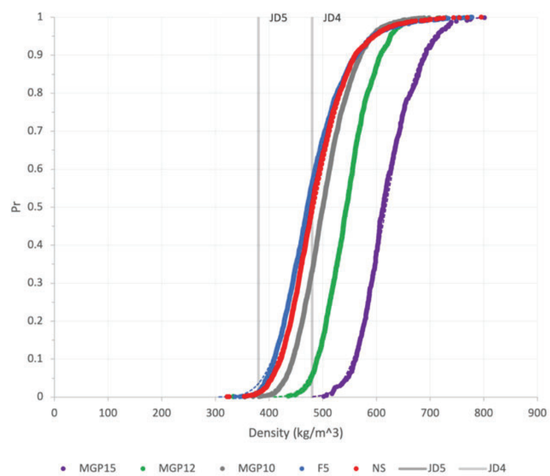

Figure 3 – Cumulative frequency diagram – 90x35 mm – Density

4.2 APPARENT MODULUS OF ELASTICITY

The AS/NZS 4063.1 [13] test setup for apparent MOE is a four point bending span of 18 times the member depth with load point equally spaced at six times the depth. Apparent MOE is calculated based on the overall deflection at mid-span. Table 2 and Figures 4 & 5 present MOE results for both the 90x35 mm and 190x45 mm boards. Summary observations from the MOE testing include:

- MOE design ratios (DRs) are all greater than 1.0.
- Log-normal distributions represent a good fit for the data (Figure 4 and Figure 5).
- The separation between structural grades is well defined.
- Non-structural MOE distribution crosses with the top of higher structural grades as shown with the red line crossing the grade distributions on Figure 4 and Figure 5; the NS will have included some higher stiffness product deemed NS from having exceeded the utility limits.

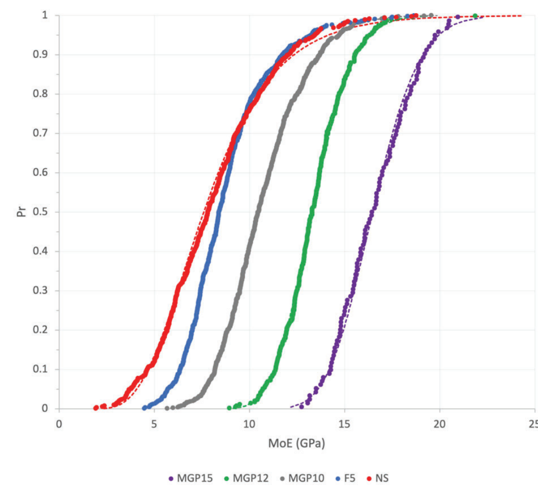

Figure 4 – Cumulative frequency diagram –90x35 mm – Average MOE parallel to grain

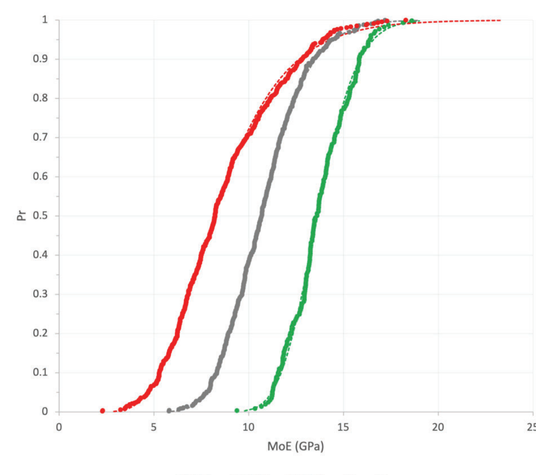

Figure 5 – Cumulative frequency diagram –190x45 mm – Average MOE parallel to grain

4.3 BENDING STRENGTH

Random position bending strength (MOR) testing was completed in accordance with AS/NZS 4063.1 [13] with the same span and load arrangement as for MOE

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testing. Bending strength was considered at the failure location where failure occurred outside the middle third zone of constant moment. Table 3 and Figure 6 present bending strength results. Summary observations from bending strength testing include:

- MOR design ratios (DRs) are all greater than 1.0.
- Log-normal distributions represent a good fit for the data (Figure 6).
- Characteristic values vary between the narrows and wides. The DRs are similar, suggesting that the current size effect incorporated in the DVs is appropriate.

