Finite Element Model of Mortise and Tenon Joint Fastened with Wood Dowel Using Kempas Species

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Abstract Finite element method (FEM) was used to model the behavior of mortise and tenon joint with wood dowel subjected to pull-out loads. The stress-state in the dowel was observed and the type of failure was indentified according to European Yield Model (EYM). The experimental results from Rohana [6] were used to validate a three-dimensional finite element model of mortise and tenon joint. In this study, linear-elastic orthotropic material was adopted to represent the Kempas wood behavior in FEM. The analysis was conducted by introducing tensile loads on the top of tenon to see the behavior of the dowel. The EYM mode of failures and load–displacement curves were then being compared between FEM results and experimental results obtained by Rohana [6].

Keywords Finite element method · Mortise and tenon · Wood dowel · EYM · Linear-elastic · Orthotropic material

1 Introduction

Mortise and tenon is the most common type of traditional timber joint used in timber structures. This type of joint has been used for hundreds of years and is recognized to be strong enough to support structural members. Mortise and tenon is a method of jointing two pieces of members by slotting a stud or tenon that is formed at the end of a member into a rectangular hole in the other member called mortise. The joint is reinforced using dowel to give ductile behavior to the joint.

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The durability of timber structure is much depending on the strength of the joint connection. Failure at any joint of the timber structure will affect the performance of the whole structure [1]. This research is focusing on mortise and tenon joint fastened with wood dowel using Kempas species of Malaysian timber. The method used in the study is Finite element method (FEM) or sometimes called finite element analysis (FEA).

There are not many papers reported on mortise and tenon joint in their studies. Among those papers, most of them are using their local timber as their research material. Shanks [2] investigated this type of traditional joint using oak timber. Kang et al. [3] reported using Chinese traditional timber. On the other hand, there are very limited researches studies on tropical timber. Rohana et al. had studied the performance of mortise and tenon joint with Kempas and Kapur species by experimental works [4–6]. However, laboratory works are time consuming and expensive. FEM is essential to minimize the time and cost consume by a project. Nevertheless, there is no FEM studies on wood connection using Malaysian timber was published. The problem in modeling the timber using FEM is to define the orthotropic material properties of the wood. Thus material testing is necessary as the mechanical properties of tropical timber are not available. In this study, the FEA of the mortise and tenon joint will be compared to the work done by Rohana [6] to see the significant of the results.

The main aim of the study was to observe the competent of FEM analysis to model the behavior of timber joint that is comparable to the existing experimental data obtained by Rohana [6] using LUSAS. To attain this aim, the specific objectives are set to model orthotropic behavior of timber made of kempas species, to simulate the stress state along the dowel subjected to pull out loads and to identify the European Yield Model mode of failure that represent the timber behavior.

This study was carried out to investigate the performance of mortise and tenon joint using finite element analysis (FEA). Several parameters were highlighted as the limitation of this research. This research only focused on mortise and tenon joint fastened with wood dowel. The entire joint including mortise, tenon and the dowel was using wood from kempas species. The analysis of mortise and tenon joint under pull-out loading was carried out using LUSAS software. The finite element model of the wood is orthotropic linear-elastic. The behavior of the timber joint was simulated to indentify the load–displacement curve of the joint and the stress state along the dowel to be compared to experimental results.

2 Application of Timber Structures

The introduction of engineered timber materials as well as the researches on timber materials in the past few years had improved the modern design of timber structures. Some countries have utilized timber structures in their construction to help preventing pollutions. Stadthaus in Hoxton, London is one of the applications of modern timber design. Stadthaus is a nine-storey residential apartment. This building had been designed using cross laminated solid timber system (CLT) that was introduced by KLH UK Ltd. The construction of Stadthaus applied the combination of reinforced concrete and solid timber [7].

In Malaysia, Malaysian Timber Industry Board (MTIB) has taken a step forward by introducing the first glulam building using Malaysian timber. The building is called Glulam Gallery and is located in Tampoi, Johor. The glulam timber was made of Resak and Keruing of Malaysian timber. The connections were using glued-in rods, bolted and welded to brackets and steel plates. The aim of MTIB is to promote the utilizing of timber structures in Malaysia construction industries [8]. Construction of hotels and resorts in Malaysia seems to favour the use of timber. This is because timber structures have aesthetic values and they symbolize the Malaysian traditions. Sunset Valley, Langkawi was constructed as a tribute to Malaysian wood. The owner of this resort is a Dutch couple Andre and Ria. They decided to build this resort to show their passion on wood [9]. Terrapuri and Tanjung Jara Resort in Terengganu are also utilizing wood as their main construction materials.

