An Experimental and Analysis Comparison of Solid Wood Bridle Joints with Various Fastener and Retrofit Methods

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ABSTRACT

Teak (tectona grandis) is a material widely used for roof framing, known for its load-bearing capacity. Many buildings, including wooden ones, suffered significant damage after an earthquake due to failure of meeting technical requirements for seismic resistance. Therefore, it is necessary to strengthen the wooden roof trusses before a strong earthquake occurs. This study examines the structural behavior of L-type solid wood trusses under different fasteners, strengthening methods, and loading directions, and compares the experimental test with analysis methods. The test specimens consisted of teak L-joints with dimensions of 2 mm³ ×70 mm³ ×140 mm³ ×800 mm³ and a total of 32 pieces. Four types of fasteners were used: wooden plugs (4ø16 mm), bolts (4ø1/2"), nails (13ø3.76 mm), each with a length of 2.5", and screws (26ø3.50 mm) each with a length of 1.5". The retrofit materials were: L35.35.3 iron profile, C70.35.0.45 stainless steel, and 60.4 strip plate. The specimens were loaded in two directions: upright and sideways using a flexure tester with a maximum capacity of 150 kN and a maximum displacement stroke of 100 mm, which continued until peak load was reached, and then stopped after a load drop. The maximum load on the L-joint was found to be higher in the upright position than in the side-up position. The highest load capacities were achieved with the following fasteners: bolts, screws, nails, and wooden dowels, for both loading directions. Retrofitting with iron profile shows the greatest increase in load capacity for both loading directions. For right-up loading, retrofitting with strip plates is better than stainless steel, while for side-p loading, stainless steel retrofit is better than the strip plate. Failure modes were mainly shear cracks in the joint area originating from the bolt and pin holes. Failures were observed as breakage in wooden pins, and shear failure in nails and screws. The comparison of the maximum load capacity of the experimental test shows higher results compared to the results of the analysis calculation, with a ratio of about 1.20. The formula for calculating the load resistance of the joint, with a constant value of 73.11, in the literature review must be corrected to 70.80 for nail joints, 70.40 for bolt joints, and 62.10 for screw joints.

Keywords-solid wooden bridle joints; retrofit methods; loading directions; load capacity ratio

I. INTRODUCTION

Wood, an anisotropic and sustainable material, is still used as a construction material for building frames and roof trusses. In rural areas, wood is widely utilized because of several advantages, such as: sustainability, production ease, and does not require high equipment and technology [1-3]. However, the structural integrity of timber buildings has been questioned after a strong earthquake, where several frame and roof trusses were damaged, showing insufficiency of connectors and poor construction conditions [4-9]. Consequently, numerous studies have been carried out on the repair and strengthening of wooden structures [10-16], with a particular emphasis on the technology of connectors for timber structures [17-22].

II. RESEARCH METHODS

A. Research Materials and Equipment

The following is a list of the materials required for the project:

- The materials used for the bridle joints are two solid teak wood beams, with dimensions of 800 mm^3×140 mm^3×70 mm^3. A total of 32 specimens were selected.
- Within each specimen, four variations of fasteners are present: 4ø12.7 mm bolts, 4ø16 mm wooden pegs, 13ø3.76 mm nails with 2.5" length, and 26ø3.50 mm screws with 1.5" length.
- The retrofit materials consist of: L35.35.3 iron profile, C70.35.0.45 stainless steel, and 60.4 strip plate.
- The Universal Testing Machine (UTM) was an UN-7001-LC50, with a capacity of 50 kN.
- The compression machine test control was 90 SB/4 with a capacity of 2000 kN.
- The load-generating equipment was a flexure tester with a maximum load capacity of 150 kN and a maximum stroke length of 100 mm.
- The vertical and horizontal deflection of the specimens was measured using two dial gauges.

As shown in Figure 1, the direction of loading for the specimens is based on the connection model between two wooden beams forming a bridle joint.

