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Bending Properties of Finger-jointed Malaysian Dark Red Meranti

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Funding Information:	

Bending Properties of Finger-jointed Malaysian Dark Red Meranti

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Abstract

The mechanical performance of dark red meranti (*Shorea* spp.) containing structural finger joints was investigated in four-point bending. The influence of variation in density on the bending strength (MOR) and stiffness (MOE) of dark red meranti (DRM) was studied. The effect on these properties of variation in end pressure when bonding was examined. The orientation of finger joints and the effect of cross-sectional area of bonded joints on the bending properties were also investigated.

The results of this study indicate a positive relationship between the density and the MOR of DRM specimens. Sufficiently high end pressure is needed to produce strong finger joints. The orientation of finger joints and the changes in cross-sectional area of bonded joints showed no influence on the MOR. The MOE of DRM was not affected by the finger-jointing of the pieces. In conclusion, finger-jointed DRM exhibits potential for structural uses, particularly for glulam beams.

Keywords: finger joint, dark red meranti, joint efficiency, end pressure, phenol resorcinol formaldehyde adhesive, modulus of rupture, modulus of elasticity

1 Introduction

In recent decades, the local timber industry in Malaysia has been working together with the government to promote structural glulam technology in construction. The key elements that influence the strength of a glulam beam are the finger joints. In general, the finger joint is considered to be the weakest component in a glulam beam along with the natural defects of wood such as knots and splits. Thus, it is pertinent to understand the behaviour of finger joints when tested in various mechanical tests in bending, compression and tension. However, this information is still lacking, particularly for finger joints produced from local Malaysian hardwood such as dark red meranti (*Shorea* spp.), which was used in this study.

The local timber industries in Malaysia are accustomed to using finger joints as one of the components in the manufacturing of non-structural products. Some confusion and hesitation arose when specifications for structural finger joints were required due to the lack of related technical information. A literature review reveals only a handful of research papers related to structural finger joints produced using local Malaysian hardwood. Hamid *et al*. (2016) managed to produce finger joints with more than 70% joint efficiency in bending (compared to unjointed wood) for kelat (*Syzygium* spp.) when using a 15 mm length finger profile. Ahmad *et al*. (2016) investigated the strength and stiffness of 15 and 25 mm length finger joints for eight Malaysian tropical timber in bending and concluded they were suitable for use in glulam production. Ahmad *et al.* (1997) produced meranti finger joints with joint efficiencies of 55%, 65% and 77% for specimens with finger length of 11, 12 and 13 mm respectively where joint efficiency is defined as the ratio of the MOR of finger-jointed specimens to the MOR of the solid specimens expressed as a percentage. In general, research on hardwood timber is also lacking in European countries due to the use of mainly softwood species in the construction sector (Aicher *et al*., 2001).

Previous published studies indicated that the strength of finger-jointed timber pieces were influenced by the specimen's geometry, joint configurations, finger profiles and end pressures (Ayarkwa *et al*., 2000; Bustos *et al*., 2003, 2011; Tran *et al*., 2014). Finger joints with adequate strength and joint efficiency of up to 75% of the solid timber pieces can be produced if they are well-manufactured using suitable machining parameters and bonding media (Frihart and Hunt, 2010; Moody *et al*., 1999).

The aim of this study is to determine the bending properties of finger joints produced from local Malaysian timber species, namely dark red meranti (DRM) and to compare properties with commonly used spruce timber. Factors influencing the bending strength of the timber pieces are also discussed in this study.

2 Materials and method

Kiln-dried DRM timber pieces were used in the preparation of the finger-jointed specimens in this study. The fabrication and testing of the finger joints followed the standard production requirements of BS EN 14080:2013 and testing methods of BS EN 408:2010+A1:2012 respectively.

2.1 Specimen preparation

Larger DRM pieces with a density range of 530 to 630 kg/m^3 and moisture content of 12% were sourced from Malaysia by Sykes Timber, Atherstone, Coventry, UK. The dimensions of the pieces were 40 mm (depth) x 105 mm (width) x 1000 mm (length) with designated timber grade of 'Selects and Better', according to The Malaysian Grading Rules for Sawn Hardwood Timber and there were no major defects when inspected visually. The finger profiles were produced using a finger cutter knife purchased from Leitz Tooling, UK. The finger cutter knife is specifically fabricated so that it can be used with a manual feed spindle moulder and is able to produce structural joints in accordance to the specifications of BS EN 14080:2013. The length and pitch of the finger joints were 10 and 3.8 mm respectively (Figure 1).

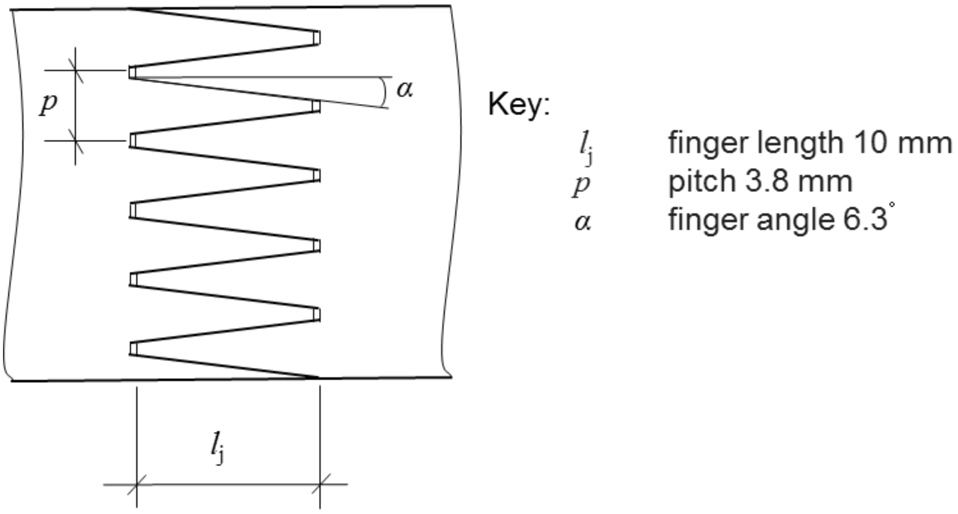

Figure 1: Finger profile descriptions

The finger joints were pressure bonded with phenol resorcinol formaldehyde (PRF) with an end pressure of 12.5 N/mm^2 as recommended in BS EN

14080:2013 for a finger length of 10 mm. Additional specimens were also prepared using end pressures of 10 and 15 N/mm^2 in order to determine the range of suitable end pressures because of the density variation within the DRM species. After bonding, the specimens were left to cure for more than 7 days and then further processed to final dimensions of 30 x 30 x 600 mm with the finger joints located in the centre of the specimen. Additional solid DRM and finger-jointed specimens with increased width (30 x 60 x 600 mm) and vertical joints (Figure 2) were prepared to investigate the influence of different test configurations on the bending strength. Solid and finger-jointed spruce (*Picea abies*) specimens were also prepared for comparison. The spruce pieces were purchased from Sykes Timber and only clear wood specimens were used in this study. The number of specimens is shown in Table 1 together with the number of measurements made of density and moisture content (MC).

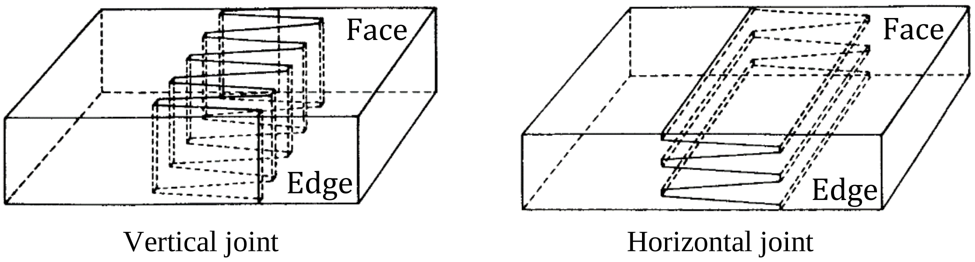

Figure 2: Finger joint types (Jokerst, 1981)

Table 1: Number of specimens for each test configurations

Specimen	Description	End pressure (N/mm^2)	Number of specimens	Density and MC*
DRM specimen				
SolidD	Solid specimen	-	10	10
FJ1	Vertical finger joints	12.5	10	20
FJ2	Vertical finger joints with wider width	12.5	10	20
FJ3	Horizontal finger joints	12.5	10	20
FJ4	Vertical finger joints with lower end pressure	10	12	24
FJ5	Vertical finger joints with higher end pressure	15	12	24
Spruce specimen				
SolidS	Solid specimen	-	12	12
FJS	Vertical finger joints	12.5	13	26

*Number of measurements made of density and moisture content

2.2 Four-point bend test

All the specimens were tested in a four-point bend test in accordance to BS EN 408:2010+A1:2012. The loading and bending span were 180 and 540 mm respectively (Figure 3). A 5 mm linear variable differential transformer transducer (LVDT) was used to measure the deformation (w) of the specimens for the determination of the local modulus of elasticity. The LVDT was positioned at the bottom of the specimen to avoid attaching a plate at the neutral axis. This prevents additional pasting or drilling on the joint area, in order to attach the plate, which may influence the bending performance of the specimen. The loading speed was 3.0 and 4.0 mm/min for finger-jointed and solid specimens respectively and the maximum load was reached within 3 to 7 minutes.

