



Failure Analysis of Glulam Lumber Beam Made from Meranti Lumber Pieces (*Shorea SP*)

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Abstract. The development of glue – laminated (glulam) lumber beam gives many good results. Meranti (*Shorea SP*) is one of the construction lumbers that can be used as glulam to optimize its use. The limitation of the glulam lumber beam is its limited length. Therefore, it must be joined to get a certain length. The lumber available in the market on average has a limited size and cross – sectional length. The larger cross-sectional size and length of the lumber leads to the higher the price. Used lumber and residual lumber also have many weaknesses, such as the length of suitable lumber is too short, lumber defects, and lumber damages. Further research needs to be done to optimize the use of new, used, and residual meranti lumber using lumber pieces as a glulam lumber beam maker. Standard specimen and test based on ASTM D-198. Glulam lumber beam is made from pieces of meranti lumber planks of certain length which are arranged into lamina beam with the size of 5.5x9.5x150 cm³. Variations in the length of the pieces of meranti lumber planks for making glulam lumber beam, among others, 40 cm, 50 cm, 60 cm, 50 cm with full length lowest layer and 150 cm (full length). The adhesive used is polyurethane glue. The span between supports is 130 cm. The beam is tested for center point loading. The analysis results show that the joints on the outermost layer that receive tensile stress of the glulam lumber beam can cause weakening in the beam because the tensile strength of the adhesive is weaker than the tensile strength of lumber. Design of joints should not be placed on layers that are subject to tensile stresses so as not to weaken the beam so that the strength of the glulam lumber beam can be optimal.

Keywords: glulam, laminated, meranti, lumber, beam.

INTRODUCTION

Lumber is a building material used in many fields because of its excellence in physical and mechanical properties and being easy to dismantle and assemble [1]. It is a renewable material because it is a part of the tree that can be planted and grown. However, the lumber used for construction purposes has a long harvest time. Planting construction lumber trees as an effort to maintain its availability of lumber is still not in balance compared with the massive exploitation of lumber. This condition has occurred in the natural forests of Central Java Province. For 16 years (1990-2006), Central Java Province has lost 446,561.09 ha of dry land natural forest or 88% [2]. If it is not accompanied by lumber engineering, its availability will not be able to meet the demand for lumber in the future.

Meranti (*Shorea SP*) is widely used as structural lumber. This lumber, which is widely distributed in various parts of Indonesia, is lumber that is widely available in the market and has been widely recognized in the wider community as strong and hard lumber construction. Meranti can be categorized as lumber with the quality code E14 [3]. The flexural modulus (E_w) of E14 quality lumber is 13,000 MPa [4].

The problem commonly found regarding the use of lumber on the market is the limited cross-sectional size and length of lumber on the market. This happens because the condition of the tree is not possible to get lumber of the size you want. The unit price of lumber in a lumber shop depends on the length of the lumber, the longer the lumber the more expensive the price is. Another problem also exists in used lumber. Used lumber usually has many lumber defects and lumber damage. Basically, used lumber can be separated between used lumber which is still proper and damaged lumber. Lumber that is still suitable can be reused for construction purposes,

while lumber that has been damaged is discarded. The problem of residual lumber usually lies in its length. Residual lumber is piece of lumber that is no longer used. This lumber is usually used as fire lumber.

Glulam is one of the engineering wood products [5]. Glulam technology is often used to engineer lumber to obtain a higher cross section and strength of lumber than the solid lumber. The cross section of the glulam is made by joining the layers of lumber to form a solid beam using glue. Lumber layers can be arranged vertically or horizontally depending on the needs, see Figure 1. The design principle of glulam lumber beam is to maximize dimensions with minimizing material [6]. The net thickness of each lamina does not exceed 50 mm and the fibers of the entire lamina are roughly parallel in the longitudinal direction.