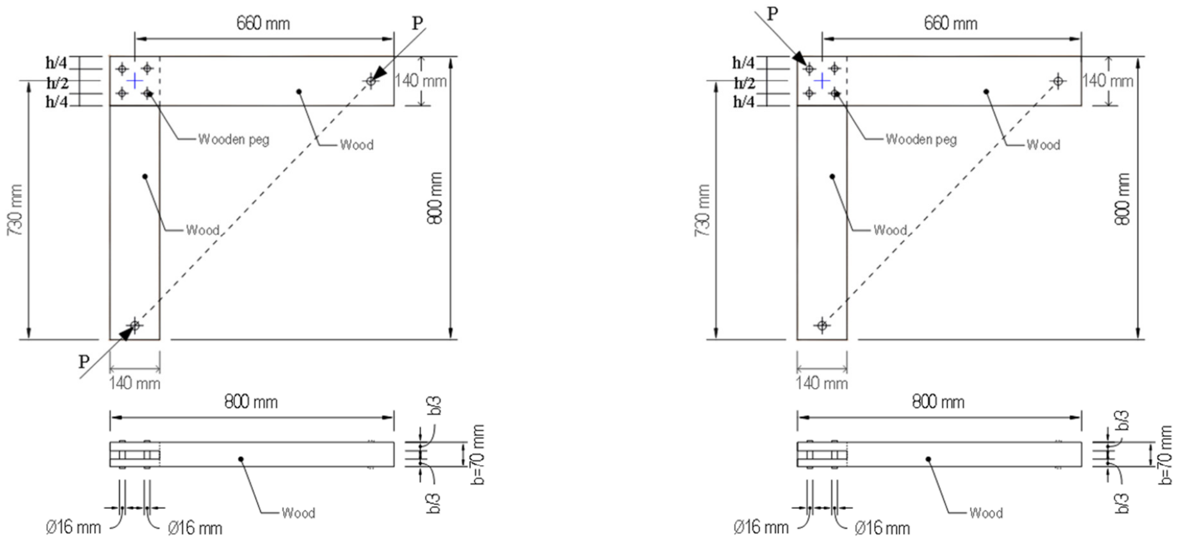


Fig. 1. Various loading directions: side-up (left) and right-up (right) positions.

B. Preliminary Material Test

A series of tests were conducted to assess the physical and mechanical characteristics of teak wood, fasteners, and retrofit materials. The objective of these tests was to ascertain the compressive strength, tensile strength, and flexural strength of each material used in this research, while the testing procedure was based on material testing standards according to Indonesian National Standard (SNI) [23-27]. Figures 2 and 3 depict the process and results of specimen fabrication, as well as the testing of connectors and retrofit materials following their tensile strength assessment.