Table 3: Bending strength results

		Bending (f'_b)				
Size (mm)	Stress Grade	Count	CV (MPa)	CoV	DV (MPa)	*DR*
90x35	**NS**	487	11.4	60.1%	N/A	*N/A*
90x35	**F5**	554	17.1	44.4%	14.0	*1.2*
90x35	**MGP10**	726	22.7	40.7%	17.0	*1.3*
90x35	**MGP12**	326	37.1	29.0%	28.0	*1.3*
90x35	**MGP15**	107	52.6	22.5%	39.0	*1.3*
190x45	**NS**	472	10.2	54.7%	N/A	*N/A*
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	427	22.3	34.7%	16.0	*1.4*
190x45	**MGP12**	187	32.8	27.2%	25.0	*1.3*
190x45	**MGP15**	-	-	-	-	-

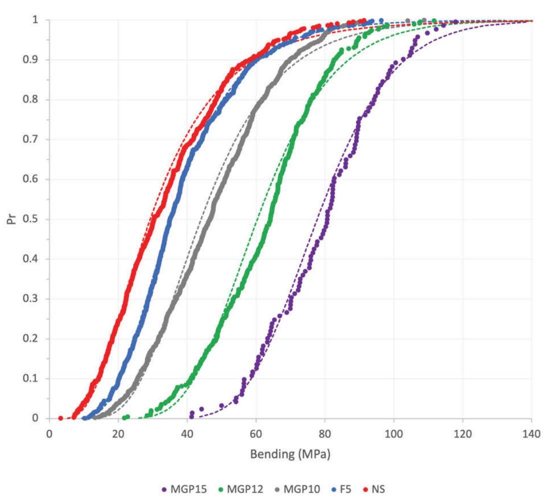

Figure 6 – Cumulative frequency diagram –90x35 mm – Bending strength

4.4 TENSION STRENGTH PARALLEL TO GRAIN

Random position tension strength parallel to grain testing was completed in accordance with AS/NZS 4063.1 [13] where the tested length between the jaws was 2720 mm for the 90x35 mm boards and 3520 mm for 190x45 mm boards.

Table 4, Figure 7 and Figure 8 present tension parallel to grain results. Thirteen tested 190x45 mm boards could not be tested to failure, limited by machine capacity. These are omitted from the top end of Figure 8. A log-normal distribution was fitted to the truncated data for the purpose of calculating the CVs. Summary observations from the tension parallel to grain testing include:

- Tension design ratios (DRs) are all greater than 1.0.
- Log-normal distributions represent a good fit for the data (including the truncated dataset, Figure 7 and Figure 8).
- The lower end of the distributions, including the 5th%ile values, are generally well separated. However, MGP10 is close to F5 which is appropriate given that MGP10 and F5 DVs are very close (7.7 and 7.3 MPa respectively).

Table 4: Tension parallel to grain results

		Tension parallel to grain (f'_t)				
Size (mm)	Grade	Count	CV (MPa)	CoV	DV (MPa)	*DR*
90x35	**NS**	485	4.2	57.0%	N/A	*N/A*
90x35	**F5**	533	7.8	40.1%	7.3	*1.1*
90x35	**MGP10**	746	10.7	39.3%	7.7	*1.4*
90x35	**MGP12**	323	17.8	32.6%	12.0	*1.5*
90x35	**MGP15**	106	23.9	28.7%	18.0	*1.3*
190x45	**NS**	471	5.0	59.3%	N/A	*N/A*
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	422	10.5	43.7%	7.1	*1.5*
190x45	**MGP12**	174	19.2	31.1%	12.0	*1.6*
190x45	**MGP15**	-	-	-	-	-

