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The Analysis of Screws Spacing Effect on The Flexural Strength of Laminated Wood Beams from Pine Pallets Waste

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ABSTRACT

Pine pallets are often used to design the interior of houses, as opposed to pine waste, which is underutilized due to its reduced strength and limited size. Therefore, this research aims to optimize the use of pine pallet waste by making laminated beams using screw joints and determining the effect of screw spacing on the strong bending of laminated beams. Flexural strength tests of laminated wood beams measuring 5 cm x 5 cm x 76 cm with varying screw spacing of 4 cm, 8 cm, 12 cm, and 16 were used to conduct this research. This is in addition to screw length, head, and body diameters of 5 cm, 8 mm, and 4 mm, respectively. Strong bending testing was carried out at the Structural Laboratory of the Department of Civil Engineering, Faculty of Engineering, Tidar University, Magelang. The test results of consecutive Modulus of Rupture (MOR) had average values of 20.996 MPa, 23.067 MPa, 20.207 MPa, 19.292 MPa. and Modulus of Elasticity (MOE) of 1352.68 MPa, 1449.35 MPa, 1146.76 MPa, and 1128.90 MPa. The result showed that the use of varying screw spacing has no significant effect on the flexural strength of laminated beams. Furthermore, the laminated pine pallet waste with screws can be used as an alternative to pure wood by paying attention to the proper joint spacing.

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1. Introduction

Indonesia is a country that has several varieties of forest products in the form of wood used for construction purposes or furniture-making. [1] These products are environmentally friendly materials that can be recycled without polluting the environment. The Central Bureau of Statistics reported that wood production in the form of sawn timber and plywood was predicted to reach 2.5 million m^3 and 4 million m^3, respectively, by 2020. [2]

Every year the need for wood increases while its availability decreases due to massive exploitation. As a result, finding quality sawn timber with relatively large dimensions in the market becomes challenging because the production of forest products tends to dwindle. The continuous logging of woody plants results in deforestation due to its acceleration with unbalanced utilization. This impacts the economic sector, such as an increase in the price of quality wood and its industry waste reaching 25% of the material volume. [3] [4]

Pine wood is characterized by its bright color, it is also light, soft, easy to shape, environmentally friendly, and cheaper than teak. Pine pallets are widely used to manufacture furniture and secure packaging goods with the intent of being sent out of town. [5] Its waste is underutilized due to its small dimensions and reduced wood strength. Efforts to overcome these problems require using technology to recycle pine pallet wastes into raw materials or special structural wood for furniture-making and light loads, thereby boosting its economic and functional values. [6]

A typical example is the adoption of technology to manufacture laminated beam products from pine pallet waste. This procedure increases the strength and quality of pine pallet wastes, including the addition of the desired dimensions. Laminated beams are several wood layers combined into one whole piece by gluing them following the grain direction parallel to one another. [7] The advantage of laminated beams with sawn wood is that it increases the wood's strength and can be made longer or larger. [8] [9]

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Wooden materials have size limitations that require joints. It is used to connect structural components to be either longer or larger than the available size. The joint is the weakest part of the structural system. [10] Therefore, many joint technologies have been developed to realize several dimensions and shapes properly. Wooden mechanical joints consist of nails, screws, bolts, and dowels. [11] [12] It also has diverse advantages and disadvantages, hence the selection of the joint type and proper spacing tend to affect the flexural strength of laminated beams.

Based on this description, the present research was carried out on spacing variations between the screw joints and the flexural strength of laminated beams. The Pine pallet was selected because the price is relatively low, and the waste is used to increase its strength and dimensions. The screw joint was selected because the thread forms a strong bond and the processing time is more efficient than adhesives. Furthermore, screws can be removed and attached and have a greater pulling force than nails.