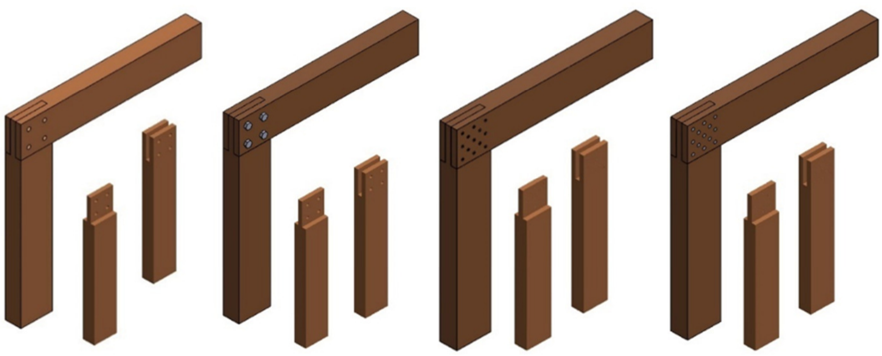


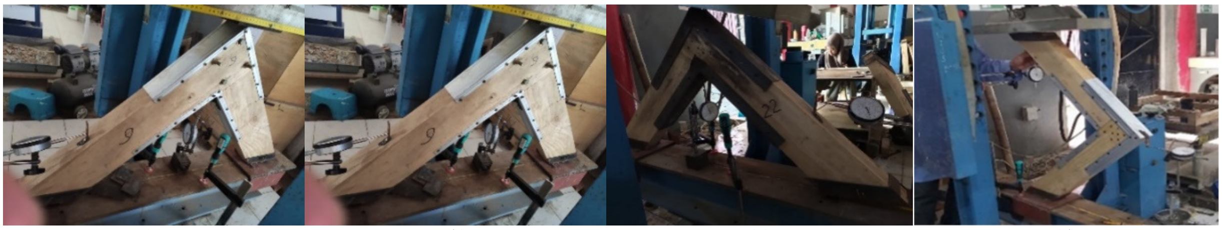
Fig. 2. Perspective and configurations of the specimens and the four connectors.

(a) (b) (c) (d)

Fig. 3. (a), (b) Specimens, (c) testing of connectors, and (d) material retrofitting.

C. Loading Procedures and Specimen Setup

The loading applications are performed using a bending test with a maximum capacity of 150 kN and a maximum stroke of 100 mm. The application of loads is based on specified test criteria, quasi-static loads. The specimens are positioned in two distinct orientations: an upright position and a side-up position, as illustrated in Figure 4. This approach enables the measurement of joint displacement after loading in both orientations.



(a) (b) (c) (d)

Fig. 4. (a), (b)Test of bridle joints with various fasteners, (c), (d) loading positions.

III. RESULTS AND DISSCUSSION

The findings of the physical characteristic testing of teak wood indicate that it is a softwood with a modulus of elasticity of approximately 6500 MPa, and is commonly used for wooden building frames and roof trusses. Notably, the wood's water content remains substantial at approximately 20%, underscoring its potential for moisture-related applications. Its specific gravity is approximately 0.6 g/cm^3. Several tests were conducted to ascertain the wood's mechanical properties: parallel to grain compressive strength, perpendicular to grain, tensile and flexural strength, with average values of 42.27 MPa, 13.31 MPa, 37.34 MPa, and 29.12 MPa, respectively. The tests on the tensile strength of bolt, nail, and screw fasteners showed stress values of 320.24 MPa, 574.28 MPa, and 400 MPa, respectively. Concurrently, for retrofit materials, the stress values for L35.35.3, C70.35.0,45 stainless steel, and 60.4 strip plate were 400.94 MPa, 550 MPa, and 318.01 MPa, respectively. The results of the tensile (σ_t), parallel ($\sigma_{c//}$), and perpendicular compressive ($\sigma_{c\perp}$) tests, as well as the bending test (σ_f), were determined in accordance with the procedures specified by SNI 03-3958-1995 (compressive strength) [24], SNI 03-3399-1994 (tensile strength) [25], and SNI 03-3975-1995 (bending strength) [26], with the mean values of the five specimens listed in Table I. A comparison of these values with the values of SNI 7973 – 2013 indicates that the teak wood used is included in the softwood category because it is only around 15 years old. The findings of the tensile test (f_y, f_{pu}) of the fasteners and retrofit material are presented in Table II. The tensile strength of the nail was found to exceed that of the bolt and screw, while the tensile strength of the stainless steel exceeded that of the iron profile and the strip plate. The testing was conducted in accordance with the guidelines of SNI-07-2529-1991 [27]. The shear stress value (τ) was set at 0.45 f_y. The shear strength values of the fasteners and retrofit materials will be used for calculating the load resistance value to compare the experimental test load capacity and the analytical load value.

