Experimental and Finite Element Method (FEM) of Dowelled Mortise and Tenon Joint for Kapur Species

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ABSTRACT

Kapur (Dryobalanops spp.) is one of the Malaysian common species used for structural construction material. It is capable of serving as a beam and column. This study focused on the experimental mortise and tenon connection fastened with wood; glass fibre reinforced polymer (GFRP), and steel dowel. The finite element method (FEM) was used to model the behaviour of mortise and tenon joint for wood dowel subjected to pull-out loads using ABAQUS software. The experimental results were used to validate a three dimensional finite element model of mortise and tenon joint. The full structural scale of

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mortise and tenon was fastened with a 21 mm diameter dowel. The investigation was carried out by applying tensile loads to the top of the tenon. This study adopted a linear elastic orthotropic material to represent the Kapur wood behaviour using the FEM. In this study, the results reveal the load carrying capacity of the mortise and tenon in a sequence of highest to the lowest is when the joint dowelled with GFRP, steel and wood. The stiffness value obtained from the FEM for wood dowel is found higher than the experimental value. Thus, the findings from finite element method (FEM) and the experimental results both had slightly dissimilar load–displacement curve shape. However, this study contributes to a better knowledge of mortise and tenon performance when secured with a wood dowel.

Keywords: *Tropical Timber; Finite Element Analysis; Wood Connection*

Introduction

The most prevalent type of traditional timber joint used in timber structures is the mortise and tenon. This type of joint has been used for hundreds of years and is known to be capable of supporting structural members. A good joint with ductile behaviour is to reinforce with rod or dowel because dowel connections are one of the most common types of joints in timber construction. The strength of the joint connection determines how long a timber construction will last. Any failure of a timber structure's joint will have an impact on the structure's overall performance [1].

Research publications especially in the mortise and tenon for structural timber connections were found to be very limited. There have been studies on using timber frames prior to the publications of a dissertation in Stanford University by Brungraber [2]. Brungraber [2] was the first person who highlighted some concerns on the performance of mortise and tenon in a timber structural framing system. He studied the mortise and tenon using a wood dowel as an individual joint, together with full-scale frame testing, finite element analysis of joint behaviour and a computer model that incorporated connection behaviour. Brungraber [2] found that the dowels and mortises failed before the tenons and also concluded that increasing the dowel diameter is the most effective way to increase the mortise and tenon connection’s strength and stiffness. His study has directed the traditional timber frame research in the modern years.

Throughout the years, the compilation of research for mortise and tenon was evolved accordingly; such as the study of design considerations for mortise and tenon connections [3]-[4]; experimental performance of mortise and tenon connections in green Oak [5]-[6]; shear and bending of mortise and tenon performance for Kempas [7]-[9] and mechanical performance of mortise and tenon joints pre-reinforced with slot-in bamboo scrimber plates [10].

Mechanical fasteners are now widely accepted as an important component of modern timber construction [11]. There are few types of fasteners such as nails, staples, bolts, dowels and screws that can be used to create mechanical connections that transmit lateral and withdrawal loads. Bearing stresses develop between the fastener and the connection members are used to transmit lateral loads. For structural or furniture joint applications, wood dowels often known as pegs are commonly used to connect traditional timber joints such as mortise and tenon. Hence, dowels are a low cost and easy to manufacture type of joint.

In this research, the Kapur species has been studied on its structural performances and behavior of failure. The FEM is used to further analyse the mortise and tenon joint fastened with the wood dowel.

Finite Element Method (FEM)

The finite element method (FEM) is now one of the most powerful and commonly utilised methods available in the engineering field. According to Amaruddin [1], many studies employ FEM to simulate the stress–strain state of a complex model under certain conditions.