2. Method

2.1 Water content

Water content is the quantity of fluid contained in the wood. Any wood with high-water content must undergo a drying process first because excessive fluid affects its strength. There are no provisions regarding the amount of water content test objects, although they have the same shapes and sizes, and the data obtained is valid. Testing the water content of laminated beams from pine pallet waste was carried out using a measuring instrument known as a moisture meter. A moisture meter is used by sticking the needle at the end of the tool in each layer of the test object to determine the water content. According to SNI 03-6850-2002 [13], the equation used to determine the water content is stated as equation (1).

$$\text{Water content (M)} = \frac{Wg - Wd}{Wd} \times 100\,\% \qquad (1)$$

where M is the water content (%), Wg is the wood wet weight (gr), and Wd is the oven dry wood weight (gr).

2.2 Density

Density is defined as the weight or mass per unit volume expressed in grams per cubic centimeter. Lower density usually occurs in young wood and vice versa. It is determined by weighing and measuring the dimensions of the laminated beam test object. Density affects mechanical properties, such as shrinkage, swelling, etc. Differences in density values are affected by volume, water content, and the gluing process. The equation used to determine the wood density according to SNI ISO 9472-2008 [14] is stated as equation (2).

$$\rho = \frac{Wg}{Vg} \qquad (2)$$

Where ρ as wood density (gr/cm^3), Wg as wood wet weight (gr), Vg as the volume of wet wood (cm^3)

2.3 Flexural strength

Flexural strength is referred to the wood's maximum strength when damaged. The failure criteria due to flexural strength with the center point loading test object model depend on the cracked condition of the wood surface. The flexural strength test refers to SNI 03-3959-1995 [15], and it is performed to obtain the MOR and MOE values as follows:

Modulus of Rupture (MOR)

Modulus of Rupture (MOR) is a mechanical property that indicates the laminated beams strength in withstanding certain loads until they become damaged. The data from the Flexural strength test result is equivalent to the maximum load when a failure occurs in the laminated beam. The MOR of wood is determined with the following equation (3).

$$\text{MOR} = \frac{3P_{maks}L}{2bh^2} \qquad (3)$$

Where MOR represent the *Modulus of Rupture* (MPa), L as the effective span length of test object between two pedestals (mm), P_{maks} as the maximum load that can be withstood (N), b is the width of the test object (mm), and h is the thickness of the test object (mm).

Modulus of Elasticity (MOE)

Modulus of Elasticity (MOE) is a mechanical property that indicates the beam elasticity level. After calculating the inertia moment, the extent of deflected load is determined by selecting one point in a straight line on the test graph. The straight line on the graph depicts that the laminated beams were still in an elastic condition when the load was removed. Therefore, laminated beams can return to their original shape. The equation used to find the MOE of the wood is stated as equation (4).

$$\text{MOE} = \frac{PL^3}{48EI} \qquad (4)$$

Where MOE represent the *Modulus of Elasticity* (MPa), P is the magnitude of the load (N), I is the inertia moment (mm^4), L is the effective span length of test object between two pedestals (mm), δ is the deflection (mm).

2.1 Laminated Beam Composition

Pine Pallet Waste Composition

The test objects for laminated beams were made from pine pallet waste with a length of 76 cm, a width, and height of 5 cm, respectively. Laminated beams consist of three layers of pine pallet wood waste with a height of 1.67 cm each.

Screw Joint

The laminated beams are attached to mechanical joints using screws with a length, head diameter, and diameter of 5 cm, 8 mm, and 4 mm, respectively. The screw joints are installed in one row by placing the screws up and down. The scheme for installing joints with four variations of screw spacing for laminated beams is shown in Figure 1 to Figure 4.