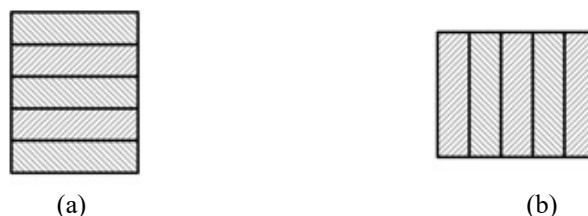


FIGURE 1. Section (a) horizontal glulam lumber beam and (b) vertical glulam lumber beam

The adhesive is one of the main components of the glulam lumber beam strength. The adhesive strength of glulam lumber beam is influenced by the interaction between the type of adhesive and the combination of lumber types, the type of adhesive with the pressing strength, the type of lumber with the pressing strength, and the type of adhesive with the combination of lumber type and pressing strength [7]. The shear strength of the adhesive is a reference in glulam lumber beam planning. If the shear strength of the adhesive is higher than the shear strength of lumber, the shear stress on the glulam lumber beam is limited to the shear strength of the lumber. on the other hand, if the adhesive shear strength is lower than the lumber shear strength, the shear stress on the glulam lumber beam is limited to the adhesive shear strength.

One type of connection that is often used in glulam lumber beams is the butt joint. The butt joint is easy to implement but weak in transmitting the stress of each glulam lumber beam cross section. The tensile strength at the cross-section of lamina lumber does not only work in the tensile plane of the joint but is also affected by the shear plane of the bond surface. Variation in placement of vertical joints has no effect on strength [8].

The purpose of this study was to determine the failure behavior of glulam lumber beam made of lumber planks of pieces. Short lumber planks can make the price of lamina lumber production more economical. Used lumber and waste lumber that has a limited proper length of lumber can also be used for construction lumber.

METHODOLOGY

The specimens used in this research were meranti lumber beam (*Shorea SP*). Lumber is graded visually and by weight to predict uniformly of strength. Preliminary testing to determine the physical and mechanical properties of lumber was carried out on the remaining pieces used to make glulam lumber beams to obtain the actual physical and mechanical properties of lumber. The physical and mechanical properties of lumber are used in terms of usage and design requirements.

The size of the glulam lumber beam refers to the American Standard Testing and Material (ASTM) D-198, Standard Test Methods of Static Test of Lumber in Structural Size. The size of the beam is 5.5x10x150 cm. Glulam is made from pieces of meranti lumber planks measuring 2.5x6xL cm. L is a variation of the length of the lumber planks to make glulam lumber beam. Variation of pieces length (L) and a sketch of the arrangement of the glulam lumber beam can be seen in Table 2. Lumber planks are arranged horizontally in 4 layers into a glulam lumber beam with a size of 5.5x10 cm, see Fig. 2. The lumber was previously 6cm width but was designed to be 5.5 cm in anticipation of lumber distortion.

The process of making glulam lumber beams begins from assembling pieces of lumber planks bonded with polyurethane (PU) glue. The arrangement of the glulam lumber beam is then compressed with a torsion wrench which has determined the compression pressure for all presses for 24 hours. Placement of the clamp on the lumber is given a steel plate whose dimensions are analyzed against the vertical compressive strength of the lumber fibers as a reference. The aim is that there is no influence of beam deformation due to local compressing [9], see Fig. 3. Pressing is carried out at room temperature. An ambient temperature of 30°C is the right temperature to get a good adhesive strength. The increase and decrease in temperature can reduce the adhesive strength [10].

TABLE 1. Variation of pieces length (L) and a sketch of the arrangement of the glulam lumber beam.

No	Length of piece (cm)	Specimen code	Sketch (cm)
1	40	BME40	
2	50	BME50	
3	60	BME 60	
4	50 with full length on the bottom layer	BMEF	
5	150 (full length)	BMEF50	
6	Solid lumber	BMES	

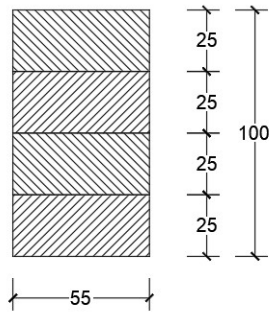


FIGURE 2. The cross section of glulam lumber beam.