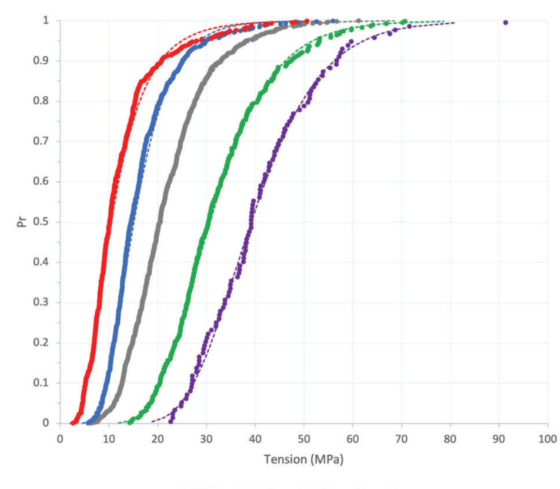

Figure 7 – Cumulative frequency diagram –90x35 mm – Tension parallel to grain

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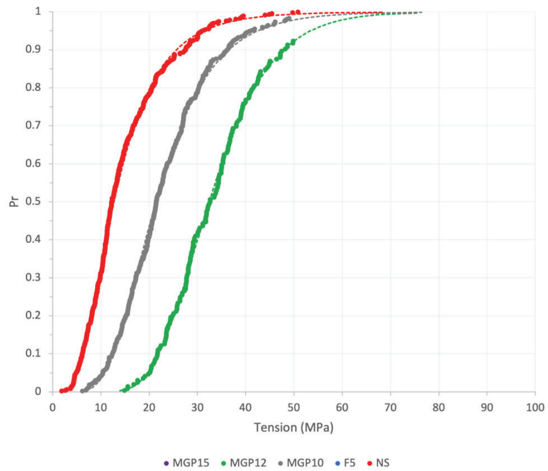

Figure 8 – Cumulative frequency diagram –190x45 mm – Tension parallel to grain

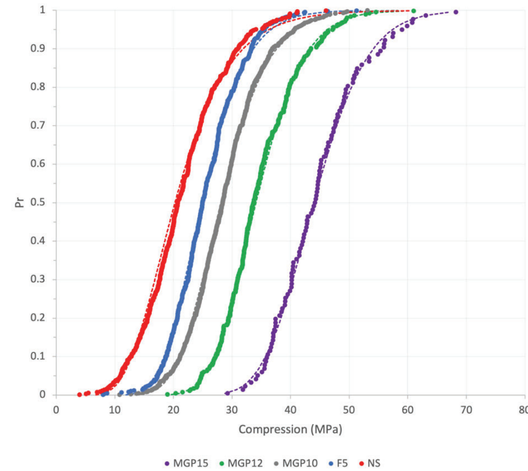

Figure 9 – Cumulative frequency diagram –90x35 mm – Compression parallel to grain

4.5 COMPRESSION STRENGTH PARALLEL TO GRAIN

Random position testing followed the 'alternative procedure' to AS/NZS 4063.1 [13] for compression strength parallel to grain using short sub-sections (eight) of the overall test specimen (2720 mm for 90x35 mm boards, and 3520 mm for the 190x45 mm boards). The lowest strength sub-section defined the compression strength in each test specimen. Table 5 and Figure 9 present compression parallel to grain results. Summary observations from the compression parallel to grain testing include:

- Compression design ratios (DRs) are all greater than or equal to 1.0.
- Log-normal distributions represent a good fit for the data (Figure 9).
- Design ratios (DRs) were lower than anticipated. There is a follow-on project comparing full specimen and short length 'alternative' test method in AS/NZS 4063.1 [13] underway at the time of writing.

Table 5: Compression parallel to grain results

Compression parallel to grain (f'_c)						
Size (mm)	Grade	Count	CV (MPa)	CoV	DV (MPa)	*DR*
90x35	**NS**	493	11.1	36.6%	N/A	*N/A*
90x35	**F5**	551	16.7	24.0%	11.0	*1.5*
90x35	**MGP10**	749	19.1	23.1%	18.0	*1.1*
90x35	**MGP12**	327	24.8	18.8%	24.0	*1.0*
90x35	**MGP15**	109	33.0	16.3%	30.0	*1.1*
190x45	**NS**	473	11.1	39.2%	N/A	*N/A*
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	431	18.6	23.0%	18.0	*1.0*
190x45	**MGP12**	192	28.9	15.3%	23.0	*1.3*
190x45	**MGP15**	-	-	-	-	-

4.6 BEAM SHEAR STRENGTH

Random position *beam shear strength* testing was completed in accordance with AS/NZS 4063.1 [13] which uses a three point bending short beam test of span six times the depth (Figure 10). Shear and bending failures are used in the calculation of shear strength.