Several research reported on the FEM to evaluate the mortise and tenon joint strength such as Shank [5] and Amaruddin [1], Jin and Wu [12] and Hu et al. [13] and Zhang and Hu [14], with the goal of finding a more general method to examine the mortise and tenon joint. According to Hu et al. [15], the suggested finite element model was capable of estimating the bending moment capacity of mortise and tenon joints when compared to previous experimental data. They conducted research by using the combination of finite element method (FEM) and response surface method to study the bending moment capacity and bending stiffness of the mortise and tenon joint in order to optimize the mortise and tenon joint's tenon size.

Based on the research done by Zhang and Hu [14], the response surface method was used to investigate the relationship between withdrawal load capacity and tenon length and width. The effect of tenon length and tenon breadth on withdrawal load capacity of the mortise and tenon (M-T) joint was explored using the finite element method (FEM). As a result, the findings demonstrated that the tenon width and length had a notable influence on the sample's M-T joint T-shaped withdrawal load capability. Thus, it stated that the expenses of materials and experiment time can be cut by using FEM to gain a better visual understanding of the M-T joint.

Other than that, Hu and Guan [16] created a new numerical model of a mortise and tenon joint using the finite element method (FEM) to evaluate the semi-rigid timber connection which takes into account the glue line and friction coefficient. To begin, experimental methods were used to evaluate the friction coefficient, glue distributions, and mortise and tenon joint strengths. Second, these parameters were entered into a T-shaped mortise and tenon joint model in order to create a finite element model of the joint. Finally, experimental and numerical approaches were used to study the pull-out and bending load capacity of T-shaped specimens. The findings revealed that the testing methods used to determine the coefficient, distributions and the glued mortise and tenon joint strengths were all efficacious in determining the mechanical properties of the timber mortise and tenon joint and that the finite element model of joint can be used to analyse the semi-rigid mortise and tenon joint with consistency exceeding 85%.

Meanwhile, Ming and Jianhua [17] have validated that finite element analysis (FEA) may be used to analyse plastic and elastic deformation of materials and point out areas that are vulnerable to damage and failure. In addition, finite element analysis (FEA) has also been used in the modelling and simulation of furniture structure analysis and studies on the evaluation of timber products using FEA has been established.

Methodology

Experimental works

The density of Kapur species is 770 kg/m^3 which can vary by 20% or more at 12% moisture content**.** Five (5) actual structural size mortise and tenon joint manufactured from Kapur for each type of wood, GFRP and steel dowels were tested. The column consists of the mortise section while the beam is the tenon section, accordingly. Each mortise and tenon joint is inserted with a single 21 mm dowel. Pre-drilling of the timber elements, with 3mm oversize to the dowel diameter was adopted in all specimens. The actual structural size of column and beam with mortise and tenon connection specimens were prepared and constructed as shown in Figure 1 and Figure 2, accordingly.

Figure 1 and Figure 2 indicate a nomenclature that is used in the description of a typical mortise and tenon joint subjected to tensile load. It shows the outline of the position of the mortise and tenon joint. Five (5) numbers of LVDTs denoted as 1, 2, 3, 4 and 5 were mounted on the column and beam to measure the respective displacements. The mortise-and-tenon joints were pulled out at the u-shape steel plate that fixed to the tenoned member using a servo-hydraulic IPC 1000 tons test machine. The rate of loading was applied at 1.7 mm/min. for all tests. Limiting rotation was defined by the maximum stroke of the hydraulic jack that is at 25 mm. All joints were tested until total failure i.e. when the tenon member was fully separated from the mortise member.