Masjid kayu or its name Masjid Ulul Albab Seberang Jertih Terengganu is one of the unique mosques in Malaysia. It was completed in August 2011. The mosque was made of Cengal, Nyatoh and Balau wood. It was built by implementing Malay traditional wood craft. The foundation of the mosque was constructed using in situ reinforced concrete while the other parts of the building were using totally Malaysian wood. The connections between members were mortise and tenon joint system without any single nail [10].

3 Properties of Kempas Species

Kempas or its scientific name *koompassia malaccensis* normally grows in the lowland and in swampy area and classified as medium heavy hardwood (MHW). It has a density in the range of 770–1,120 kg m^{-3} air drying. MS 544 classified Kempas in strength group S.G 2 together with dedaru, merbatu and mertas for designs purpose [11]. Kempas is medium durable and it requires treatment before use. When treated, Kempas is suitable for heavy constructional works [12]. The information on kempas mechanical properties is also available in wood handbook [13]. The summary on mechanical properties of Kempas from three different sources is shown in Table 1.

4 Previous Studies on Fem of Joint

FEM is widely used in many researches to simulate stress–strain state of a complex model under specific conditions. This method is also competent to model joint behavior under unusual loading. It is also able to model the effect on the behavior of the joint while changing the parameters.

Table 1 Summary of kempas properties

Kempas properties	Moisture content (%)	Density (kg/m^3)	Specific gravity	MOE (MPa)	MOR (MPa)
Gan et al. [12]	–	945	–	18,600	122
MS 544, 2001	19	910	0.74	17,700	–
Wood handbook [13]	12	–	0.71	18,500	122

Geramitcioski and Vilos [14] studied the problem associated with the contact between end-plate connections of a steel structure using numerical approach. The researchers used FEM to obtain moment-rotation diagram of the end-plate connection. In the end, the researchers found that FEM simulation gave better solution for maximum loading of the end plate compared to EUROCODE 3. In addition, Anizahyati [15] used FEM to study on corrugated web beam to column connection with extended end-plate welded to beam. The aim was to investigate moment-rotation response of the joint and compared it with the experimental results. She found that the stiffness from the FEM was identical to the experimental value.

On the other hand, Sabuwala et al. [16] simulated the behavior of beam to column connection under blasting loads. The research was carried out using reinforced and unreinforced connection for both experimental and finite element analysis. The results obtained were then compared. They found that reinforced connection performed better under blast loading and the FEM was successful.

Finite element method of analysis had successfully proven the modeling of timber connection. Many studies had been conducted to analyze timber to timber connection using FEM. Xu et al. [17] conducted a study on timber connections with glued-in rods as dowel. The model developed was based on FEM of contact and non-linear behavior of material. They suggested that the gap between the connected timbers has a small effect on the ultimate moment capacity.

Guan and Inoue [18] utilized FEM to model failure mechanism of reinforced timber fasteners. They used bamboo plywood and carbon fiber as the local reinforcement. They successfully simulate the failure mechanism. The correlation between failures mode from FEM and experimental tests are identical.

In addition, Racher and Bocquet [19] developed finite element modeling to investigate non-linear behavior of wood beneath the fasteners and embedding properties of the wood. They concluded that shear strength and friction coefficient could affect the plastic behavior of timber beneath fastener. Villar et al. [20] modeled roof trusses with traditional joint using FEM. The purpose of the modeling was to perform detailed analysis of the strain–stress state of the joint. They concluded that friction on the contacting area is important as it affects the performance of the joint.

Dowelled timber connection under fire was investigated by Laplanche et al. [21]. They used 3D-FEM to represent the thermo-mechanical analysis of the connection. They found that the strength and stiffness reduction of dowel subjected to tensile force parallel to grain is depending on the length of exposure.

Daudeville and Yasumura [22] in their paper analyzed the failures of bolted wood joint. In the FEM, the wood was considered as transverse isotropic materials. The behavior of the wood in radial and tangential was considered as the mean value of the mechanical properties in these two directions. Linear–elastic was adopted. In this study the dowel was considered as fit without any friction. They found that the wood fracture was similar to experiment results. Franke and Quenneville [23] simulated the timber behavior in FEM to study the behavior of dowel under tension load perpendicular to the grain. They found that the FEM model of the cracks growth was similar to the laboratory test.

Chen et al. [24] studied on the effect of parameters such as the end distance, the material properties of the wood and the characteristic of joint element to the behavior dowel type timber joints subjected to tensile and compression loads. The study used plane stress analysis in 2D CASTEM FEM application. Three nodes elements, THR13 were used to model the timber and JO12 elements to model the contact between the dowel and the holes. From the FEM results, they observed that the compressive and tensile stresses were inversely proportionate to the length of end distance.