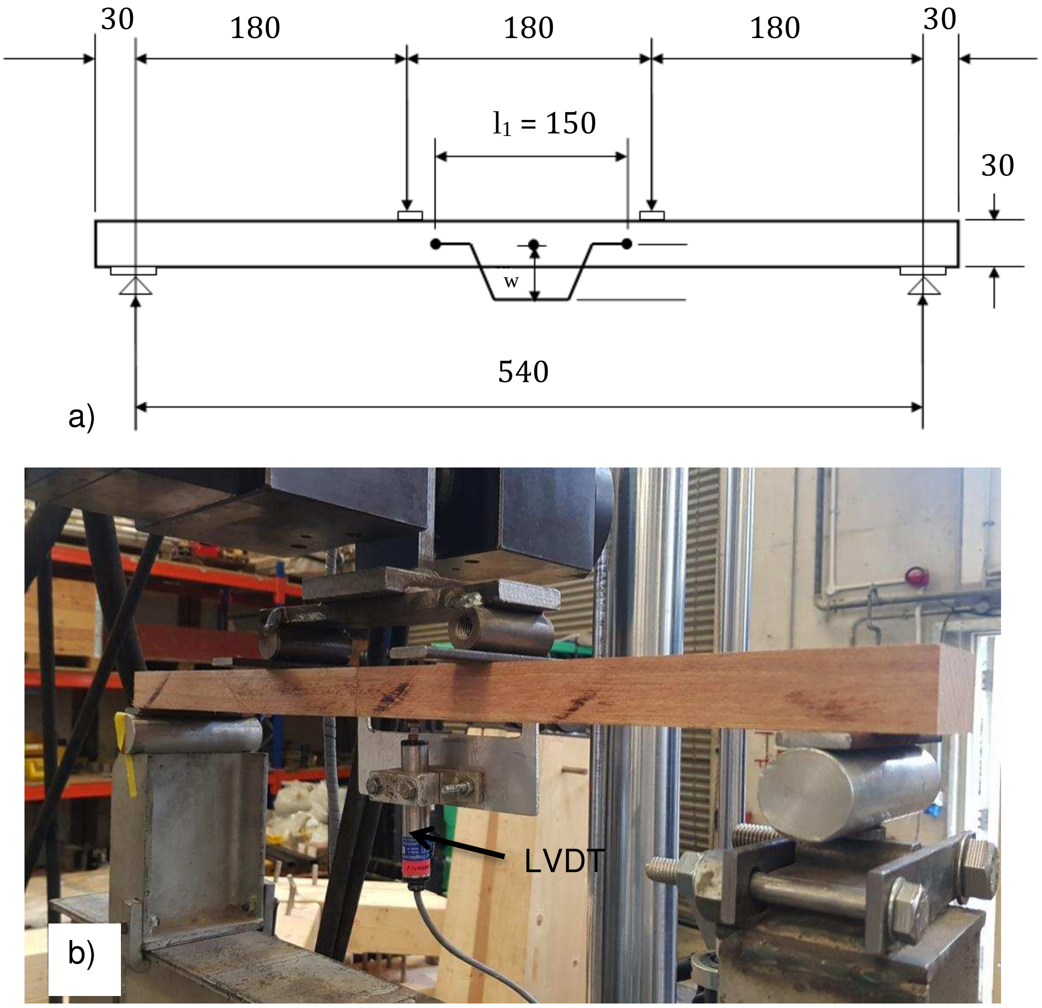

Figure 3: Four-point bending a) test configuration (BS EN 408:2010+A1:2012) b) actual set-up (dimensions in mm)

The modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated as follows (BS EN 408:2010+A1:2012):

MOR (N/mm^2), $f_m = \frac{3Fa}{bh^2}$

Local MOE in bending (N/mm^2), $E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)}$

F	load, (N)
a	distance between the loading point and nearest support, (mm)
b	width of cross section, (mm)
h	depth of cross section, (mm)
$F_2 - F_1$	increment of load below the proportional limit of the load deformation curve (see BS EN 408:2010+A1:2012), (N)
$w_2 - w_1$	increment of deformation corresponding to $F_2 - F_1$, (mm)
l_1	gauge length for determination of MOE, (mm)
I	second moment of area, (mm^4)

Local MOE describes the resistance to deflection (elastic modulus) of the specimen. The MOE value is derived from the slope of its load-deformation curve in the elastic deformation region with higher values indicating stiffer material.

2.3 Density and moisture content

A 30 mm length test piece was cut along the grain of each specimen. The outer dimensions and the mass of the test piece were measured for calculation of the density. This test piece was later dried in an oven until constant mass was achieved. The oven-dried mass was recorded and the moisture content of the test piece was determined as a proportion of dry mass.

3. Results and discussion

3.1 Bending strength of solid and finger-jointed specimens

The mean bending results of solid and finger-jointed DRM and spruce specimens are shown in Table 2.

Table 2: Bending properties of solid and finger-jointed DRM and spruce specimens

Specimen	MOR (N/mm^2)		MOE (N/mm^2)		MC (%)		Density (kg/m^3)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DRM specimen								
SolidD	93.1	8.03	16000	1440	11.5	0.2	564	60
FJ1	71.9	6.50	15500	2250	12.1	0.2	599	79
FJ2	69.6	8.02	15000	2230	12.3	0.2	602	79
FJ3	67.8	11.9	13900	1210	12.1	0.4	606	92
FJ4	59.4	6.46	17000	2920	12.5	0.2	585	61
FJ5	65.4	9.09	20300	2040	12.7	0.3	658	56
Spruce specimen								
SolidS	81.8	16.2	16900	3850	12.4	0.3	497	61
FJS	52.9	9.31	16100	2710	12.4	0.6	505	77

Note: SD = standard deviation

As expected, the solid DRM and spruce specimens possessed higher MOR values than their respective finger-jointed specimens. Although solid DRM specimens exhibited a 12% higher mean MOR than solid spruce specimens, a one-way ANOVA (analysis of variance) test indicated no significant differences at the 95% confidence level between the MOR values of solid DRM and spruce specimens. The density range of solid DRM specimens (492 – 651 kg/m^3) and solid spruce specimens (429 – 597 kg/m^3) are similar. For comparison, the density of DRM specimens in this study is comparable to the mean density of 610 kg/m^3 for Malaysian DRM species published by Chu *et al*. (1997). Density is known to influence bending strength because it is positively correlated with the mechanical properties of the timber, specifically for clear wood specimens (Dinwoodie, 1981). Figure 4 shows a positive relationship between the MOR values and density of both solid DRM and spruce specimens.

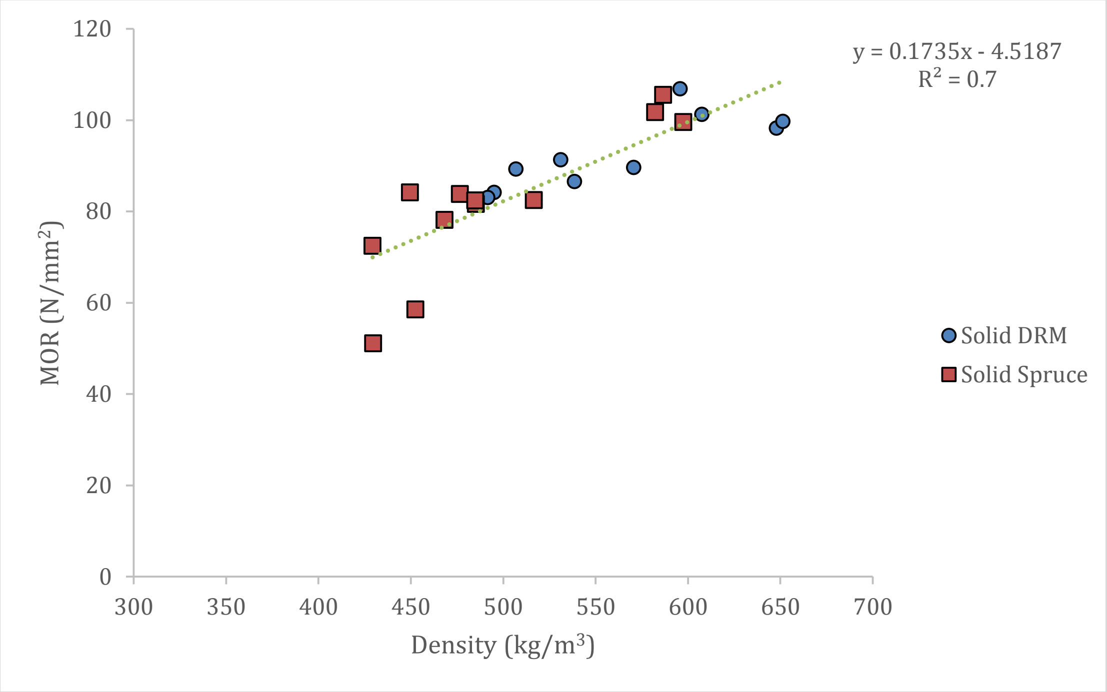

Figure 4. Bending strength as a function of density for solid DRM and spruce specimens

Joint efficiency of the specimens was determined based on the ratio of MOR of finger-jointed specimens to the mean MOR of solid specimens of the same species. In this study, the mean joint efficiency of vertical finger-jointed DRM (FJ1) and spruce (FJS) specimens were 77% and 65% respectively. The mean MOR of FJ1 specimens was 26% higher than the mean MOR of FJS specimens. Further ANOVA analysis showed a statistically significant difference at the 95% confidence level between MOR values of FJ1 and FJS, indicating the bending strength of finger-jointed DRM specimens was higher than the bending strength of finger-jointed spruce specimens in this study.