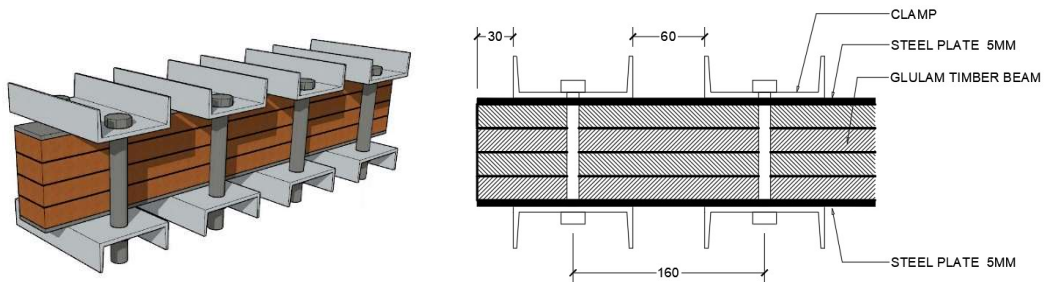
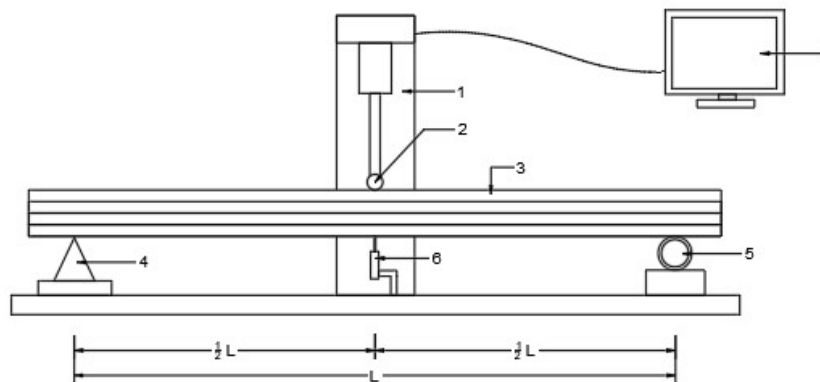


FIGURE 3. Compressing of glulam lumber beam.

The experimental test carried out on the specimen was the flexure test on American Standard Testing and Material (ASTM) D198-15, Standard Test Methods of Static Test of Lumber in Structural Size [11]. Specimen was tested statically at center point loading, see Fig 4. Beam length is 150 cm and the distance between the supports is 130 cm. The loads are placed in the center of the span with a distance to each support is 65 cm. Dial gauge is installed in the middle of the span to measure beam deflection. Time for flexure test is at least 4 minutes.



Code	Information
1	Hydraulic flexural frame
2	Load bearing
3	Test specimen
4	Joint reaction bearing
5	Roller reaction bearing
6	Dial gauge
7	Computer control
L	Distance between supports

FIGURE 4. The test set-up.

Beam failure needs to be analyzed whether failure occurs due to flexural or shear. Beam damage needs to be analyzed whether it occurs due to shear or not. It is necessary to analyze whether the actual shear stress that occurs in the beam exceeds the reference shear stress. The shear stress formula by using Eq a.

$$fv = \frac{3V}{2b.d} \quad (a)$$

f_v is shear stress, V is shear strength, b is width of cross-sectional and d is height of cross-sectional.

Based on the test setting up, if the maximum load that the beam can accept is known (P). The shear strength can be obtained by equation b.

$$V = \frac{P}{2} \quad (b)$$

The strength of lumber can be seen from the modulus of elasticity (MOE) and modulus of rupture (MOR). MOE on a flexural center loading based on ASTM D-198-15 can be determined by Eq c and MOR in Eq d [11].

$$MOE = \frac{Pl^3}{4b^3\Delta} \quad (b)$$

$$MOR = \frac{3P_{max}l}{2bd^2} \quad (c)$$

MOE is modulus of elasticity, P is load difference below proportional limit, l is the total distance between reactions on which a flexure specimen or shear modulus specimen is supported to accommodate a transverse load, Δ is largest change in deflection on the neutral axis of the beam in the middle of the span, I is inertia of the cross section.

The stiffness of the beam is a representation of the load to deflection. Stiffness is also often defined as the force required to make every unit of deflection. If depicted, the stiffness of a beam can be seen from the curve of the load curvature against the deflection that occurs. The equation for stiffness (k) can be calculated by.

$$k = \frac{P}{\Delta} \quad (d)$$

k is stiffness, P is load and δ is deflection.

TEST RESULT AND DISCUSSION

Physical and Mechanical Properties of Meranti Lumber

Meranti is lumber which is widely used as a construction structure. The test results show that meranti lumber has a modulus of elasticity (MOE) 10370 MPa and is included in the classification of the quality code E11 [4]. Other mechanical properties of this lumber can be seen in Table 2.