Shanks [2] used FEM to validate his experimental work. He investigated the stress-state of timber dowel, mortise and tenon subjected to pull out of tenon. He also observed the effect of variation in joint parameter to the stiffness. He found that the FEM had been successfully predicted the connection stiffness and changes of connection behavior due to the changes in parameters.

Johnn et al. [25] conducted a research on the effects off varied angle of timber frames on the performance of mortise and tenon connection subjected to tensile load. The yields mode of failures of the dowel, mortise and tenon members were observed. The researcher found that mortise splitting, tenon tear out, dowel bending and dowel shear were the obtained mode of failure. The type of dowel failures is given in Fig. 1 where I_s is crushing of mortise members, I_m is crushing of tenon, III_s is the rupture and bend of dowel with a plastic hinge at the centre of tenon and IV is crushing of both mortise and tenon members with two plastic hinge formed in the dowel. The researchers concluded that the mode of failure governed the ductility of a connection. The connection ductility decreased for small angle as compared to 90 degrees angle.

On the other hand, Rohana did a study on mortise and tenon joint with dowel fastener. The aim was to observe the behavior of the joint under shear, bending and tensile. The researcher compared the performance of mortise and tenon joint with steel, GFRP and wood dowel. The mode of failures of the joint followed EYM for double shear as stipulated in NDS [26]. The mode of failure for double shear connection has four types (Type I_m, I_s, III_s, IV). It was obtained that wood dowel failed under mode IV [6].

The results obtained from Rohana [6] were used as the basis of this research. This research studied the performance of mortise and tenon joint with wood dowel using FEM and validate the FEM findings with Rohana work. The finite element model in this study adopted the maximum yield loads in the experimental as the loading of the modeling. The modeling followed the tensile test conducted in the

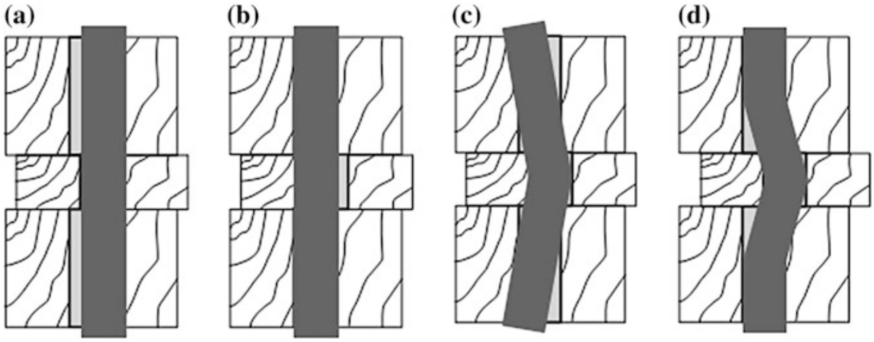

Fig. 1 Dowel mode of failures. **a** I_s, **b** I_m **c** III_s, **d** IV [25]

laboratory. The point of consideration in load displacement comparison was taken at the tenon top similar to the laboratory test.

5 Research Methodology

This study was divided into three phases. The first phase was the identification of wood mechanical properties such as the young modulus, shear modulus, Poisson's ratio, and mass density. The second stage was the development of the finite element model of the mortise and tenon joint. Several numbers of models were formed to obtain the most suitable meshing elements types and material properties. The third part of the study was the analysis process of the mortise and tenon joint model. The stress states and the failure behaviors of the dowel and the members were investigated.

The joint dimensions were briefly described in the subsequent topic which adopted the actual tensile test in the laboratory. To reduce computing time, only part where the tenon fit into the mortise was drawn and it was further simplified by introducing symmetry plane. The dimension of the mortise and tenon joint is shown in Fig. 2. The column size is 200 × 200 mm with a rectangular mortise hole of 41 × 100 × 150 mm. While the beam was 100 × 150 mm with 41 × 89 × 150 mm tenon at the end. The wood dowel diameter was 20.6 mm. To simplify the modeling process, a part where the tenon fit into the mortise hole was modeled instead of the actual size of the tested mortise and tenon joint.