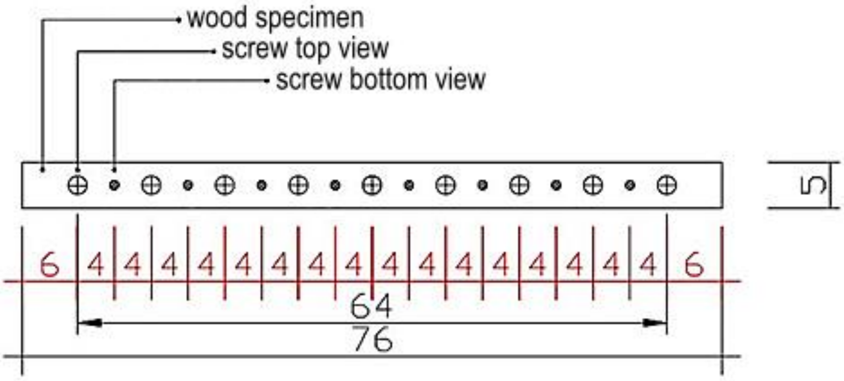

Figure 1. Laminated beam with 4 cm screw spacing

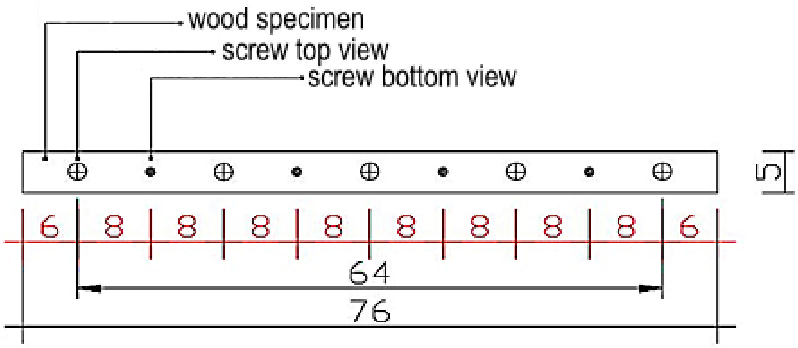

Figure 2. Laminated beam with 8 cm screw spacing

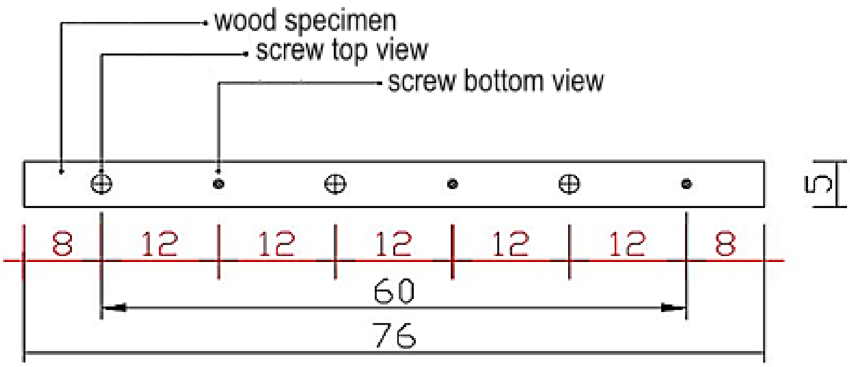

Figure 3. Laminated beam with 12 cm screw spacing

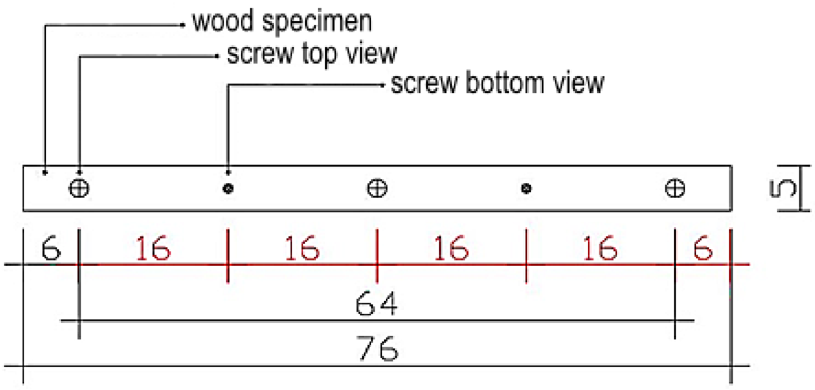

Figure 4. Laminated beam with 16 cm screw spacing

2.2 Test Scheme

Flexural strength testing was carried out at the Civil Engineering Laboratory, Faculty of Engineering, Tidar University. The flexural strength of pine pallet waste laminated beams measuring 760 mm x 50 mm x 50 mm was tested using a Flexure Testing Machine with a concentrated load. In addition, 25 mm spacing was taken from the right and left ends of the test object. The flexural strength test is then used to determine the MOR and MOE values. The test schematic image is shown in Figure 5. The flexural strength test object code is shown in Table 1.