TABLE 2. Preliminary test results of meranti lumber.

No	Type of Testing	Test Results
1	Specific gravity	0.5 gr/cm ³
2	Moisture content	0.11%
3	Tensile strength	72.16 MPa
4	Compressive strength parallel to grain	38.15 MPa
5	Compressive strength perpendicular to grain	16.43 MPa
6	Shear strength parallel to grain	19.63 MPa
7	Modulus of elasticity	10370 MPa

The result of the moisture content of the lumber from the test results is 11%, because it is below 19% so it can be concluded that the lumber is in a dry service condition [4]. The result of shear strength test for polyurethane adhesive is 9.59 MPa. The shear strength of lumber is 19.63 MPa. It is greater than the shear strength of the adhesive. Therefore, the shear design of glulam lumber beam is designed based on the lowest shear strength that is the shear strength of adhesive.

Load Capacity

Fig. 5 shows the ratio of load capacity of solid and glulam meranti lumber beam. Load capacity of solid meranti beam is 15.5 kN and glulam lumber beam of BMEF is 18 kN, BMEF50 is 13.1 kN, BME40 is 3.25 kN, BME50 is 6.4 kN and BME60 is 5.4 kN. Glulam lumber beam of BMEF has a better load capacity than solid meranti beam because lumber defects can be broken down more evenly so as not to cause significant weakness in the beam. Glulam lumber beam of BME40, BME50 and BME60 has a low load capacity because the joints at the bottom layer make the beam weak. The failure starts from the release of the bonds between the joints of the rods at the bottom layer which experience tensile stress. The design without joint at the bottom layer is proven to increase the load capacity of the glulam lumber beam from pieces of lumber board. It can be seen at the glulam lumber beam of BMEF50, the percentage ratio of glulam lumber beam load capacity compared with solid beam can be seen in the Table 3.

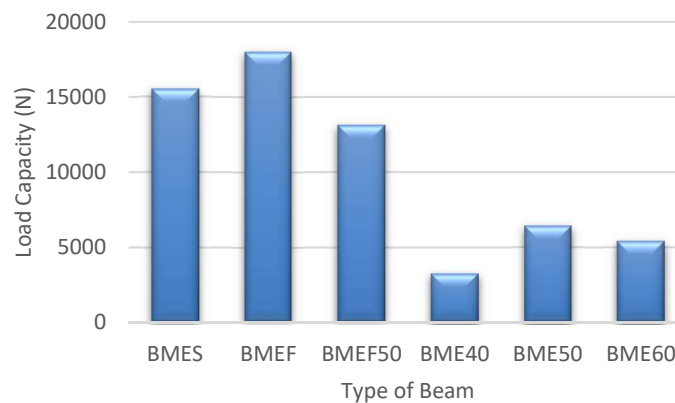


FIGURE 5. Ratio of glulam lumber beam load capacity compared with solid beam

TABLE 3. The load capacity ratio of glulam to solid beam.

No	Type of beam	Difference
1	BMEF	16%
2	BMEF50	-15%
3	BME40	-79%
4	BME50	-59%
5	BME60	-65%

Based on Eq 1 and 2, it is found that the shear stress of BMES is 1.96 MPa, BMEF is 2.28, BMEF50 is 1.66 MPa, BME40 is 0.41 MPa, BME50 is 0.81 and BME60 is 0.68 MPa. The adhesive shear stress is 9.59 MPa so that the adhesive shear force has not been exceeded. It can be concluded that beam failure is not affected by shear forces.

Flexural Strength

Table 4 shows test results of solid and glulam lumber beam. MOE (modulus of elasticity) is the ability of a material withstand loads without changing shape to permanent. MoE is a design reference measure in the planning of construction lumber structures. The classification of lumber quality codes can be compared with the modulus of elasticity [4]. Solid lumber beam (BMES) has MoE value of 10370 MPa. The average glulam lumber beam has MoE under the BMES. This condition occurs because the adhesive has ductile characteristics so that the deflection is greater.