TABLE I. PROPERTIES OF TEAK WOOD

Material properties						
$\sigma_{c//}$ (MPa)	$\sigma_{c\perp}$ (MPa)	σ_t (MPa)	σ_f (MPa)	γ (gr/cm^3)	ω (%)	E_w (N/mm^2)
42.27	13.31	37.34	29.12	0.59	19.68	6458.78

TABLE II. PROPERTIES OF FASTENERS AND RETROFIT MATERIALS

Codes	Properties of fasteners and retrofit materials						
	Amount of fasteners or retrofit materials	Ø or t (mm)	f_y (MPa)	f_{pu} (MPa)	τ (MPa)	ε_y (mm/mm)	ε_y (mm/mm)
Bolt (L = 4”)	4	12.70	320.24	480.36	216.16	0.002	0.17
Nail (L=2.5”)	13	3,76	574.28	765.71	258.43	0.002	0.16
Screw (L = 1.5”)	26	3,50	400*	600*	180.00	0.002	0.18
Wooden Peg (L = 3”)	4	16.00	27.92	37.34	13.31	0.031	0.07
Iron profile $L35{\times}35{\times}3$	8	3.00	400.94	601.41	180.42	0.002	0.15
Stainless Steel 70×35×0.45	4	0.45	550*	825.00	247.50	0.003	0.25
Strip plate 60.4	4	4.00	318.01	477.02	143.10	0.002	0.17

Table III portrays the test results of the 16 objects loaded in the right-up and side-up directions. The test specimens, categorized into four groups, include eight specimens without retrofit, eight specimens with retrofit using L35.35.3 angle iron, eight specimens with retrofit utilizing C70.35.0.45 stainless steel, and eight specimens with retrofit using 60.4 strip plates. Four connector variations were used: bolts, nails, screws, and wooden pegs showing the load and deflection at the first and maximum cracks.

TABLE III. TREATMENT AND RESULTS OF SPECIMEN TESTING

Types of fasteners	**Treatment of specimens**					**Testing results**			
	Loading direction		Material retrofit			Load (kN)		Displacement (mm)	
	Right-Up	Side-Up	Iron profile L35×35×3	Stainless steel C70×35×0.45	Strip plate 60×4	*P* crack	*P* max	*Δ* crack	*Δ* max
Bolt	✓					11.75	13.75	8	23
Nail	✓					10.25	12.50	14	24
Screw	✓					9.50	11.00	14	27
Wooden peg	✓					6.00	6.75	7	15
Bolt		✓				6.00	8.65	19	44
Nail		✓				6.00	7.35	20	38
Screw		✓				4.70	6.75	16	42
Wooden peg		✓				2.50	6.40	16	45
Bolt	✓		✓			19.75	54.00	13	25
Nail	✓		✓			23.50	52.50	11	24
Screw	✓		✓			17.50	38.05	12	26
Wooden peg	✓		✓			11.75	27.70	12	27
Bolt		✓	✓			13.40	15.50	25	48
Nail		✓	✓			10.00	12.90	19	48
Screw		✓	✓			10.00	12.50	23	47
Wooden peg		✓	✓			7.80	12.00	17	44
Bolt	✓			✓		11.50	35.50	5	19
Nail	✓			✓		12.25	34.50	10	25
Screw	✓			✓		12.25	31.00	6	25
Wooden peg	✓			✓		8.50	25.00	9	20
Bolt		✓		✓		5.50	13.90	25	49
Nail		✓		✓		5.50	12.80	29	52
Screw		✓		✓		5.25	12.50	28	52
Wooden peg		✓		✓		4.50	10.50	22	52
Bolt	✓				✓	7.50	50.00	4	30
Nail	✓				✓	8.25	43.00	5	30
Screw	✓				✓	8.25	36.05	5	30
Wooden peg	✓				✓	8.25	30.50	4	30
Bolt		✓			✓	6.00	10.50	17	41
Nail		✓			✓	6.40	9.00	18	41
Screw		✓			✓	6.20	8.80	16	49
Wooden peg		✓			✓	6.50	8.00	8	47