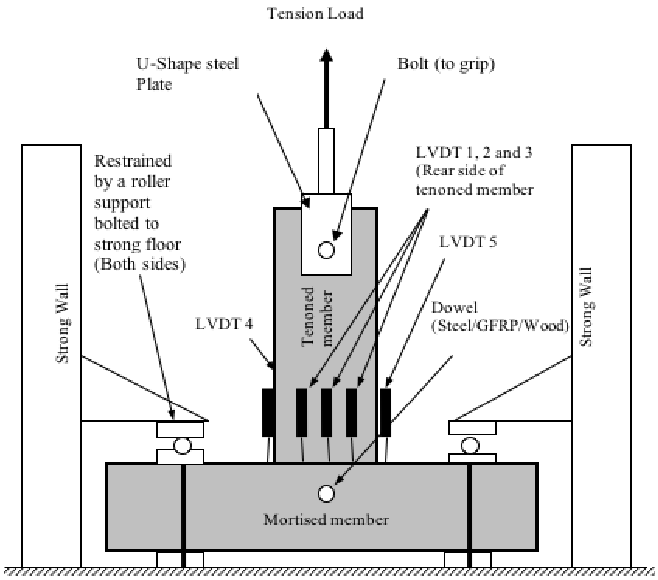

Figure 1: Experimental tensile test set up

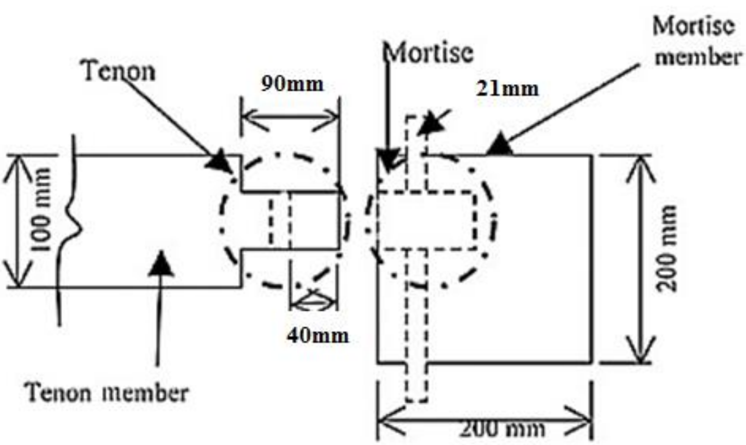

Figure 2: Mortise and tenon joint

Table 1 shows the mechanical properties of Kapur wood used in the finite element model taken from Hassan et al. [18].

Table 1: Material properties of Kapur wood

Mechanical properties of Kapur wood	
Modulus of Elasticity, E (N/mm^2)	13700
Poisson's Ratio, υ	0.69
Shear Modulus, G (N/mm^2)	2812
Tensile Strength, σu (N/mm^2)	116.7

Finite element model using ABAQUS

Abaqus FEA or formerly ABAQUS is one of the application software suites for finite element analysis and computer-aided engineering that was originally released in 1978. The FEM is used to generate accurate and approximate solutions for all linear and non-linear stress, dynamics and thermal problems. The ABAQUS 6.14-1 (academic version) was used in this study. As this version is for academic use, limitation on number of nodes and some functions applied. Therefore, this study is bound to those limitations.

To describe the joint in tension, the connection could only be represented in the elastic range, since the linear elastic orthotropic material was employed [4]. However, the behaviour of elastoplastic materials may be similar to timber's behaviour because timber has some ductility before failure. In this study, solid orthotropic material properties were defined for all members as guided by Amaruddin et al. [1]. For solid orthotropic material, nine mechanical properties must be identified in finite element modelling as indicated in Table 2. The size of this FEM element is similar to the experimental work explained earlier.

The rod of wood dowel may necessitate higher order meshing components, necessitating the addition of more nodes. As the number of nodes grows, so does the amount of time it takes to analyse them. In this project, a fit dowel was assumed. Therefore, there are 64,136 nodes and 42,083 quadratic tetrahedral elements of type C3D10 applied in the finite element model as shown in Figure 3.