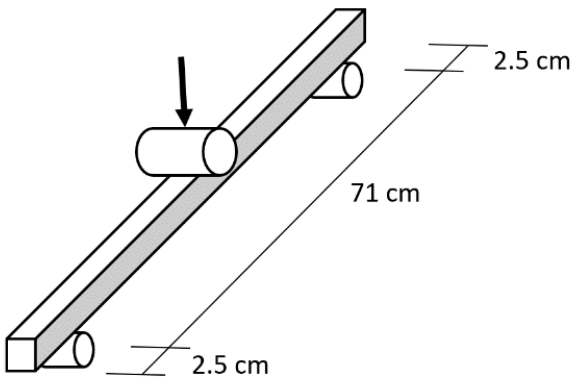

Figure 5. Flexural strength test scheme

Table 1. The object code of the flexural strength test

Code	Screw Spacing (cm)	Layer Segment
A1	4	Pine-Pine-Pine
A2	8	Pine-Pine-Pine
A3	12	Pine-Pine-Pine
A4	16	Pine-Pine-Pine

2.3 Laminated Beam Manufacturing Process

The following are the steps employed when making a laminated beam test object from pine pallet waste:

1. The 60 layers of wood have a size of 760 mm x 50 mm x 16.7 mm and were made using sawing and planer machine.
2. The layers of wood are dried by exposing them to the wind. These layers of wood should not be stacked during the drying process.
3. Each layer of laminate has a suitable size, and the surface is cleaner and parallel, resulting in some attachment with the others.
4. The spacing between each variation on the laminate beam is marked.
5. The Joints with varying screw spacing are installed according to Figs. 1 to 4. A drilling machine or tool was used to install the screw diameter.
6. The pressing step is conducted, hence the attachment process between layers tends to be maximally bonded.
7. The pressing tool is removed from the laminated beam.

2.4 Testing Process

Water Content Testing

The following are the steps employed for testing the water content of pine pallet waste laminated beams:

1. The moisture meter tools, and test objects are prepared.
2. Each test object is marked.
3. The moisture meter tool is inserted in each layer of laminated beams.
4. The average water content of each test object is calculated.

Density Testing

The density test was carried out to determine the proportion of the cavity volume in the pine pallet waste. The following steps were adopted for testing the density of pine pallet waste laminated beams:

1. The tools and materials for the wood density test were prepared.
2. Each test object is marked.
3. Each test object is weighed with a digital scale.
4. The length, width, and height of the test object are measured.
5. The wood density is calculated using the stipulated formula.

Flexural Strength Testing

Flexural strength testing is performed to determine the maximum load value received by the test object (Figure 6). The following steps are used to test the Flexural strength of laminated beams:

1. The test objects are prepared, and a code is assigned to them. A good number of objects are subjected to flexural strength testing.
2. The Flexure Testing Machine is set.
3. The test object is placed on the machine and is held using a pedestal at each end.
4. The pressure bearing is placed on the test object by placing a load at one point, specifically in the middle of the wood.
5. The Flexure Testing Machine is operated to obtain maximum load data in each variant of the test object made.

Figure 6. Flexural Strength Test

3. Results and Discussion

3.1 Water Content Test

Wood tends to get stronger, supposing there is a decrease in water content. Therefore, the water content value and strength relationship are inversely proportional. A high-water content value means that wood binds much fluid, making it less optimal for accepting loads. This causes shrinkage, which results in deformation and a decrease in strength. Low water content values have strong fibers that increase strength in receiving loads. Factors that affect the water contents are air humidity, drying process, age, and wood part. The following graphic image of the water content test results is shown in Figure 7.