3.2 Factors influencing the bending properties of finger joints

DRM finger-jointed specimens produced with the recommended end pressure of 12.5 N/mm^2 (FJ1) possessed higher MOR values compared to the specimens finger-jointed with lower end pressure of 10 N/mm^2 (FJ4). ANOVA analysis showed a significant difference between the MOR values of FJ1 and FJ4 specimens. In contrast, DRM finger-jointed specimens FJ5 produced with higher end pressure of 15 N/mm^2 exhibited mean MOR value comparable to the FJ1 specimens finger-jointed with the recommended end pressure of 12.5 N/mm^2. ANOVA test results revealed no significant difference at the 95%

confidence level between MOR values of FJ5 and FJ1. Figure 5 shows the distribution of MOR values for finger-jointed specimens produced with different end pressures.

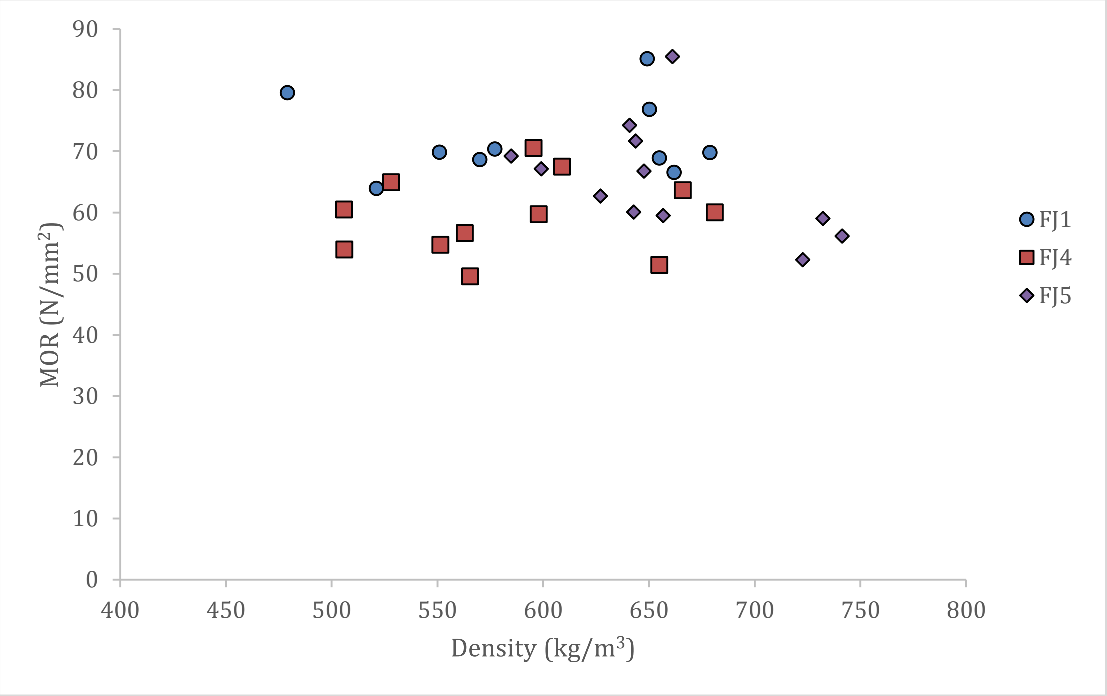

Figure 5: Bending strength as a function of density for DRM finger-jointed specimens with different end pressures

The results for the finger-jointed DRM specimens (FJ2) with wider dimensions (30 x 60 mm) were compared to the FJ1 specimens with cross-sections of 30 x 30 mm. The aim was to determine if there was any effect of size on the bending strength. From the results, FJ2 specimens possessed similar mean MOR value to FJ1 specimens. ANOVA analysis revealed no significant difference between the MOR values indicating that an increase in the specimen width does not influence the bending strength of the finger-jointed specimens. A study by Madsen (1992) indicated that variation in the length of specimen (length effect) and load configurations influenced the bending properties of timber. The specimen's length and load configuration in this study remained constant, thus these factors did not influence the bending strength results of the DRM specimens. Figure 6 shows the distribution of MOR values for FJ1 and FJ2 specimens.

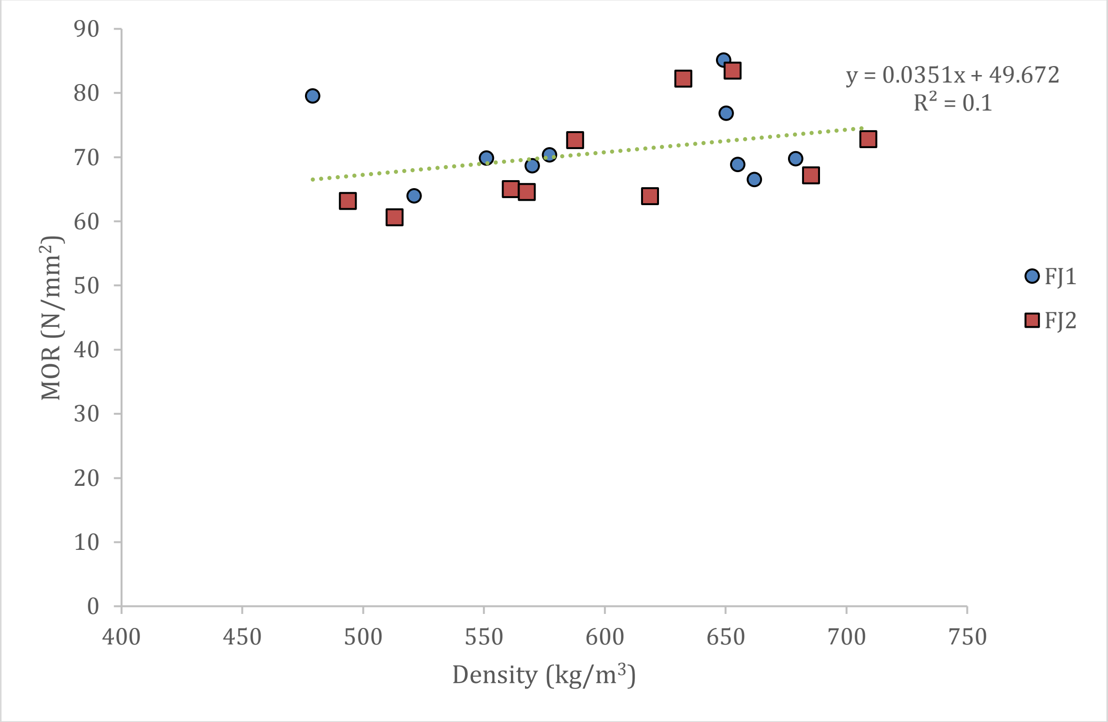

Figure 6: Bending strength as a function of density for FJ1 and FJ2 specimens

Finger-jointed specimens FJ3 with horizontal joint orientation were tested in four-point bending (Figure 7a). The mean MOR value for FJ3 specimens was slightly lower than the mean MOR for specimens with vertical orientation (FJ1) as shown in Table 2. ANOVA analysis indicated no significant difference between the MOR values of FJ3 and FJ1. The cross-sectional dimension of FJ3 specimens were similar to FJ1 specimens, thus both specimens have similar bonding areas that resulted in comparable bending strength. In the production of glulam beams, the width of the specimen is not equal to its depth, thus the bonding area of the finger joints with vertical finger orientation will be different from the pieces with horizontal finger orientation (see Figure 2). In the finger-jointing process, the outer fingers will be inclined to spread out because of the end pressure applied. This resulted in weaker joint strength and thicker glue lines at the edge (vertical joint) and face (horizontal joint) of the pieces. The weaker sections of the bonding area at the edges of the vertical joint are smaller compared to the bonding area at the faces of the horizontal joint, resulting in higher joint strengths for the vertical joints compared to the horizontal joints also reported by Jokerst (1981).