All members were given solid orthotropic material properties. MS544 provided the mechanical properties of Kapur species. For solid orthotropic materials, nine mechanical properties must be established in finite element modelling. Since there are no orthotropic material properties for Malaysian timber in MS544, the Poisson's ratio of Kapur was assumed to be similar to the Poisson's ratio of Red Oak, which has an approximate specific gravity as described in the Wood handbook. In addition, Kapur and Red Oak are medium hardwoods where the densities for both species are comparable, 770 kg/m^3 and 740 kg/m^3 respectively. Nevertheless, the strength group of Kapur which is S3 (unseasoned) and SD4 (seasoned) is slightly higher than Red Oak with the strength group of S6 (unseasoned) and SD6 (seasoned). The young modulus ratios in the three orthotropic axes, E_x:E_y:E_z, were considered as

1:6:14 as stated in the Wood Handbook for red oak wood, while the shear modulus, G_{xy}, was obtained as a 1:12 proportion to the young modulus in the longitudinal direction, E_x.

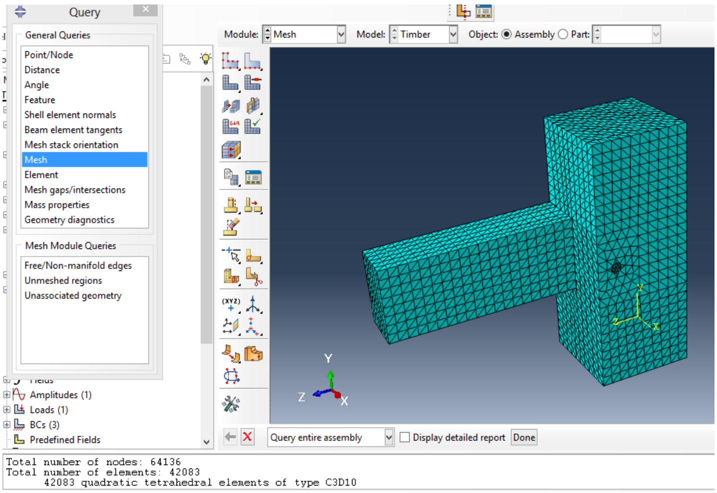

Figure 3: Number of nodes and number of elements applied in the finite element model

Table 2: Orthotropic material properties for Kapur in finite element model

Property	Kapur	Value
E_L (N/mm^2)	E_X	13700
E_R (N/mm^2)	E_Y	2109
E_T (N/mm^2)	E_Z	1123
G_{LR} (N/mm^2)	G_{XY}	1219
G_{LT} (N/mm^2)	G_{XZ}	1109
G_{RT} (N/mm^2)	G_{YZ}	122
μ_{LR}	μ_{XY}	0.35
μ_{LT}	μ_{XZ}	0.448
μ_{RT}	μ_{YZ}	0.56
Mass density		770

As a result, E_y equals 0.154 E_x, resulting in E_y of 2109 N/mm^2. The E_x comes from MS 544 Part 2 with a value of 13700 N/mm^2. E_z has a value of 1123 N/mm^2 when its value is equivalent to 0.082 E_x. While the value of shear modulus (G) was calculated using the supplied ratio of G_{xy} equals to 0.089 E_x, obtaining G_{xy} equals to 1219 N/mm^2. The shear moduli in the xz and yz planes were determined using the Sangree and Schafer relation. G_{xy}:G_{xz}:G_{yz} in the ratio of 10:9.4:1 was used to describe the relationship between the shear modulus in the three planes. Similar to the experimental laboratory test, the pull-out loading was applied to the tenon top surface. The loading was applied as an incremental concentrated load with a total load of 8 kN. By introducing load factors, non-linear analyses were undertaken to see how the stress state behaved. The loading was then increased to 30 kN to observe the wood dowel behaviour under higher loading. The mortise and tenon joint was modelled in three dimensions in finite element modelling to closely resemble the actual mortise and tenon joint in the laboratory.

Results and Discussion

The failure mode behavior of the mortise and tenon has been observed accordingly. Figures 4 and 5 are showing the mortise and tenon physical failure mode after total fracture under tensile loads, respectively. The result of an experimental test of tensile and stiffness capacity of mortise and tenon joints manufactured from Kapur species is shown in Table 3.