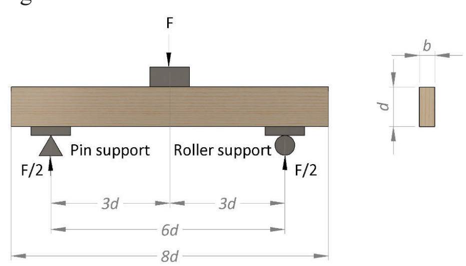

Figure 10 – Beam shear strength test setup

Summary observations from the beam shear strength testing include:

- Beam shear design ratios (DRs) are all greater than 1.0.
- Log-normal distributions represent a good fit for the data (Figures 11 and 12).

The size effect presented in the DVs from AS 1720.1 [8] does not reflect the CVs for the wides compared to the narrows (Table 6), with DR for wides closer to the 1.0 than the narrows. Size effect and the beam shear test method compared with an inclined plate method is the subject of a follow-on study ongoing at the time of writing this paper.

Table 6: Shear in beams results

Shear in beams (f'_v)						
Size (mm)	**Grade**	**Count**	**CV (MPa)**	**CoV**	**DV (MPa)**	***DR***
90x35	**NS**	480	2.3	38.0%	N/A	*N/A*
90x35	**F5**	547	2.8	31.4%	1.6	*1.7*
90x35	**MGP10**	739	3.4	27.5%	2.6	*1.3*
90x35	**MGP12**	326	4.5	21.6%	3.5	*1.3*
90x35	**MGP15**	106	5.4	20.4%	4.3	*1.3*
190x45	**NS**	473	1.8	40.9%	N/A	*N/A*
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	429	2.9	25.9%	2.5	*1.1*
190x45	**MGP12**	194	3.9	19.2%	3.3	*1.2*
190x45	**MGP15**	-	-	-	-	-

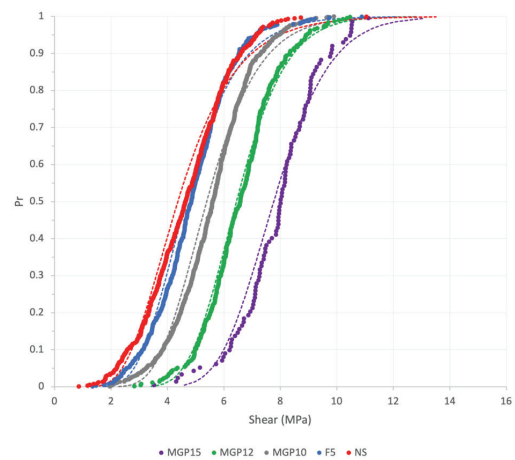

Figure 11 – Cumulative frequency diagram –90x35 mm – Beam shear strength

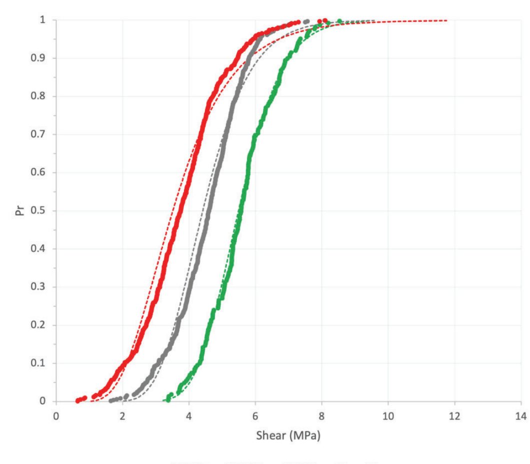

Figure 12 – Cumulative frequency diagram –190x45 mm – Beam shear strength

5 – INDICATOR AND INFERRED PROPERTY RELATIONSHIPS

In this section the relative performance between the indicator properties (those verification tested through production) and the inferred properties (those not verification tested through production).