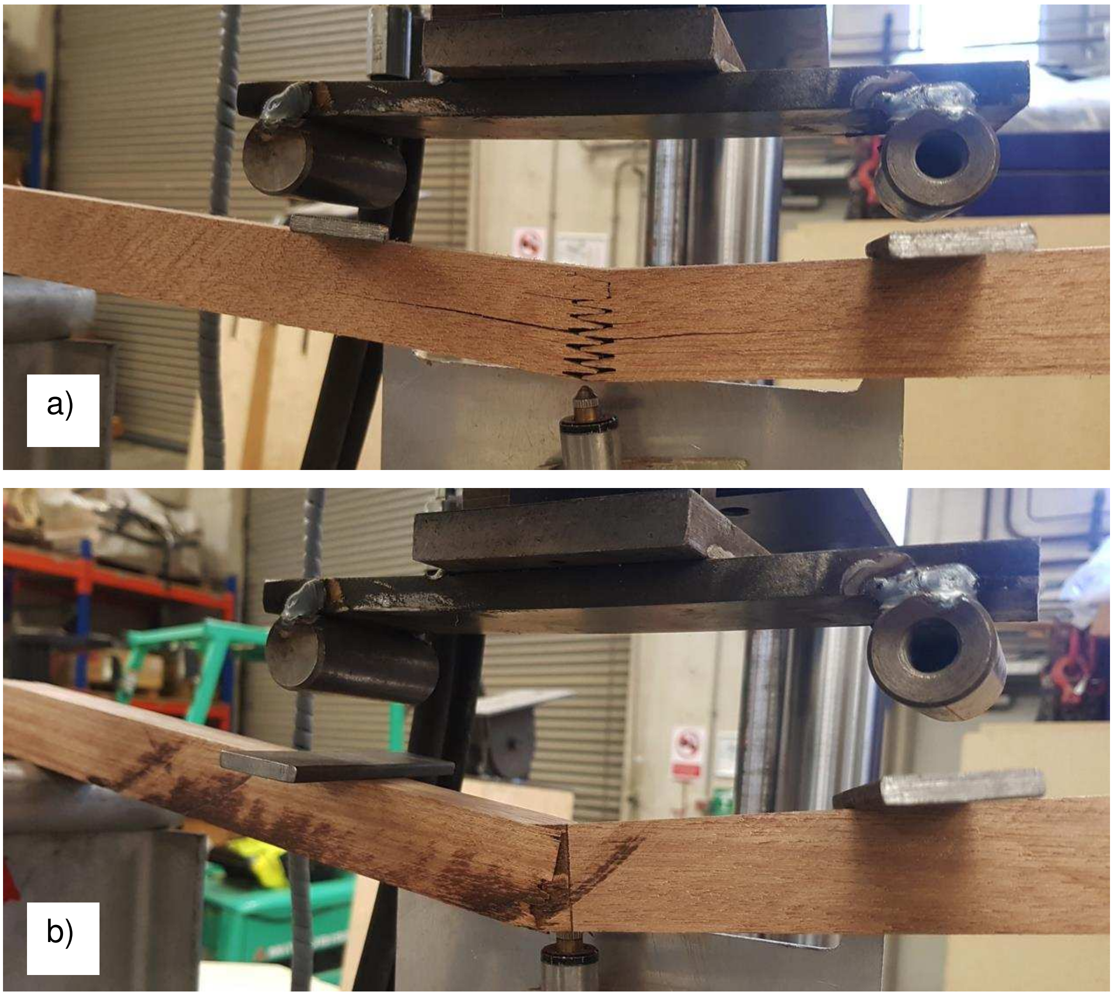

Figure 7: Failed bending test specimens a) horizontal joint; b) vertical joint

The mean MOE of the solid DRM specimens was similar to the mean MOE of DRM finger-jointed specimens (FJ1) as shown in Table 2. Further analysis using ANOVA showed no significant difference between the MOE values of the solid and finger-jointed DRM specimens. It can be concluded that the bending stiffness of the DRM specimens was not influenced by the finger-jointing process because MOE values were determined by the initial slope of the force-deflection curve in the elastic region in bending. The distribution of MOE values for both solid and finger-jointed FJ1 DRM specimens is shown in Figure 8.

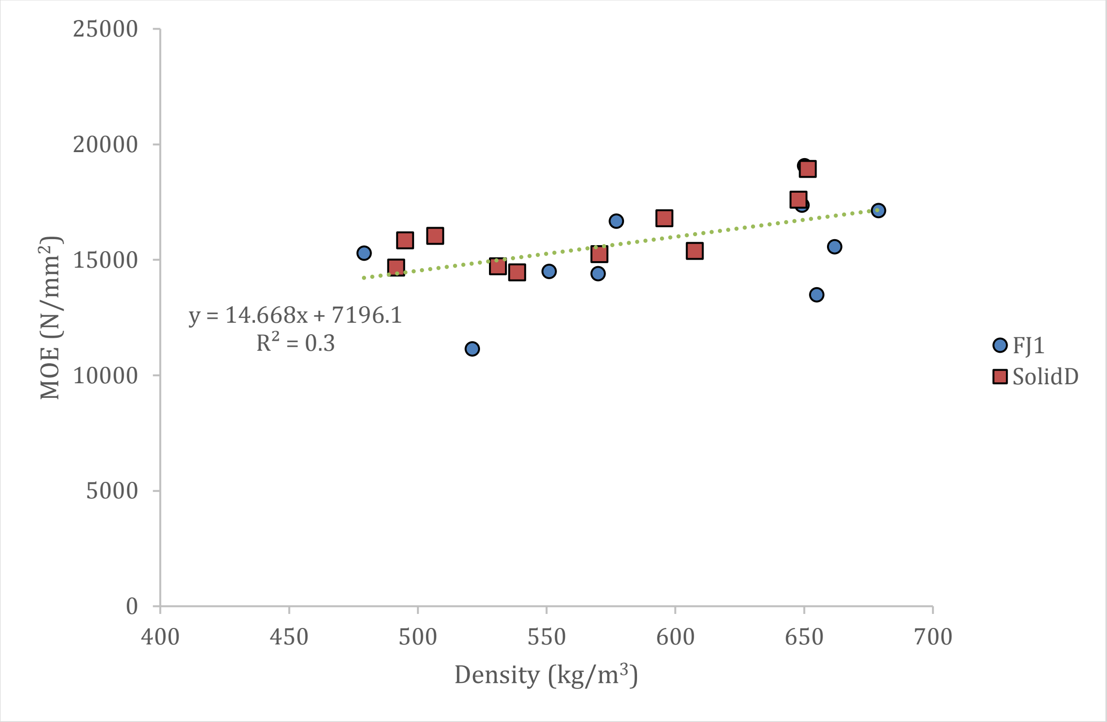

Figure 8: Bending stiffness as a function of density for solid DRM and FJ1 specimens

4. Conclusions

DRM finger-jointed specimens exhibited superior bending strength compared to finger-jointed spruce specimens. The findings of this study can be summarized as follows:

- DRM finger-jointed specimens possessed better joint efficiency than spruce specimens. The MOR values of solid DRM were not significantly different to MOR values for solid spruce when analysed with the ANOVA test but the DRM finger-jointed specimens exhibited higher MOR values when compared to spruce finger-jointed specimens.
- DRM finger-jointed specimens manufactured using end pressures of 12.5 and 15 N/mm^2 possessed higher bending strengths compared to specimens produced with a lower end pressure of 10 N/mm^2. It can be concluded that hardwood species, such as DRM in this study, may require higher end pressures to produce adequate strength finger joints compared to softwood species.
- The increase in the width of the DRM finger-jointed specimen had no influence on the bending strength.

- Finger-jointed DRM specimens with horizontal joints exhibited similar bending strengths to specimens with vertical joints because of the similar bonding area.
- MOE values of solid DRM specimens were similar to the finger-jointed specimens, indicating no influence of the finger-joints on the bending stiffness.
- The bending strength of both solid DRM and spruce specimens in this study appears to have a positive relationship with the density of the specimens. This relationship could be confirmed by increasing the number of specimens and including specimens from various sources, so that it is representative of the species population, especially for DRM timber that reportedly has a wide range of density.

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Biographical Notes

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Chee Beng Ong is currently a research officer at the Timber Engineering Laboratory, Forest Products Division, Forest Research Institute Malaysia (FRIM). He obtained his BSc in Physics and MSc in Wood Science from the Universiti Putra Malaysia, and his PhD in Civil Engineering from the University of Bath, UK. His research interests are in structural glued-laminated timber, utilisation of fast-growing plantation timber and non-destructive testing of Malaysian hardwood timber.

Martin P. Ansell

Martin Ansell graduated with a degree in materials science from the University of Sussex in 1971 and a PhD in the field of solid state physics at the University of London in 1975. Following two years as a research engineer at Standard Telecommunication Laboratories he took up a post-doctoral position at the University of Bath investigating the structure-related properties of wood, funded by NATO.