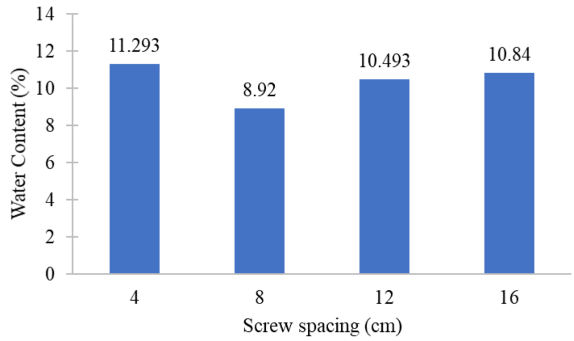

Figure 7. Graph of Water Content Test Results

Based on the water content test carried out on the pine pallet waste laminated beams, the average water content of test objects A, B, C, and D with a screw spacing of 4 cm, 8 cm, 12 cm, and 16 cm was 11.293%, 8.92%, 10.493%, and 10.840%, respectively. Test object B, with a screw spacing of 8 cm, has the lowest water content value, therefore it has the greatest strength. According to SNI 7973-2013, the results of the average water content of pine pallet waste laminated beams met the design specifications for wood construction, which does not exceed 19%.

3.2 Density Test

The relationship between the density value and the strength is directly proportional. Therefore, the higher the density value, the stronger the wood, and vice versa. Wood with a relatively young age has a lower density. Differences in density values are affected by volume, water content, and the gluing process. The following graphical image of the density test results is shown in Figure 8.

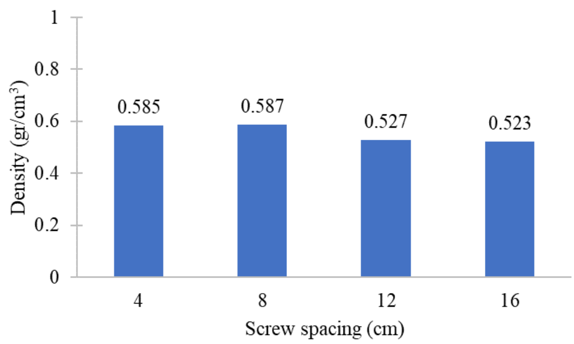

Figure 8. Graph of Density Test Results

Based on the calculation of the density of the pine pallet waste laminated beams, the average values for test objects A, B, C, and D with screw spacing of 4 cm, 8 cm, 12 cm, and 16 cm are 0.585 gr/cm^3, 0.587 gr/cm^3, 0.527 gr/cm^3, and 0.523 gr/cm^3, respectively. The laminated beam test object D has the lowest density value because the number of screws attached is the least compared to the others. As a result, the adhesive level between layers is less than optimal and tend to affect the density value.

3.3 Flexural Strength Test

Modulus of Rupture (MOR)

The Modulus of Rupture (MOR) test results are shown in Figure 9 and Table 2. In accordance with the MOR calculation of pine pallet waste laminated beams, the average value for variations A (screw distance 4 cm), B (screw distance 8 cm), C (screw distance 12 cm), and D (16 cm screw spacing) are 20.996 MPa, 23.067 MPa, 20.207 MPa, and 19.292 MPa, respectively. The graph in figure 9 shows that the laminated beam variation B with screw spacing of 8 cm has the largest MOR value of 23.067 MPa. Beam variation B has an average maximum load of 2342 N, which is accepted. This load is the largest compared to the other variation beams and has the highest MOR value.

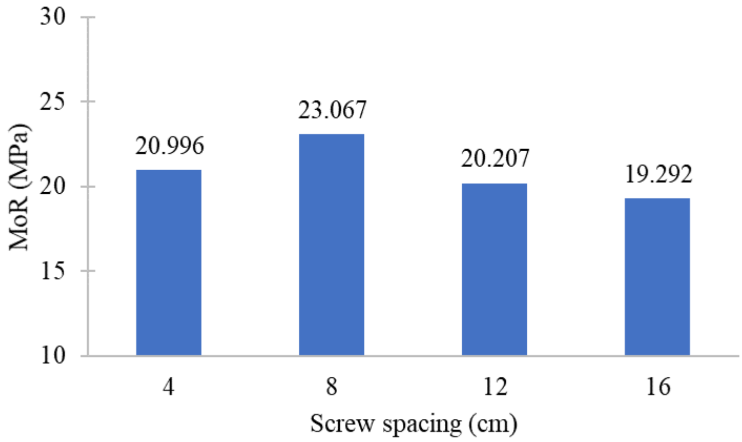

Figure 9. Graph of MOR Results

Table 2. MOR Test Results (Building Materials Laboratory, Tidar University, 2021)