5.1 BENDING STRENGTH AND APPARENT MODULUS OF ELASTICITY

Table 7 presents the design ratios for all tested properties. For the MGP grades the bending strength design ratio is approximately 1.2 times the MOE design ratio, suggesting that the product is typically stiffness limited in production as intended when the MGP design characteristic values were developed in the *2010 MGP Properties Study* [7]. However, the bending strength design ratio for F5 is approximately 1.0 times the MOE design ratio. F5 tension strength design ratio is 1.1.

Figure 13 presents the relationship between characteristic bending strength and MOE from *2023 In-Grade Study* [9]. The black dashed line (a lower-bound envelope line from test data in a previous in-grade study) from the *2010 MGP Properties Study* [7] presents the relationship assumed in the development of the MGP grades presented in table H3.1 of AS 1720.1 [8]. The blue dots represent the 90x35 mm *2023 In-Grade Study* results mill-by-mill by grade. Data points above the black dashed line represents mills that tend to be stiffness limited in production. All but one product from one mill tend to be stiffness limited with the current relationship between design characteristic values for bending strength, f'_b and MOE in table H3.1 AS 1720.1 [8]. The blue dotted line represents the line of best fit through the *2023 In-Grade Study* data. It is approximately parallel and offset from the black dashed line. This demonstrates the bending strength to MOE relationship in AS 1720.1 [8] is still appropriate for the products tested in the *2023 In-Grade Study* [9]. Relationships for other indicator or inferred properties are discussed in the sections below.

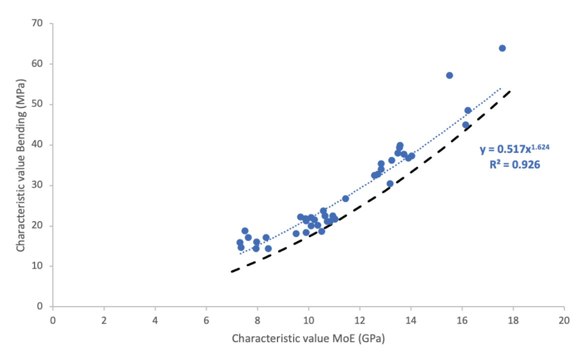

Figure 13 – Bending strength to MOE relationship (90x35 mm boards including F5)

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Table 7: Design ratios for all products

Size (mm)	Stress Grade	Bending (f'_b)	Tension parallel to grain (f'_t)	Compression parallel to grain (f'_c)	Shear in beams (f'_v)	Average MoE parallel to grain (*E*)
90x35	**NS**	N/A	N/A	N/A	N/A	N/A
90x35	**F5**	1.2	1.1	1.5	1.7	1.2
90x35	**MGP10**	1.3	1.4	1.1	1.3	1.1
90x35	**MGP12**	1.3	1.5	1.0	1.3	1.1
90x35	**MGP15**	1.3	1.3	1.1	1.3	1.1
190x45	**NS**	N/A	N/A	N/A	N/A	N/A
190x45	**F5**	-	-	-	-	-
190x45	**MGP10**	1.4	1.5	1.0	1.1	1.1
190x45	**MGP12**	1.3	1.6	1.3	1.2	1.1
190x45	**MGP15**	-	-	-	-	-

5.2 TENSION STRENGTH PARALLEL TO GRAIN

Tension strength parallel to grain is an inferred property for most mills as assumed in the development of the MGP properties for AS 1720.1 [8]. Design ratios in table 7 show that for the MGP grades the design ratio for tension strength (inferred) is approximately 1.1 times the design ratio for bending strength (indicator) for the MGP grades as anticipated. This means that monitoring bending strength in verification testing will generally also confirm tension strength which has a higher margin above the DV. However, F5 design ratio for tension strength is approximately 0.9 times the design ratio for bending strength, meaning that the product is limited by an inferred strength property. This makes machine stress grading and verification process more complex for F5 timber and requires elevating the target MOR property in verification in response to the inferred tension strength, as required in AS/NZS 1748.2.