He secured the post of lecturer in 1979 and in the following years won research grants from UK Research Councils, EU, industry, TSB and KTP concerned with timber science and engineering and natural materials. The research included fatigue of laminated wood for wind turbine blades, the evaluation of the performance of dowel connections bonded-into structural timber, the development of natural fibre composites and the formulation of photocatalytic coatings for wood-based panel products.

Martin has supervised 26 graduate PhD students and has an h-index of 31 on Google Scholar with over 100 journal papers and over 6,800 citations. He was president of the Institute of Wood Science from 1994-96 and is currently Honorary Reader in Materials at the University of Bath. He has recently edited a book on Wood Composites published by Woodhead Elsevier. He sits on the Board of the Wood Technology Society and is on the Editorial Board of the International Wood Products Journal and the journal Wood Science.

Wen-Shao Chang

Wen-Shao Chang joined the Sheffield School of Architecture in 2017. Prior to this appointment, he was attached to Kyoto University, Japan as a JSPS Fellow and the University of Bath as a lecturer. He has a dual background in Architecture and Structural Engineering, and holds the degrees of BS Arch, MS Arch and PhD all from National Cheng Kung University, Taiwan.

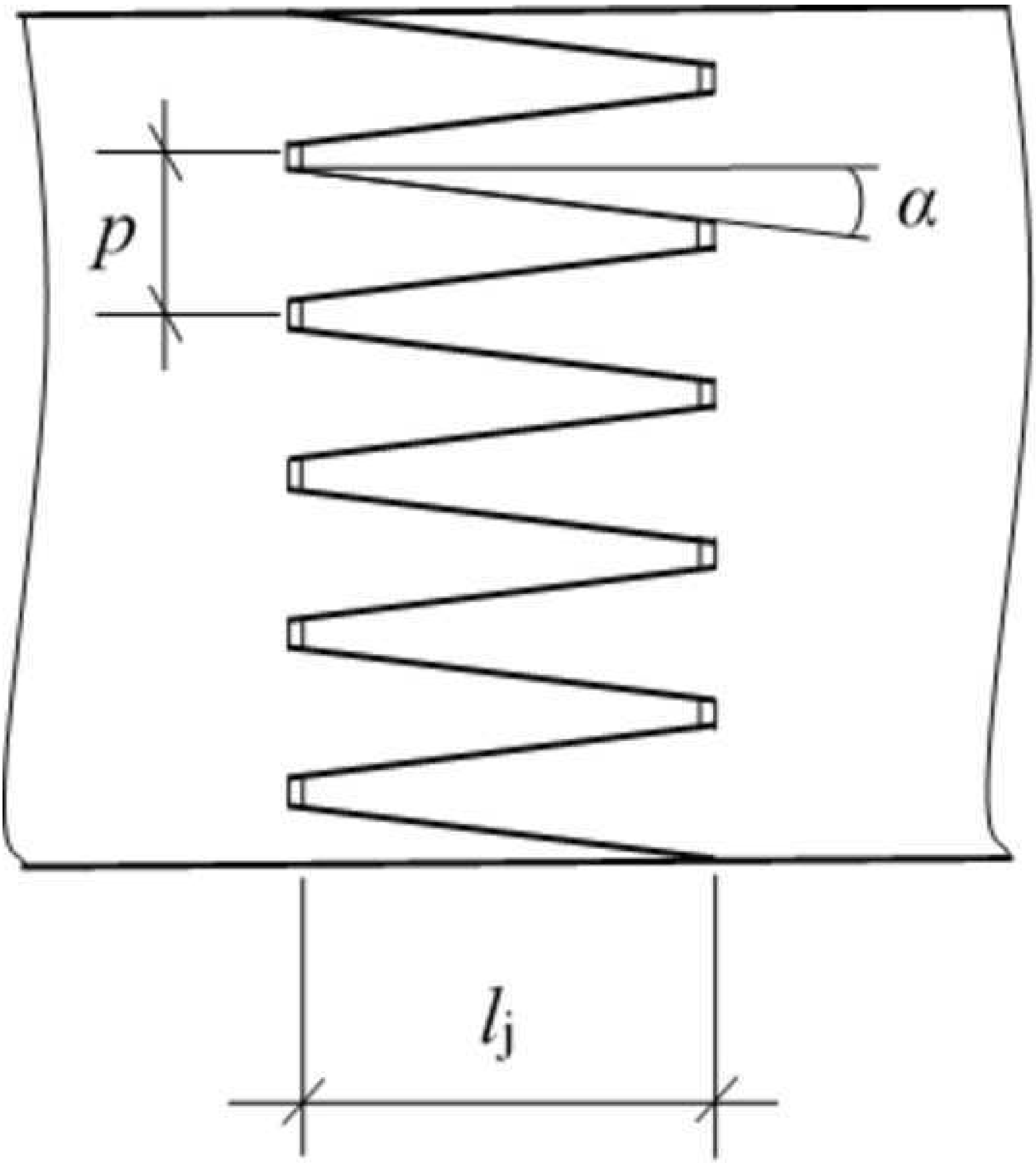
He is interested in exploring how natural materials can be used to minimise the environmental impact caused by the construction industry as well as strategies to achieve low impact in buildings. He works with industry and provides specialist advice to engineers and architects all over the world, He is partner of a UK-based consultancy firm: Time for Timber Ltd. He also sits on a number of committees to facilitate the development of design guidelines for the industry.

Pete Walker

Pete Walker is a chartered civil engineer and a member of both the Institution of Engineers Australia and The Institution of Civil Engineers (UK). Pete studied at Sheffield City Polytechnic, now Sheffield Hallam University, (BSc Civil Engineering) and the University of Edinburgh (PhD Structural Engineering). Having previously worked in Zimbabwe (University of Zimbabwe) and Australia (University of New England), Pete joined the University of Bath in 1998. He was promoted to Professor in 2006 on becoming Director of the newly formed BRE Centre for Innovative Construction Materials.

His current research interests include bio-based construction materials, materials for improved indoor air quality, structural masonry and innovative timber engineering. Since joining Bath he has led various research projects, having attracted funding as PI or CI from the BRE Trust, Carbon Connections, DEFRA, EASME, EPSRC, FP7, Knowledge Transfer Partnerships, Great Western Research, and the Technology Strategy Board (TSB). Pete has also received substantial financial and in-kind support from a number of SME and large scale industrial partners. The total value of his research projects awarded to date exceeds £10 Million.

He is currently Editor of the ICE Construction Materials journal and editorial panel member for Building Research & Information journal.



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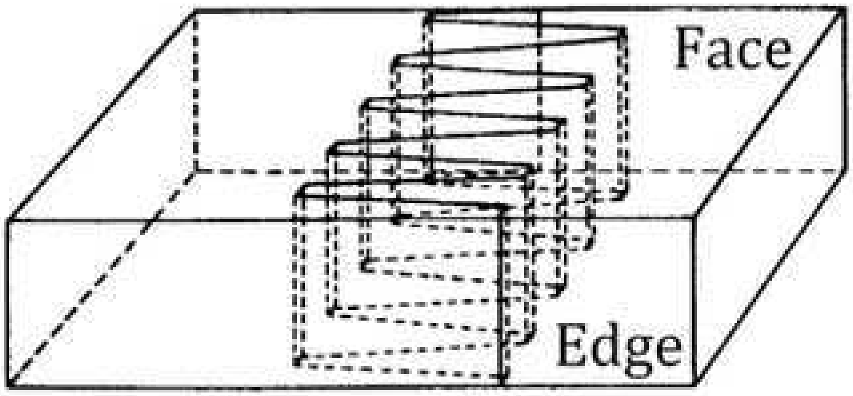
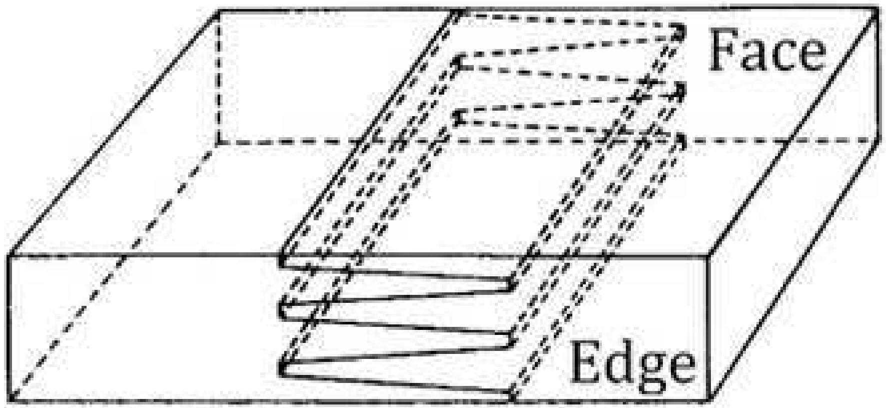