The load resistance of joints is calculated using [21]:

$$R = f_v \mathrm{D}.t_w \quad (1)$$

$$R = 73.11G^{5/2}.D.t_w \quad (2)$$

where R is the resistance load of the joint, f_v is the shear stress of the connectors, D is the diameter of the connectors, t_w is the thickness of the shear plane on the specimen, and G is the specific gravity value of wood. A comparison between the maximum load capacity in the right-up direction of the experimental test and the analysis calculation using (1) is displayed in Figure 5 , indicating that the maximum load value measured by the experimental test is higher than that measured by the analysis. The joint capacity load value was calculated by (2) and the comparison revealed that the constant value of 73.11 was reduced to 70.80 for nail connections, 70.40 for bolt connections, and 62.10 for screw connections. As shown in Table IV, the load capacity (R) of the test specimens was calculated, with variations in connecting devices and reinforcement materials. The value in the eighth column is based on (1), depending on the shear stress of the connector, the diameter of the connector, the thickness of the reinforcing material, and the thickness of the wood shear plane. Conversely, the value in the last column is given by (2), depending on the specific gravity of the wood, the diameter of the connecting tool, and the thickness of the wood shear plane. As presented in Table V, the ratio of load capacity supported by the joints is based on a comparison of the values obtained from the experimental tests and the analytical methods. The values range between 1.05–1.50, with a mean value of 1.23 for R_1, and 0.97–1.47 with a mean value of 1.17 for R_2. This indicates that there is no statistically significant difference between the experimental testing and analytical values. The maximum load capacity without retrofit test specimens with a right-up position loading direction is found in the bolt with a value of 27.50 kN, and the lowest in the wooden peg with a value of 13.50 kN. For the side-up position loading direction, the values are 7.50 kN and 4.00 kN, respectively. It is noteworthy that these observations align with the findings for the retrofit test specimens, thereby underscoring the reliability and consistency of the experimental approach. The retrofit with

L35.35.3 iron profile gives the highest load capacity of 54.00 kN and the lowest of 27.50 kN in the right-up loading direction. Conversely, the load capacity of the bolt and wooden peg joints is 15.50 kN and 12.00 kN, respectively, when subjected to side-up loading.

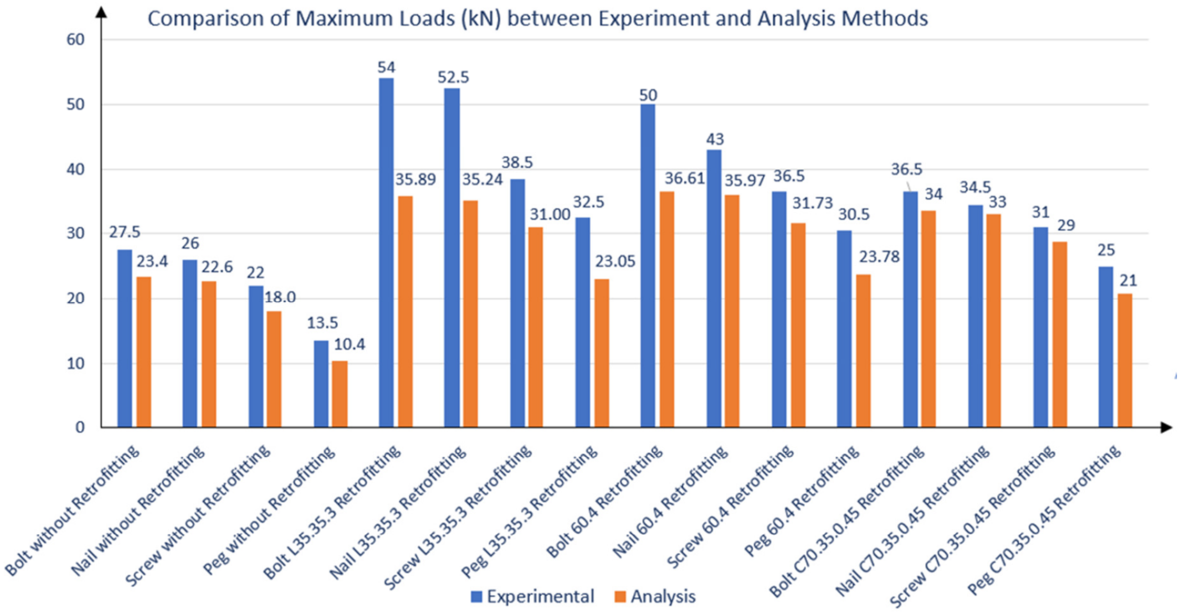


Fig. 5. Right-up direction loading comparison of experimental and analytical methods.