Figure 14 presents the *2023 In-Grade Study* [9] tension strength to bending strength relationship along with the *2010 MGP Properties Study* [7] analysis used to generate the current MGP property relationships in AS 1720.1 [8]. There is a strong relationship between characteristic tension strength and characteristic bending strength in this study with an R^2 of 0.87.

The black line in Figure 14 includes the k_{ntp} factor for inferred properties. This factor aims to introduce appropriate conservatism for the inferred properties compared to the indicator properties. It aimed to give a 75% confidence that the tension strength exceeded the design property given that the bending strength exceeds its design strength. Figure 14 shows that 30 of the 41 mill/grade/size data points from this *2023 In-Grade Study* [9] are above the *2010 MGP Properties Study* [7] relationship and 11 are below; 75% of MGP products have a higher design ratio for tension than bending strength as expected. This demonstrates the tension strength to bending strength relationship represented in AS 1720.1 [8] for the MGP products is confirmed by the tests in the *2023 In-Grade Study* [9].

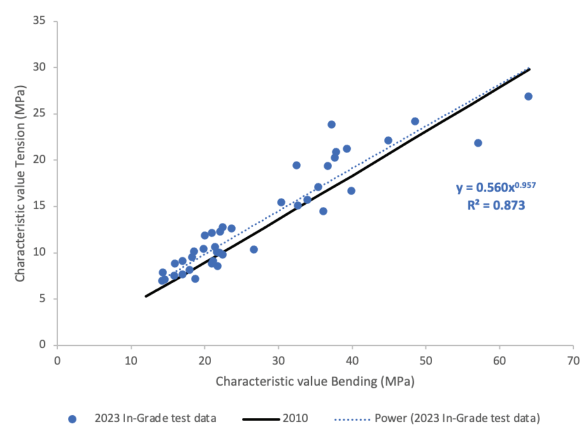

Figure 14 – Tension strength vs bending strength

5.3 OTHER INFERRED PROPERTIES

Beam shear strength and compression parallel to grain design ratios (DRs) are all greater than or equal to 1.0 for the national population tested. Results for both properties from the *2023 In-Grade Study* [9] warranted further investigation which is ongoing at the time of writing (early 2025).

5.4 DENSITY

Design ratios for density cannot be calculated in this study as there are no characteristic design values for density in AS 1720.1 [8]. In AS 1720.1 density is related to connection performance through Joint Design (JD) groups covered in AS 1720.2 [16] Table 3 as 'Average Minimum density at 12% moisture content'. The detail of the JD density requirement is covered in AS 1649 *Timber – Methods of test for mechanical fasteners and connectors* [17] clause 1.8. AS 1649 requires that the 'mean air-dry density' for the timber selected to represent the joint group in connection tests is at the 'bottom end of the range' of densities given, which relate in turn to those values presented in AS 1720.2 [16]; 380 kg/m^3 for the lowest value in the JD5 range and similarly 480 kg/m^3 for JD4. This implies that the connection strength is characterised by densities near the bottom of the density distribution of a stress-grade. Figure 3 presents density CFDs for 90x35 mm product from the *2023 In-Grade Study* with average minimum density requirements from AS 1720.2 Table 3 [16] for JD5 (380 kg/m^3) and JD4 (480 kg/m^3) overlaid as relevant for MGP10 and MGP12/15 respectively as presented in Table H3.1 AS 1720.1 [8].

Future development of AS 1720.1 [8] will include connection design models similar to European Yield Models. Characteristic densities for possible use with connection design models are calculated in this *2023 In-Grade Study* [9] using AS/NZS 4063.2 Appendix B2 Method 1 [11] for strength properties. Characteristic densities by size and grade are presented in Table 1. MGP10 90x35 and 190x45 mm populations have similar density as measured on the whole-of-board. MGP12 190x45 mm has higher CV for density than 90x35 mm boards which is likely influenced by the absence of MGP15 product recovered from above MGP12 in 190x45 mm.