Vertical joint



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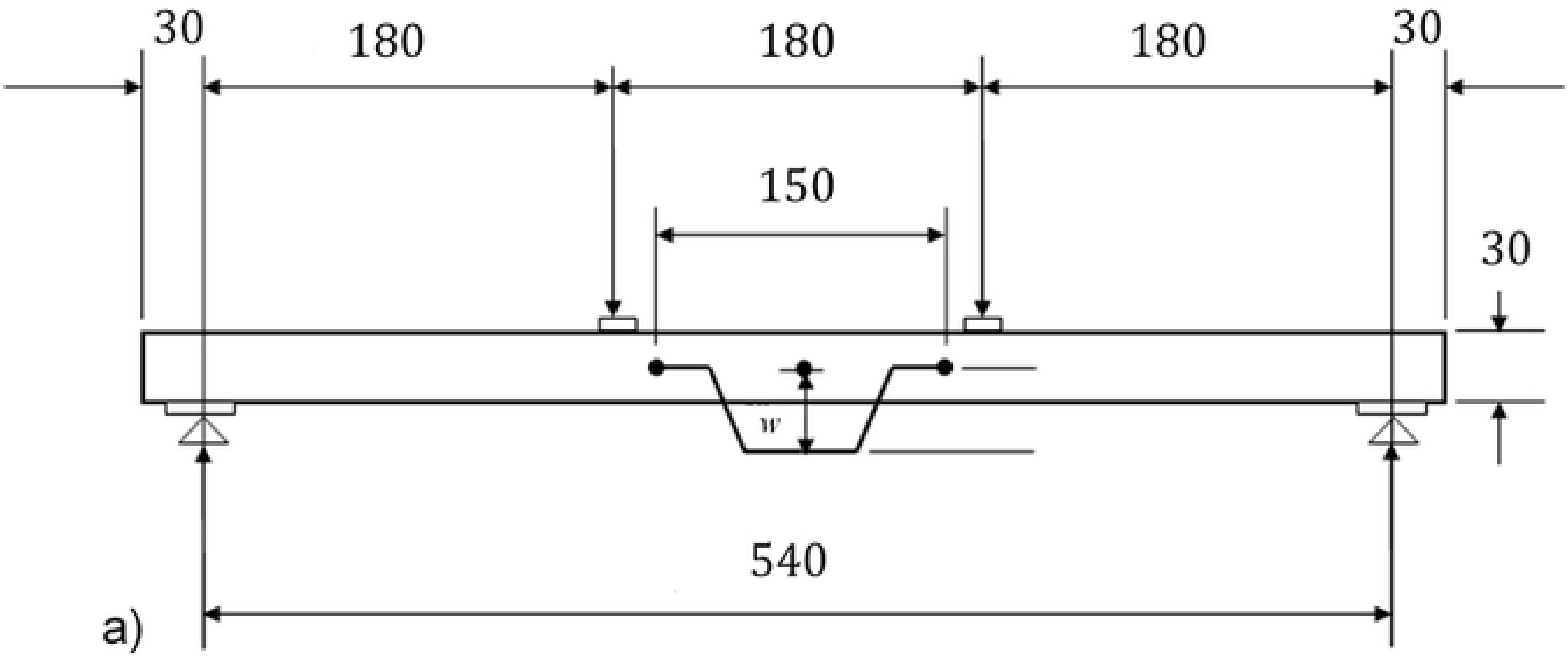
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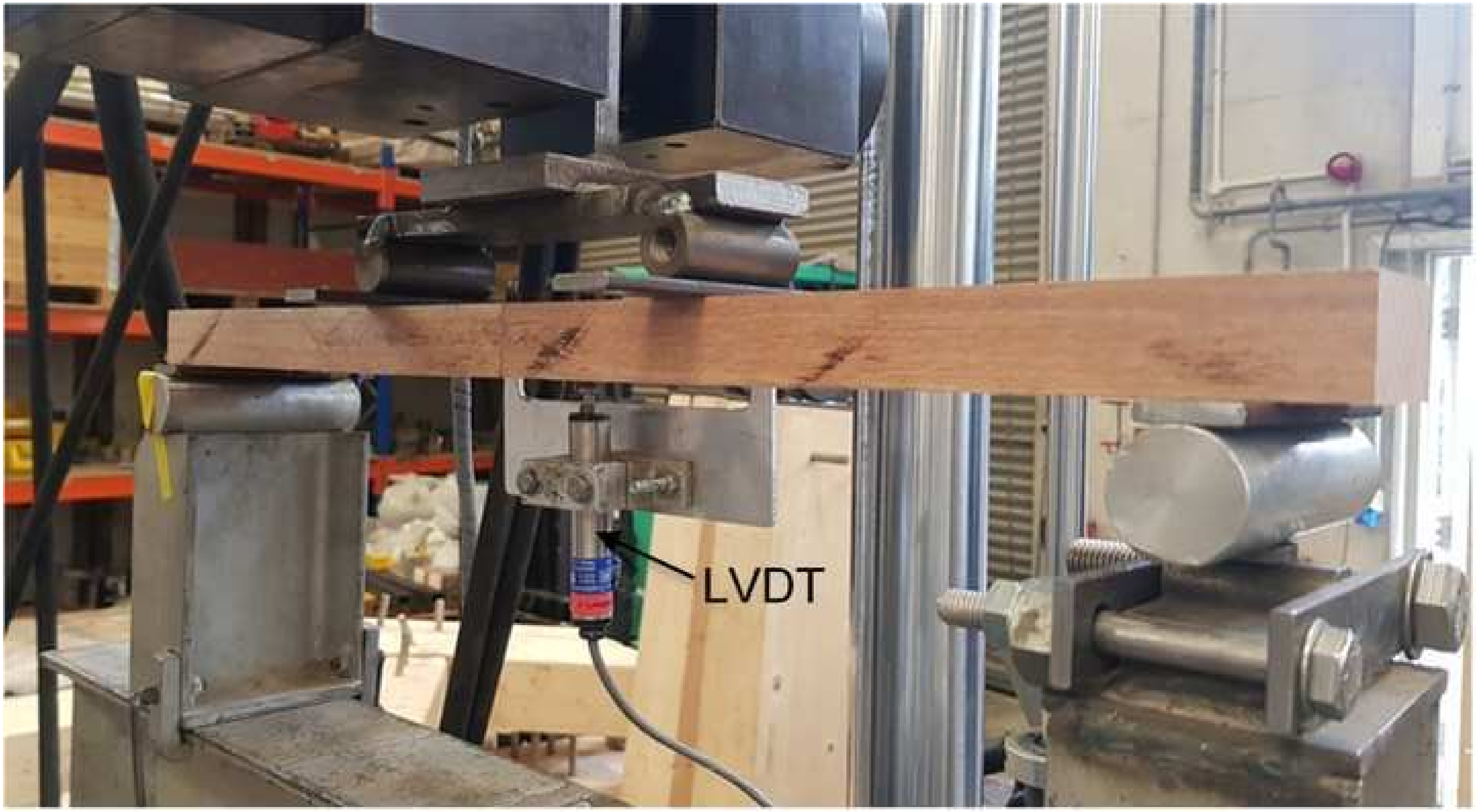
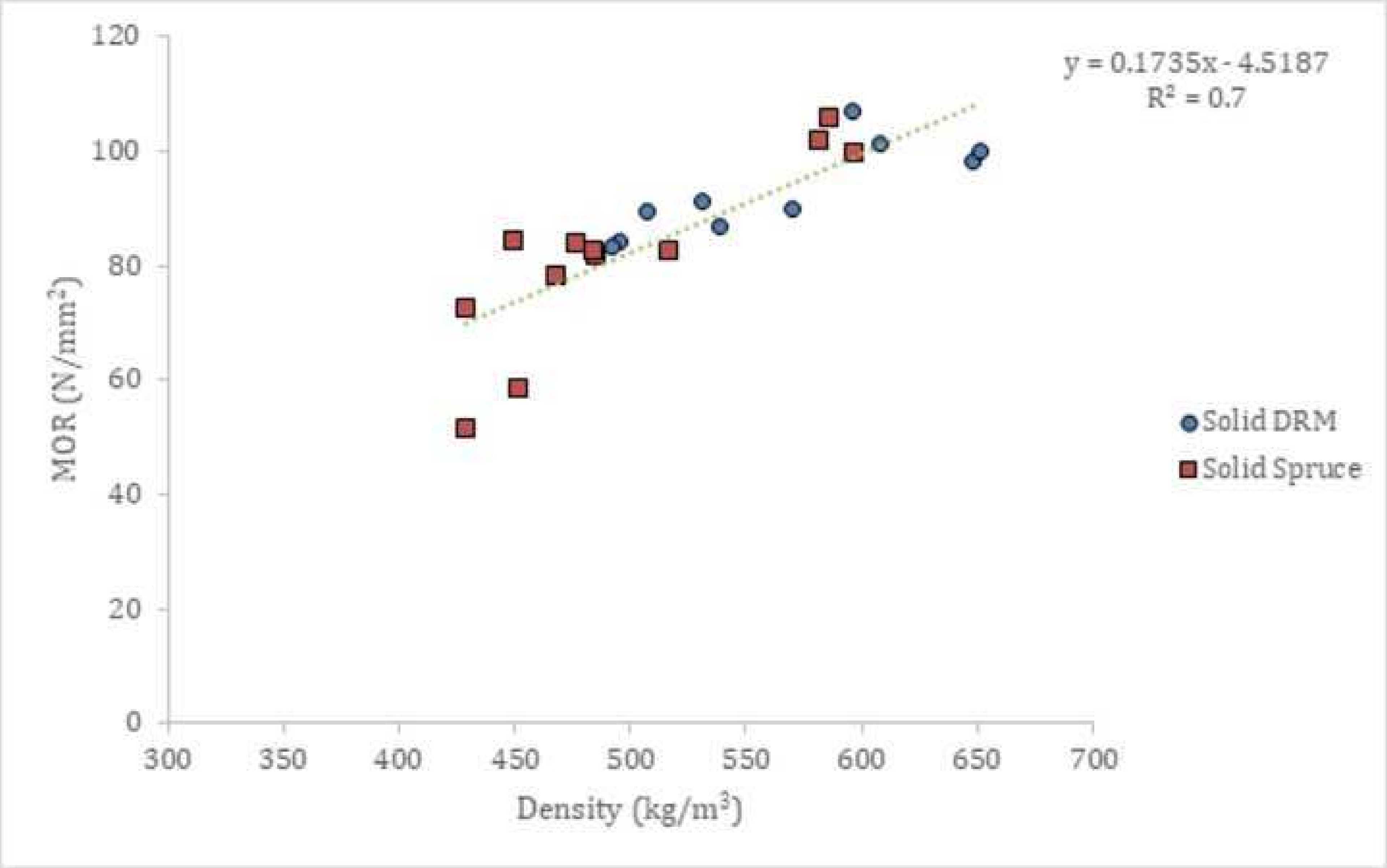
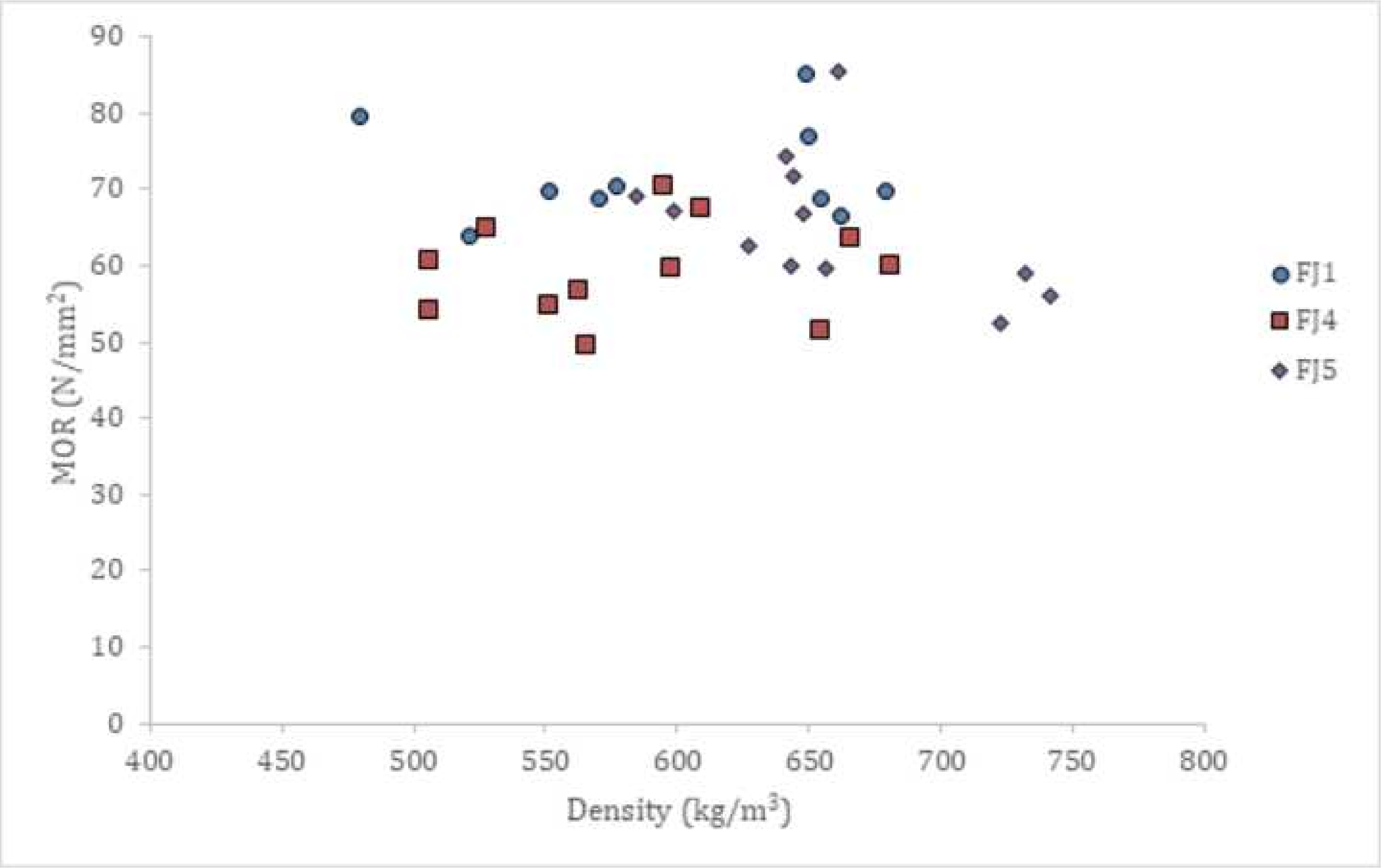
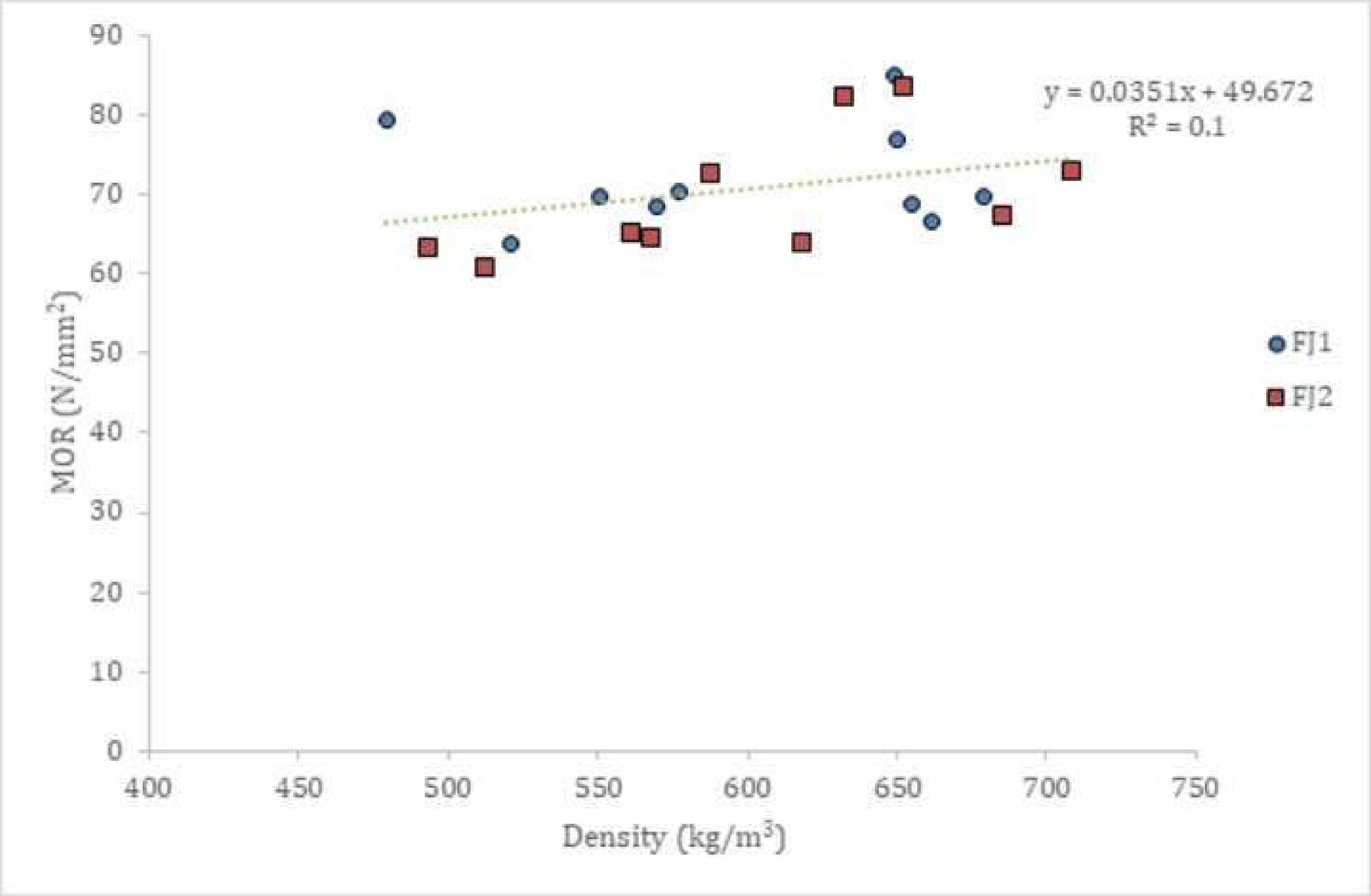