(a) (b)

Figure 4: Mortise and tenon failure; (a) side of the mortised-member failed in major failure – heavy splitting or shearing-out of the mortise, and (b) tenon-end failed in major failure – heavy splitting or shearing-out of the tenon end

For the mortise and tenon dowelled using steel dowel, only 3 out of 5 joint failed in mode I_m and others failed in mode I_s. This means that after the tests, steel dowel remains in its straight form. Though all joints did not fail in the dowel, the mortise failed in different modes (M_{II} and M_{III}). Tenoned-end was found with splits and shearing out and experienced a major mortised-side failure. Due to the lower density of Kapur, it shows that pulling-out the tenoned member from the mortise will affect the mortise side member. The lesser density and weaker strength in Kapur has made the tenoned-member disperse the energy to the mortised-member and subsequently major cracks or split occurred in the mortise-side member. The weaker and less densifications of Kapur affected the tensile strength of the joints.

Figure 5: Half of hole can be seen and associated with decreasing load

The behaviour of mortise and tenon joint fastened with wood dowel under pulling-out loads was demonstrated by the load-displacement graph (Figure 6) and bar (Figure 7). The load-displacement behaviour of mortise and tenon in tensile passes through four phases as the load increases.

The dowel's distorted shape was in mode IV of the European Yield Model (EYM) mode of failure which was identical to the failure behaviour of wood dowels in the laboratory. There were two plastic hinges with concomitant wood crushing formed as the loads rose during the investigation. Consequently, the plastic hinge was found to be under greater stress.

As a conclusion, tensile strength capacity of different dowel material connections is affected by the dowel materials. Different dowel material was dominant to the different species. The connection shows the highest strength when dowelled with GFRP followed by steel and wood dowelled. The failure modes of mortise and tenon dowelled with steel or GFRP correspond to mode I_m or I_s failure based on National Design Specification (NDS), 2005 [19] classifications. Whilst all joints dowelled with wood failed in mode IV. Steel or GFRP dowel occurred without the yielding of the dowel due to the stiffness of the materials. This also indicates that the mortise and tenon joint dowelled with steel or GFRP performed in a similar manner and they are better than those dowelled with wood.

Table 3: Tensile load and stiffness capacity of mortise and tenon joints

Type of Dowel	Descript.	Stiffness at 5% Offset Load	Proport. Load	5% offset Load	Ultimate Load
		N	N	N	N
Steel	Mean	85,154.84	13,928	16,032.01	19,929.99
	Std.dev.	3,553.25	314.90	668.07	491.67
	CoV(%).	18.87	9.86	18.87	10.77
GFRP	Mean	84,387.26	16,292.01	16,955.19	19095.99
	Std.dev.	2,871.93	353.93	664.13	780.67
	CoV(%).	15.27	9.88	17.07	17.96
Wood	Mean	26,010.97	5,369.98	5,695.01	12,042.49
	Std.dev.	707.49	242.95	279.95	431.76
	CoV(%).	11.68	19.76	21.56	16.16

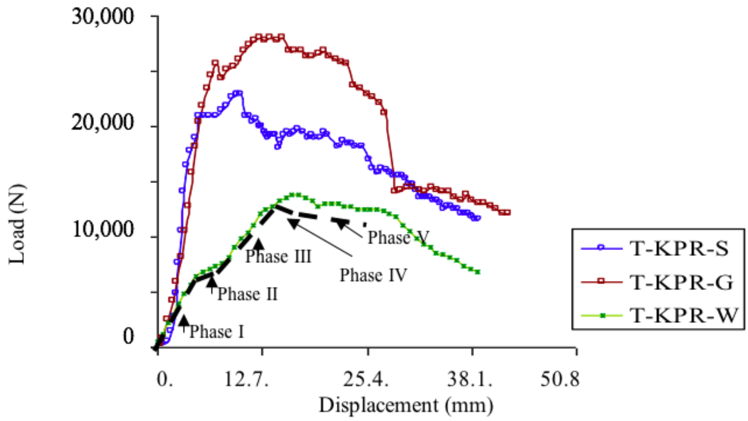

Figure 6: The Load versus displacement of mortise and tenon dowelled with steel, GFRP and wood