5.1 Finite Element Model Using LUSAS

LUSAS is one of the application software based in United Kingdom's that uses finite element method in its analysis. The FEM is used to generate accurate approximate solutions for all linear and non-linear stress, dynamic and thermal

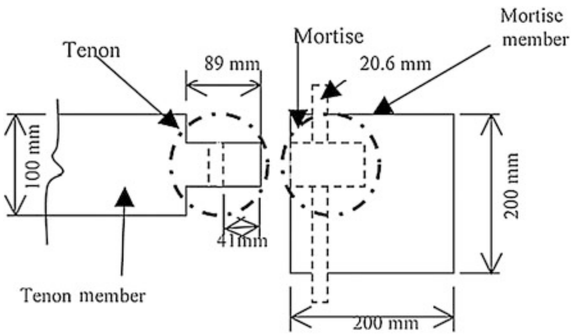

Fig. 2 Plan view of mortise and tenon joint [4]

problem. The LUSAS 14.7 (academic version) was used in this study. As this version is for academic used, limitation on number of nodes and some functions applied. Therefore, this study is bounded to those limitations.

Similar to Shanks [2], linear elastic orthotropic material was adopted to represent the joint in tensile because the connection was modeled in the elastic range only. However, elasto-plastic material behavior may closely represent the timber behavior as timber may have some ductility before failure. Shanks [2] also had proven that modeling nonlinear material behavior will increase the computing time for modeling and analysis but would give a small difference on the global response. Therefore, the timber behavior was assumed to be linear under pull out loading with brittle failure. The loading was the yield load taken from experimental test conducted in the laboratory by Rohana [6] since only the elastic part was modeled.

The shape of the dowel was assumed square to simplify the modeling process. Rod dowel may require higher order meshing elements thus required more nodes. The available LUSAS software in the Faculty of Civil Engineering, Universiti Teknologi MARA has its limitation in numbers of nodes of the whole model. Exceeding the limit will lead to fatal errors. Increasing number of nodes requires longer time to analyze. Fit dowel was assumed in this study since the available FEM application did not support contact element.

Solid model was used to imitate the actual timber joint. Bottom lines of the model were created for the half of the joint model. The lines were then being swept in the y direction to form surfaces. Volume geometry was defined by sweeping the surfaces in the z-axis. The volume that represented the hole was deleted.

Defining suitable element meshing is an important part in finite element modeling. A 3D solid continuum element was chosen and the model was meshed using 8 nodes, hexahedral element with three degree of freedoms on each node was known as ‘HX8M’. Xu et al. [12] and Gonzalez et al. [1] also used similar mesh in their model. Regular mesh type was chosen. Automatic mesh tool is the best to be used to generate the mesh by specifying the element size. The total elements created for the dowel were 1,743 while for mortise and tenon members were 6,171 elements.

Table 2 Finite element model for orthotropic material properties

Property	Kempas	
E_L (N/mm^2)	E_x	17,700
E_R (N/mm^2)	E_y	2,885
E_T (N/mm^2)	E_z	1,274
G_{LR} (N/mm^2)	G_{xy}	1,522
G_{LT} (N/mm^2)	G_{xz}	1,431
G_{RT} (N/mm^2)	G_{yz}	152
υ_{LR}	υ_{xy}	0.369
υ_{LT}	υ_{xz}	0.618
υ_{RT}	υ_{yz}	0.428
Mass density (tonne)		0.93×10^{-9}

Solid orthotropic material properties were set to all members. The mechanical properties of kempas species was given by MS 544 [11] as in Table 2. In finite element modeling, nine mechanical properties must be identified for solid orthotropic material. The ratio of young modulus in the three orthotropic axis, E_x:E_y:E_z were taken as 1:6:14 as specified in Wood handbook [13] for white oak wood while the shear modulus, G_{xy} was taken as proportion of 1:12 to the young modulus in the longitudinal direction, E_x. The Poisson's ratio in this study was assumed to be similar to Poisson's ratio of white oak given in Wood handbook which has equivalent specific gravity.

Therefore, the E_y is equal to 0.163 E_x and gives E_y as 2,885 Mpa. The E_x is taken as 17,700 Mpa from MS 544 [11]. The value of E_z is equal to 0.072 E_x and gives E_z as 1,274 Mpa. While the value of shear modulus (G) was also computed from the given ratio which was G_{xy} is equal to 0.086 E_x and gives G_{xy} as 2,885 Mpa. The shear moduli in xz and yz planes were calculated with the relation suggested by Sangree and Schafer. The relationship between the shear modulus in the three planes was given as G_{xy}:G_{xz}:G_{yz} in the ratio of 10:9.4:1 [27].

Boundary conditions were applied to the model. The mortise member was fixed in all directions where the faces continuous in the full joint. Half model was created due to symmetry axis in yz plane. Thus symmetry boundary condition was assigned to the surfaces. For the tenon, the translation in x and z direction was zero.

The pull-out loading was applied to the tenon top surface similar to the experimental laboratory test. The loading applied as incremental of concentrated load where the total load had been set to 8 KN. Non-linear analyses was performed to see the behavior of the stress state by introducing load factors. The loading was then increased to 30 KN to observe the wood dowel behavior under higher loading.