Test Object Name	Test Object Dimensions			Maximum Load (N)	MOR Value (MPa)	Average MOR (MPa)
	Length (mm)	Width (mm)	Height (mm)			
A1	710	50	1970	1343	21.010	
A2	710	49	2019	1890	24.569	
A3	710	48.5	2009	2576	27.314	20.996
A4	710	48.3	2097	2641	26.852	
A5	710	49.2	1877	2103	15.592	
B1	710	49.3	1863	2112	18.386	
B2	710	49.4	1899	2443	15.666	23.067
B3	710	48.2	1981	2754	18.055	
B4	710	49.1	1976	2758	26.034	
B5	710	49.8	2019	1645	22.896	
C1	710	49.9	2023	2018	23.091	20.207
C2	710	48.3	1973	1637	16.404	
C3	710	48.2	1877	1867	18.146	
C4	710	49.6	1863	2633	15.808	
C5	710	48.8	1876	2288	23.008	19.292
D1	710	49.1	1915	2463	21.010	

This is due to several factors affecting each variation's MOR value, namely the wood's physical properties. These include water content, the laminated beams' density, and the presence of defects. The test on the laminated beams B, where the variation has the smallest and largest water content and density values, makes the wood fibers strong. In addition, the laminated beams tend to receive the maximum load.

Modulus of Elasticity (MOE)

The magnitude of the deflection load is used to find the MOE by selecting a point in a straight line on the test graph. The straight line on the graph shows that the laminated beams are still in an elastic condition. In circumstances where the load is removed, the laminated beams can return to their original shape. The MOE test result is shown in Figure 10 and Table 3.

Based on the MOE calculation of pine pallet waste laminated beams, the average value for variations A, B, C, and D is 1352.681 MPa, 1449.350 MPa, 1146.760 MPa, and 1128.901 MPa, respectively. Figure 10 shows that the variation D laminated beam with 16 cm screw spacing has the smallest MOE value of 1128.901 MPa. This is due to several factors that affect its strength, such as water content, density, age, and parts. Moreover, this is with respect to the fact that the material used is wood waste, following the test on the laminated beam variation D. This variation has the highest and smallest water content and density values, which causes delamination. It is further predicted that the beam is not optimal for receiving loads. Sulistyawati (2008) stated that the maximum flexural strength of laminated beams would be smaller, supposing there is slip damage between the composite layers (delamination). This happens because the screw spacing is large and makes the bond between the wood layers less perfect, causing the laminated beams to not function properly.

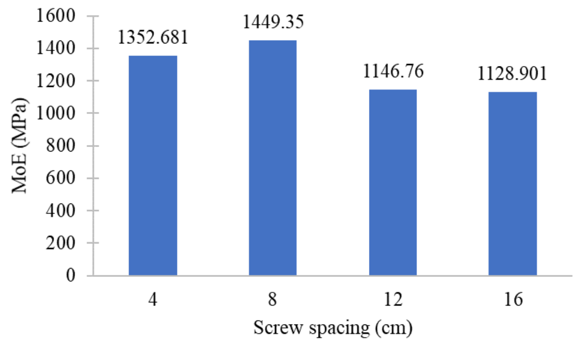

Figure 10. Graph of MOE Results

Table 3. MOE Test Results (Building Materials Laboratory, Tidar University, 2021)