The highest MoE is BMES. Glulam lumber beam from lumber planks has a lower MoE and varies. MoE of glulam lumber beam is influenced by the number of layers, thickness of laminate and type of lumber on the mechanical strength of the lumber [12]. MoE in table 4 is not in line with the beam maximum load. This condition illustrates that MoE does not reflect the strength of the beam to withstand the maximum load. The MoE more describes the strength of the material against deflection under elastic conditions as shown by the slope of the linear elastic curve in Fig 10.

MoR (modulus of rupture) is a measure of the strength of material while receiving its maximum load that cause damage [11]. MoR is a measure of the strength of structural lumber because it describes the original

strength condition of lumber rather than MoE. The BMES have an MoR value of 72.25 MPa. Failure at BMEF is a bending failure (see Fig. 6).

TABLE 4. The beam test results.

No	Type of beam	P proportional		P max		MOE (MPa)	MOR (MPa)	Stiffness k
		P (kN)	Δ (mm)	P (kN)	Δ (mm)			
1	BMES	10.42	14.90	15.50	45.00	10370	72.25	699
2	BMEF	15.87	23.60	18.00	38.80	9379	80.32	672
3	BMEF50	6.70	10.32	13.10	25.22	9229	59.50	649
4	BME40	3.17	6.88	3.25	7.29	6829	15.08	461
5	BME50	3.91	5.50	6.40	9.00	10141	29.00	711
6	BME60	3.62	5.90	5.40	9.40	8965	24.87	614

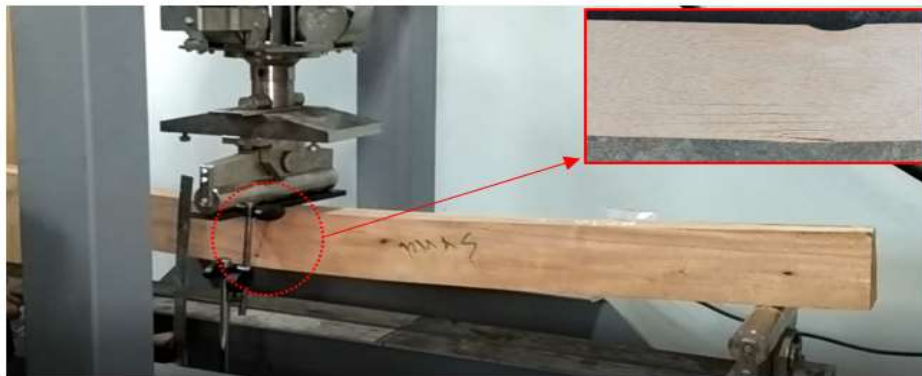


FIGURE 6. BMES beam failure patterns.

The BMEF has a higher MoR than BMES which is equal to 80.32 MPa, meaning that BMEF has a better structural strength than BMES. Failure at BMEF is a bending failure (see Fig. 7). BMEF are made of lumber planks layers so that the lumber defects break down evenly. This condition makes the reduction in strength due to lumber defects can be minimized. BME40, BME50 and BME60 has MoR far below the BMES. Beam failure begins with the disconnection of joint of the lowest layer. The tensile strength of the adhesive is weaker than the tensile strength of the lumber so that the connection at the lowest layer weakens the beam. When the joints at the lowest layer receiving tensile stress fail, the beam shear stress becomes more dominant and causes the beam to experience shear failure in the adhesive, see Fig. 8. BMEF50 has a better MoR than BME40, BME50 and BME60 but is still below the BMES. Although the length of the beam is made of lumber plank joints, if the lowest layer is made of solid lumber without joints, failure patterns such as those of BME40, BME50 and BME60 can be avoided. However, the MoR of BMEF50 cannot exceed the BMES. The adhesive shear strength is lower than the shear strength of lumber so that failure is prone to shear, see Fig. 9.



FIGURE 7. BMEF beam failure patterns.