TABLE IV. ANALYSIS OF LOAD RESISTANCE OF JOINTS

Fastener/Retrofit material	D or t (mm)	n (unit)	A (mm^2)	A_{tot} (mm^2)	f_v (N/mm^2)	t_w (mm)	$R = f_v\, D\, t_w$ (N)	$R = 73.11G^{5/2}\, D\, t_w$ (N)
Bolt	12.70	4.00	153.94	615.754	144.20	23.3	23,258.42	24,140
Nail	3.75	13.00	11.10	144.348	258.43	23.3	22,612.28	23,350
Screw	3.50	13.00	9.07	117.928	225.00	23.3	18,375.00	21,640
Wooden Peg	16.00	4.00	153.94	615.754	27.92	23.3	10,421.97	
60.4 Strip Plate	4.00	2.00	339.46	678.925	143.10	23.3	13,356.00	
C70.35.0,45	1.80	2.00	252.00	504.000	247.50	23.3	10,395.00	
L35.35.3	3.00	4.00	840.00	840.000	180.42	23.3	12,629.61	

TABLE V. RATIO OF EXPERIMENTAL TESTS TO ANALYSIS

Types of retrofitting	Analysis-1	Analysis-2	Experiment	R_1 (experiment/analysis-1)	R_2 (experiment/analysis-2)
Bolt + Iron Profile	35,888	36,770	54,000	1.50	1.47
Nail + Iron Profile	35,242	35,980	52,200	1.48	1.45
Screw + Iron Profile	31,005	34,270	38,500	1.24	1.12
Peg + Iron Profile	23,052	24,700	27,500	1.19	1.11
Bolt + Stainless Steel	33,653	33,745	35,500	1.05	1.05
Nail + Stainless Steel	33,007	33,745	34,500	1.05	1.02
Screw + Stainless Steel	28,770	32,035	31,000	1.08	0.97
Peg + Stainless Steel	20,817	22,465	25,000	1.20	1.11
Bolt + Strip Plate	36,614	37,496	50,000	1.37	1.33
Nail + Strip Plate	35,968	36,706	43,000	1.20	1.17
Screw + Strip Plate	31,731	34,996	36,500	1.15	1.04
Peg + Strip Plate	23,778	25,426	30,500	1.28	1.20