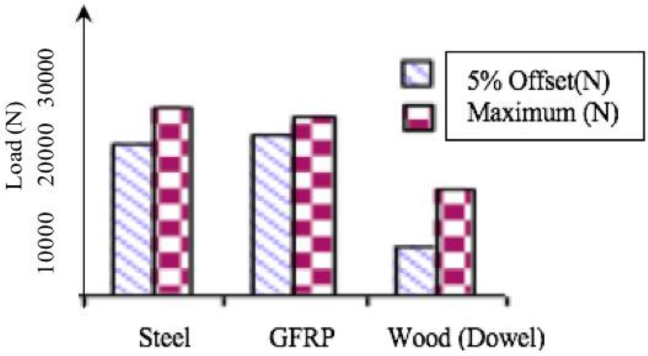

Figure 7: The bar of load carrying capacity differences between the mortise and tenon dowelled with steel, GFRP and wood for 5% offset (N) and maximum (N)

Stress state along the wood dowel under tensile loads

The behaviour of mortise and tenon joint fastened with wood dowel using Kapur species under pulling-out loads was demonstrated by the deformed mesh. As seen in Figure 8, the finite element outputs of stress results were shown in a colour contour. The colour contour can be compared to the key plot to determine the stress state of the dowel at any position. The red colour denotes an area with a higher level of stress where the data has been tabulated in Table 4 according to the tensile load applied.

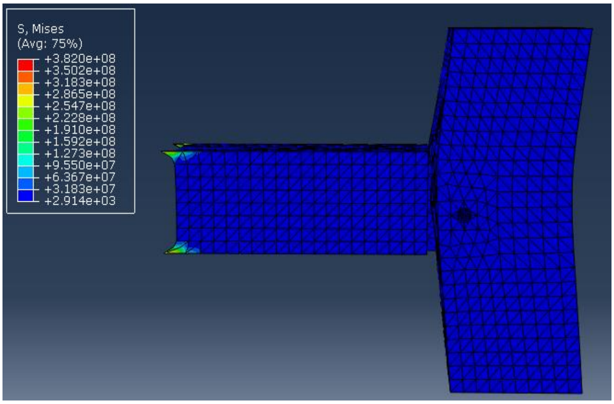

Figure 8: The stress state along the wood dowel subjected to 30kN tensile load

Table 4: Stress of wood dowel obtained from ABAQUS

Load (N)	Stress (N/mm^2)
8000	333.5
16000	335.7
24000	338.1
30000	382.0

From the modelling result, it was observed that the higher stress concentration was focused in the bearing area. Referring to the result from Table 4, the 8 kN load has the least stress value equivalent to 333.5 N/mm^2 while the highest tensile load of 30kN has the maximum stress value which is 382.0 N/mm^2. The result shows that the stress state along the wood dowel increases as the tensile load increases. The dowel began to bend as the tensile load rose, forming two plastic hinges at the edge between the tenon and mortise surfaces. Thus, these locations were under a heavy strain zone.

The behaviour of mortise and tenon joint fastened with wood dowel using Kapur species under pulling-out loads was demonstrated by the deformed mesh. The load-displacement behaviour of mortise and tenon in tensile goes through four phases as the load increases. These four phases are easily distinguishable and noticeable by observing Figure 9.