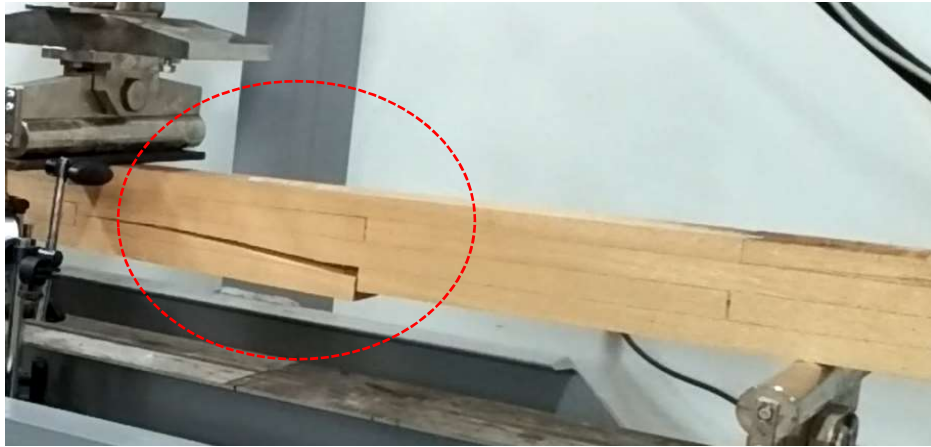


FIGURE 8. BME40, BME50 and BME60 beam failure patterns.



FIGURE 9. BMEF50 beam failure pattern.

The stiffness of the beam is a representation of the load/deflection. Stiffness is also often defined as the force required to make every unit of deflection. The stiffness of solid and glulam lumber beam have values that are not much different. This happens because the glulam lumber beam is made of the same wood. Glue has properties that are more ductile than wood so that the stiffness of glulam beam is slightly smaller than solid beam (BMES). Load capacity in elastic condition of BMEF is greater than BMES. This occurs because wood defects in the BMEF are parsed during beam making so that the reduction in strength can be minimized. Beam stiffness can be seen from the slope of the load-deflection line, see Fig. 10.

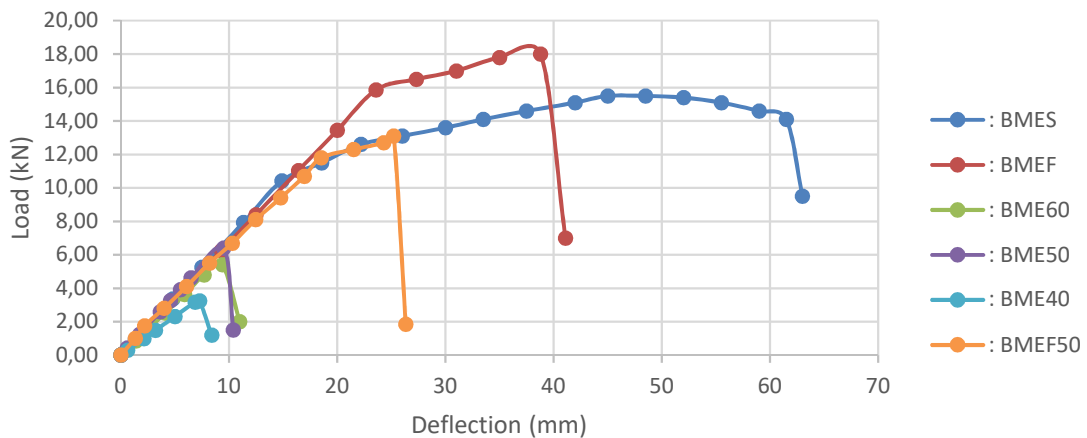


FIGURE 10. Load-deflection curvature.

CONCLUSION

Based on the result of this study, the following conclusions can be drawn:

1. Classification of the quality code of meranti lumber is E11.
2. The shear strength of polyurethane adhesive is lower than the shear strength of meranti lumber.
3. Glulam lumber beams of full-length lumber plank can have structural strength equal to or better than solid lumber beams when sorted from lumber without wood defects. If there is a wood defect it can be broken down so that they do not collect in one place.
4. The failure of glulam lumber beam from pieces of lumber planks (BME40, BME50 and BME60) starts from the release of the bonds between the joints of the rods at the bottom layer.
5. The joints on the outermost layer that receive tensile stress of the glulam lumber beam can cause weakening in the beam.
6. The BMEF50 can increase the load capacity of glulam lumber beam from pieces of lumber planks even though they are still not the same as solid wood beams. However, beam failure still occurs due to the joints in the layers that receive the tensile stress.
7. Design of joints should not be placed on layers that are subject to tensile stresses so as not to trigger shear failure modes so that the strength of the glulam lumber beam can be optimal.

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