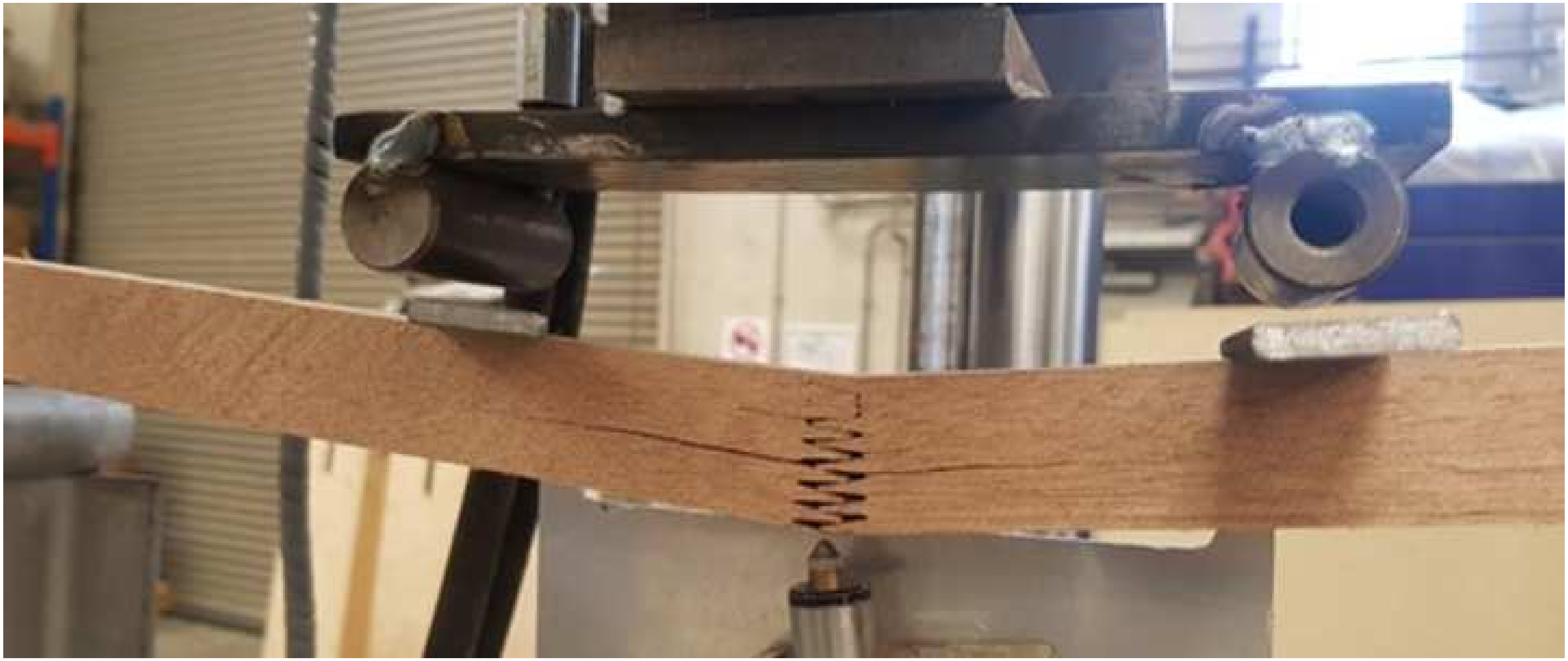
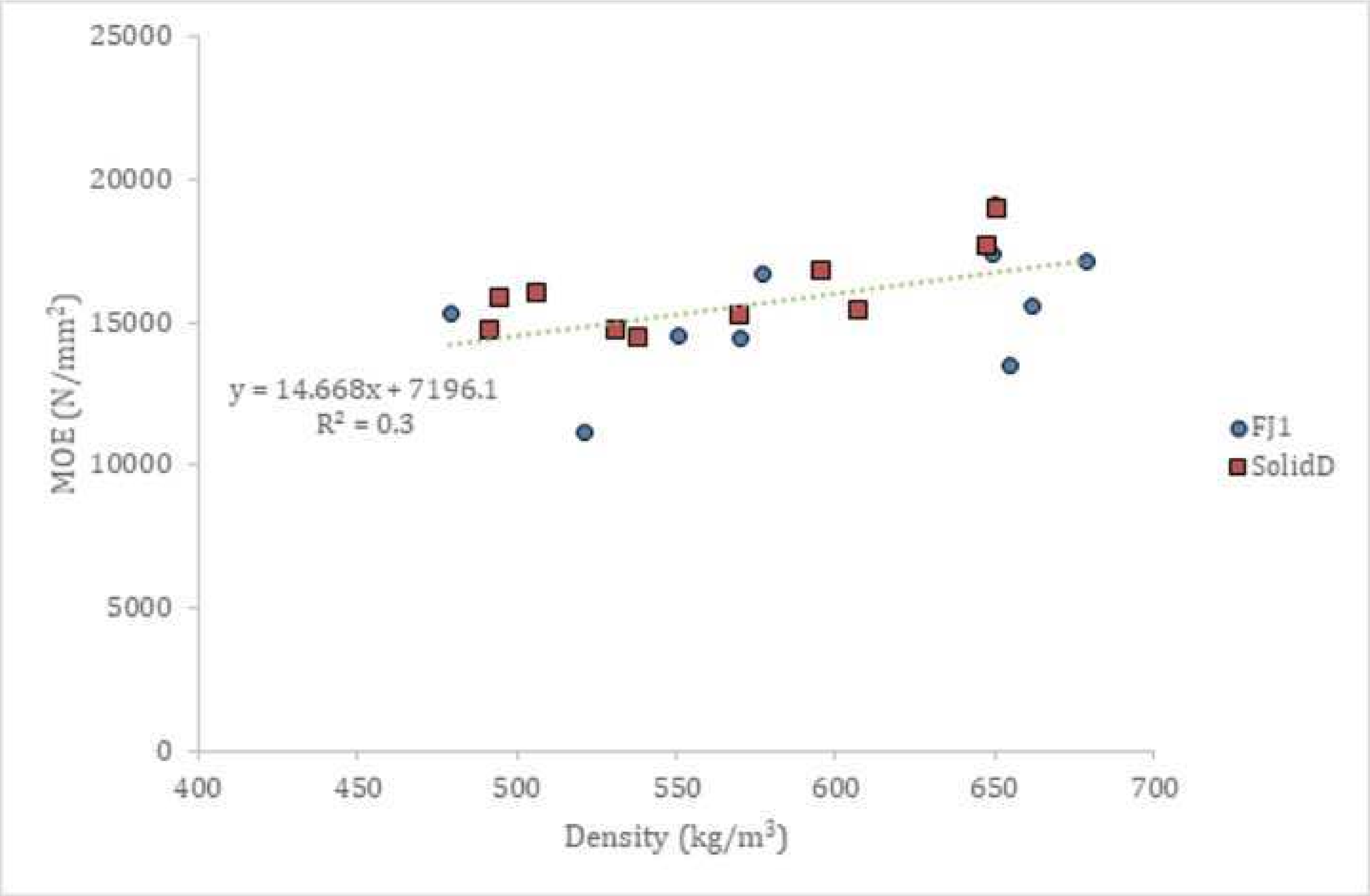

LVDT


y = 0.1735x - 4.5187
R² = 0.7
MOR (N/mm²)
Density (kg/m³)
120
100
80
60
40
20
0
300
350
400
450
500
550
600
650
700
● Solid DRM
■ Solid Spruce


90
80
70
60
50
40
30
20
10
0
MOR (N/mm²)
400
450
500
550
600
650
700
750
800
Density (kg/m³)
● FJ1
■ FJ4
◆ FJ5


90
80
70
60
50
40
30
20
10
0
400
450
500
550
600
650
700
750
MOR (N/mm^2)
Density (kg/m^3)
y = 0.0351x + 49.672
R^2 = 0.1
● FJ1
■ FJ2




25000
20000
15000
10000
5000
0
MOE (N/mm²)
400
450
500
550
600
650
700
Density (kg/m³)
y = 14.668x + 7196.1
R² = 0.3
● FJ1
■ SolidD