The retrofit with C70.35.0.45 gives the highest load capacity of 35.00 kN and the lowest of 25.00 kN in the right up loading direction. Conversely, the load capacity of the bolt and wooden peg connections is 13.90 kN and 10.50 kN, respectively, when loaded side-up. A retrofit with 60.4 strip plate results in the highest capacity of 50.00 kN and the lowest capacity of 30.50 kN in the right-up loading direction. In the side-up direction, the load capacity is rated at 10.50 kN and 8.00 kN for the bolt and pin connections, respectively. The retrofit in the right-up loading direction demonstrates the highest load capacity of 50.00 kN for nail connections with L35.35.3 retrofitting, while the lowest load capacity of 30.50 kN is achieved with C70.35.0.45 retrofitting with wooden peg connections. Furthermore, the retrofit in the direction of side-up loading is the highest for nail connections with C70.35.0.45, and the lowest for retrofitting with strip plates with wooden pin connections. It is noteworthy that the load capacity of a joint without retrofit is approximately three to four times greater than the load capacity of a joint with retrofit. Conversely, the amount of deflection is inversely proportional to the load, with half of the side-up loading resulting in the same deflection. Furthermore, retrofitting in the right-up direction results in increased stiffness compared to loads in the side-up direction. The retrofitting process is best with L35.35.3 iron profile, followed by 60.4 strip plates, and the smallest is C70.35.0.45 stainless steel. In the case of retrofitting directed towards side-up loading, the L35.35.3 iron profile material achieves the highest load capacity, while the 60.4 strip plate retrofit achieves the lowest. A comparison of the load capacity of the experimental test results with that of the analytical calculations gives a ratio ranging from 1.05 to 1.50, with an average ratio of about 1.20. The maximum load capacity of the experimental test results exceeds the analytical calculation value. The original joint crack pattern was around the wood pin and bolt connection tools, in a direction parallel to the wood grain. This can be reduced by reinforcing angle iron and light steel sections. Tensile and shear failure in the nail and screw fasteners was another defect that occurred because the fasteners experienced shear stress in the shear plane region as a result of the load. The f_y value is derived from the tensile test, while the f_v value is defined as the shear stress value, which is 0.45. The parameters f_y, D, t, and t_w are the diameter of the connecting tool, the thickness of the reinforcement material, and the thickness of the wood scrap, respectively. The thickness of the wood scrap, t_w, is $b/3$ (23.33 mm), where b is the width of the cross-section. Table VI presents a comparison between this study's results and those of several previous studies. The stiffness values obtained from this study are comparatively lower than those observed in stiff connection types, such as adhesive materials and steel dowels. However, they are analogous to those observed in bolted connections.

TABLE VI. RESULT COMPARISON

Reference	Connectors types	Maximum load (kN)	Displacement (mm)	Stiffness (kN/mm)
[3]	Adhesive	27.50	8.00	3.44
[20]	Steel Dowel	42.30	9.75	4.34
[28]	Bolted	17.00	12.00	1.42
[29]	Adhesive	26.50	6.70	3.96
This study	Bolted	35.50	19.00	1.87
	Nail	34.50	25.00	1.38
	Screw	31.00	25.00	1.24
	Wooden Peg	25.00	20.00	1.25

IV. CONCLUSIONS

In the absence of retrofitting, the test specimen with bolt fastener had the highest load-bearing capacity, followed by nails, screws, and wooden dowel for the right-up and side-up loading directions. In the retrofit test specimen, the one with L35.35.3 iron profile had the largest load-bearing capacity, followed by 60.4 strip plate and C70.35.0.45 stainless steel for the right-up loading direction. Conversely, the largest value of side-up direction loading was found for the L35.35.3 iron profile retrofit, followed by C70.35.0.45 stainless steel and 60.4 strip plate. The major difference in the maximum load capacity between right-up and side-up loading was caused by the fact that the right-up loading was affected by friction between the specimen and the support during the test. In contrast, the side-up direction loading did not exhibit this friction factor. The maximum deflection value in the side-up position loading direction was found to be 2 times greater than the right-up position loading direction. This occurred both in conditions without retrofitting and with retrofitting. This finding indicates that the side-up position direction test exhibits greater ductility, while the right-up direction loading is more rigid. A comparison of the maximum load capacity values from the test and the analysis results shows that the experimental results are greater than the analysis results for all types of tests. The values that are closest to each other occur in test objects without retrofit and retrofit with 60.4 strip plates, while the retrofit with L35.35.3 iron profile and C70.35.0.45 stainless steel has a significant difference. The crack pattern and failure of the test object are parallel in the area of the wooden peg and bolt holes. In test objects having nail and dowel joints, shear failure occurs in the joints. The reduction of these cracks can be achieved through retrofitting with L35.35.3 and iron, as well as C70.35.0.45 stainless steel. Further research is necessary to examine the reinforcement of non-conventional materials, such as carbon strip or other modern materials, to enhance the durability and performance of the test objects. To ensure the validity of the findings, it is important to employ numerical modeling for verification.

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