Test Object Name	Test Object Dimensions Length (mm)	Width (mm)	Height (mm)	Moment of Inertia (mm^4)	Deflection (mm)	Deflection Load (N)	MOE value (MPa)	Average MOE (MPa)
A1	710	50	1970	460800.000	15.830	1180.000	1206.209	
A2	710	49	2019	397455.333	27.920	1787.500	1201.092	1352.681
A3	710	48.5	2009	408995.230	22.220	1540.000	1263.549	
A4	710	48.3	2097	423245.043	18.250	1440.000	1390.086	
A5	710	49.2	1877	414898.254	17.330	1641.670	1702.470	
B1	710	49.3	1863	415741.543	20.750	1468.750	1269.522	1449.350
B2	710	49.4	1899	408590.887	17.310	1533.300	1616.498	
B3	710	48.2	1981	422368.759	17.370	1660.000	1687.137	
B4	710	49.1	1976	430255.313	15.050	1525.000	1756.066	
B5	710	49.8	2019	444763.281	17.130	937.500	917.527	1146.760
C1	710	49.9	2023	471471.434	12.500	891.670	1128.165	
C2	710	48.3	1973	445132.800	19.230	1075.000	936.426	
C3	710	48.2	1877	438681.664	15.770	918.750	990.262	
C4	710	49.6	1863	418271.410	18.500	1560.000	1503.241	1128.901
C5	710	48.8	1876	414180.090	17.500	1142.860	1175.708	
D1	710	49.1	1915	455339.656	23.530	1837.500	1278.803	

3.4 Laminated Beam Failure

The failure form for each variation of laminated beams is the same. This includes the bending failure, where the difference lies in the type of wood crack, as stated in the SNI 03-3959-1995. Figure 11 to Figure 15 show the damage form that occurs in the laminated beams for each variation.

Figure 11. The Damage Pattern of Test Object A

Figure 12. The Damage Pattern of Test Object B

Figure 13. The Damage Pattern of Test Object C

Figure 14. The Damage Pattern of Test Object D

Test objects A (screw spacing 4 cm) and B (screw spacing 8 cm) had flexural damage that led to the cracking of the wood surface, specifically fibrous cracks. Filamentous cracks are shown in Figures 11 and 12. A crack pattern breaks the fiber in the strain and stress area. Test objects C and D have flexural damage that led to the cracking of the wood surface, specifically tensile cracking. In addition, tensile cracks are shown in Figures 13 and 14. A crack pattern is parallel to the grain direction in the strain section.

With respect to the occurrence of the beam failure behavior, it was concluded that the farther apart the screws, the greater the delamination process. This causes the laminated beams not to function effectively, thereby leading to the detachment of each lamina. The load received by the laminated beams also tends to get smaller. This is because the load of one screw used to prevent horizontal sliding is getting bigger.

3.5 Data analysis

Single Factor ANOVA Analysis of MOR

The MOR test result was calculated, and the statistical analzyed using the Single Factor ANOVA method by comparing F_{table} with F_{crit}. F_{count} (0.6212) is less than the F_{crit} (3.2389), thereby leading to the emergence of results that are insignificantly different. Based on these results, it was concluded that screw spacing on laminated beams did not significantly affect the MOR because the difference in value varies, although not significantly. This is due to several factors, including the physical properties of each test object, such as the density value, which differs slightly between variations and the water content, as well as the number of defects in the wood on the laminated beam. However, this is since the raw material used is wood waste, and no grading was conducted.

The Single Factor ANOVA calculations result for MoE proves that the F_{value} (2.0662) is less than the F_{crit} (3.2389). This led to an insignificant difference between the independent and dependent variables. It was concluded that screw spacing for pine pallet waste does not significantly affect the MOE value. This is because the difference between the variations is insignificant. Meanwhile, this occurred due to several factors, namely the physical properties of each test object, which includes slightly different density and unequal water content values between one variation and another, as well as the number of wood defects in laminated beams considering the raw material used is wood waste, and grading was not performed.

4. Conclusions

1. Based on the MOR test result, the A variation (4 cm screw spacing) obtained was 20.996 MPa. The B (8 cm screw spacing), C (12 cm screw spacing), and D variations (16 cm screw spacing) were 23.067 MPa, 20.207 MPa, and 19.292 MPa, respectively. Laminated beam variation B (screw spacing 8 cm) has the largest MOR value of 23.067 MPa.
2. The MOE results of pine pallet waste laminated beams obtained an average value for variations A, B, C, and D of 1352.681 MPa, 1449.350 MPa, 1146.760 MPa, and 1128.901 MPa, respectively. Laminated beam variation D (screw distance 16 cm) has the smallest MOE value of 1128.901 MPa.

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