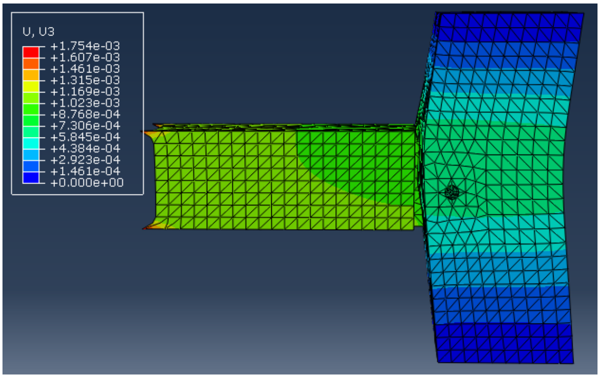

Figure 9: The displacement of mortise and tenon joint fastened with wood dowel subjected to 30 kN tensile load

By referring to Figure 10, it is clear that the results from FEM for the wood dowelled mortise and tenon have linear and well consistent curve shape with those of the experiment in pulling out loads. This is due to the assumption that the finite element model would react linearly elastically which may not be the scenario in a laboratory test. The curve shape was slightly incomparable to the laboratory data in which the stiffness was considered as yield at a highest value. The graph, on the other hand, reveals that the stiffness of the joint is over-estimated using FEM.

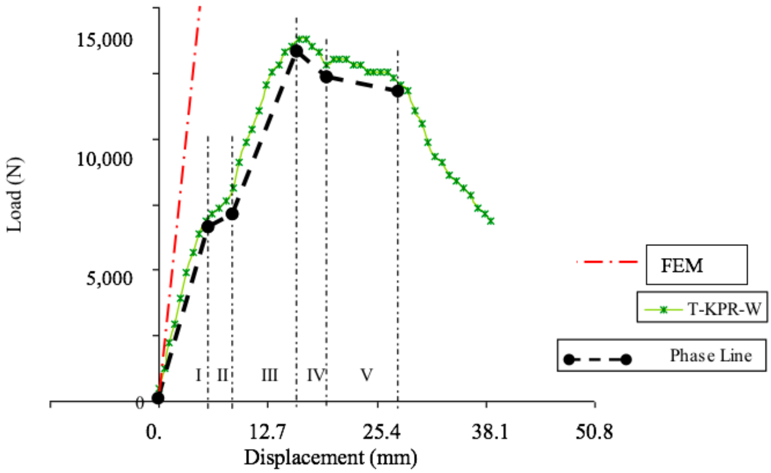

Figure 10: Comparisons of load-displacement curve between laboratory test and finite element method for wood dowel

The value of stiffness at 15 kN obtained from the FEM is 3.94 kN/mm which is high compared to the value of 1.18 kN/mm from laboratory tests. At the yield tensile load of 8 kN, the FEM simulated the displacement at 2.82 mm whilst the laboratory test displaced at 6.35 mm. The displacements obtained from FEM fails to exactly replicated the experimental by 44% differences. In comparison to Hu and Guan [16], they reported their achievement between FEM simulation and laboratory work at 85% similarity where this study found a lower percentage capacity. As stated in the methodology sections, this study is bound to the limitations on the number of nodes and some functions available in the applied FEM. Therefore, the exact simulations of nonlinear performances were not achieved. However, this result supports the finding reported by Amaruddin et al. [1]. Their FEM simulations was achieved only up to linear behaviour for the Kempas species with the similar experimental T-shaped mortise and tenon joint. The simulation was made using LUSAS software and has limited nodes similar to this study.

Conclusion

The findings of this study contribute to a better knowledge of mortise and tenon performance when secured with a different type of dowel. The experimental work successfully showed a sequence of strength in an order dowelled with GFRP, steel and wood material when mortise and tenon were loaded under tensile load. In this study, the FEM findings and the experimental results both had slightly dissimilar load–displacement curve shape. The linear FEM on the other hand, overestimates the stiffness of the connection for the wood dowel strengthening as well as the incomparable displacement value with experimental tests since the actual behaviour were in non-linear performances.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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