Figures 15 and 16 present the property relationship between density and MOE for 90x35 mm and 190x45 mm respectively. The dots represent each mill and product CV MOE plotted against CV density and are colour coded by grade. The black dotted line is the linear best fit through the mill data for all data points. This relationship is adjusted to generate the proposed relationship between CV MOE and density design characteristic values (orange line) which is the lower-bound of the mill-by-mill CV Density to CV MOE mill-by-mill relationships from this study. The proposed grade density CVs shown with horizontal banding. The relationship (orange line) is the same for both 90x35 and 190x45 mm (narrows and wides) and is represented by;

$$\rho_k = 16.61\,E + 235 \qquad (2)$$

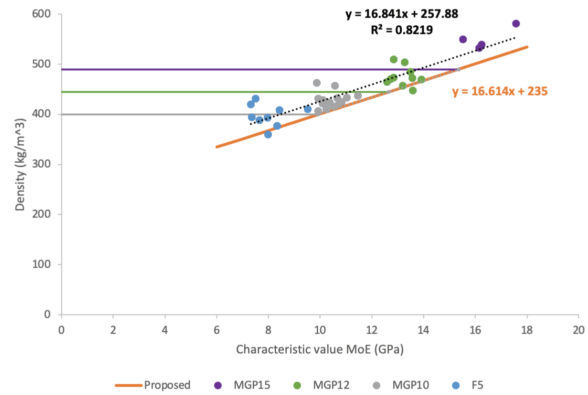

Figure 15 –90x35 mm - Characteristic Density to MOE relationship

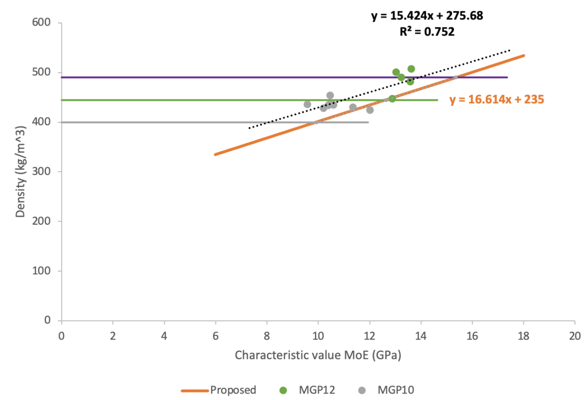

Figure 16 –190x45 mm - Characteristic Density to MOE relationship

Characteristic design density values at 12% moisture content evaluated using Equation (2) at the design MOE are presented in Table 8 rounded to the nearest 5 kg/m^3.

Table 8: Proposed density design characteristic values by stress grade

Stress grade	MOE DV *(E)* (GPa)	Density DV *(ρ_k)* (kg/m^3)
MGP10	10	400
MGP12	12.7	445
MGP15	15.2	490

The proposed 5%ile design characteristic density is equal for narrows and wides in a given grade which is appropriate given density is measured as a board average. However, further work is required to investigate the density variation within the wide board cross-section for use with connection design models with density local to the fasteners likely varying with placement in a wide board.

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5 – CONCLUSIONS AND RECOMMENDATIONS

This paper presents a summary of the *2023 In-Grade Study* which should be referenced for more information. Completion of a national in-grade study in a contemporary context allowed for capture of grading data to improve testing quality assurance through board identification, and has provided a critical legacy dataset for future interrogation and studies.

In-Grade testing across major (indicator) and minor (inferred) properties demonstrated that the nationally combined resource exceeds the design values required for the sampled and tested grades, indicating that mill grading processes within the framework of AS/NZS 1748 are performing as anticipated.

Relative relationships between properties compared well with those used in *2010 MGP Properties Study* [7] in defining the MGP properties currently presented in AS 1720.1. Differences identified in compression parallel to grain results has led to a follow-on research project (commenced at the time of writing). Beam shear strength to MOE relationship for 'narrows' as developed in *2010 MGP Properties Study* was as anticipated, but confirming the beam shear strength size effect associated with 'wides' requires further testing (commenced at the time of writing).

Design characteristic values for density have been proposed for use in future development of AS 1720.1 connection design models. A relationship between characteristic density and MOE has been proposed to allow future development of characteristic design values for density independent of the MGP system if required in the future.

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