6 Finite Element Method Output

In the finite element modeling, the mortise and tenon joint was modeled in 3D to closely represent the actual mortise and tenon joint in the laboratory. The finite element results were displayed in color contour as presented in Fig. 3. The stress

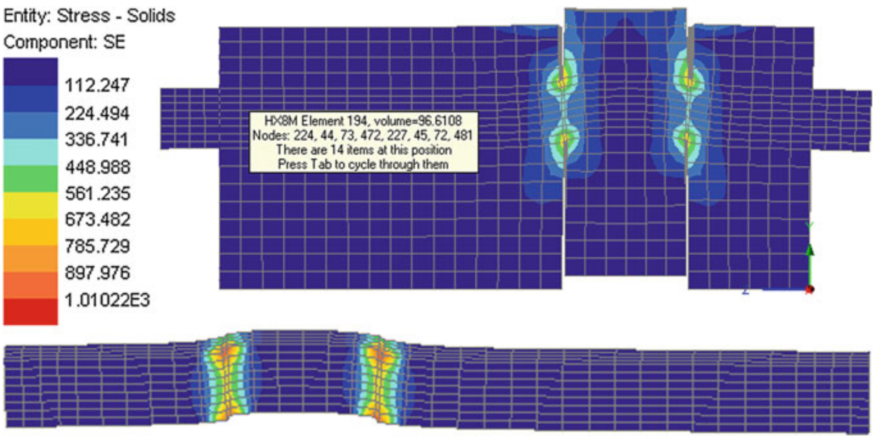

Fig. 3 Stress concentration in the joint

Fig. 4 Total failure of wood dowel in laboratory test (*top*), deformed shape of dowel in FEM at higher tensile load (*bottom*)

state of the dowel at any point can be determined by comparing the color contour with the key plot. The red color represents the higher stress location. The stress was mostly concentrated at the bearing area. The maximum stress at dowel was 1,434 N/mm^2. As the loading increased, the dowel started to bend to form two plastic hinges at the edge between the tenon surface and the mortise surface. These areas were experiencing higher stress.

The deformed mesh illustrated the dowel behavior under tensile. The deformed shape of the dowel was in mode IV of EYM mode of failure which was similar to wood dowels failure behavior obtained in the laboratory. There were two plastic hinges with associated wood crushing formed as the loads increased during the analysis. Higher stress was observed at the plastic hinge. The deformed dowel shows in Fig. 4.

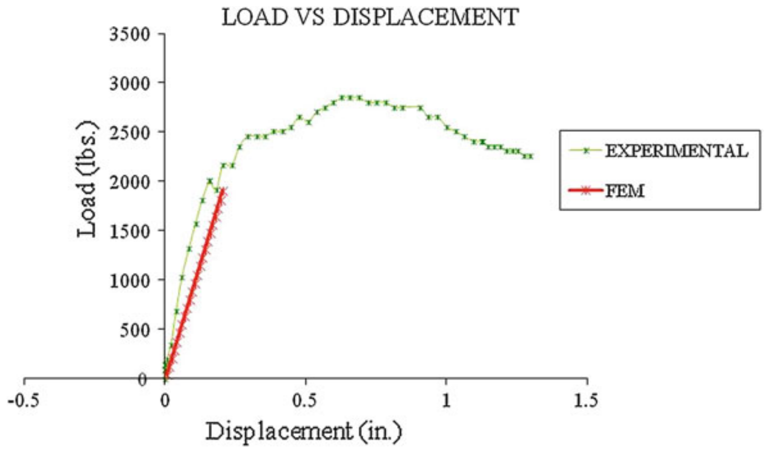

Fig. 5 Comparison of Load displacement *curve* from laboratory test and FEM [6]

A point on the wood dowel which experienced the most stress was taken as the reference point. The point was located on the plastic hinge area of the dowel. Stress–strain curve was plotted at the reference point. The shape of the curve is linear. This is because the finite element model was assumed to behave linear elastically. This might not be true in the laboratory test. The wood dowel had some ductility against tensile before total damage occurred as shown in the load-deformation curve obtained in the laboratory by Rohana [6] in Fig. 5. The FEM graph was plotted on the graph obtained in the laboratory to compare the shape of Load–displacement curve. The shape obtained was identical to the laboratory results where the stiffness was taken as yield at proportionate value. However, the graph shows that FEM underestimate the stiffness of the connection.

The obtained stiffness was low might be due to several factors. The material properties in the modelling were the approximated values taken form MS 544 and wood handbook. The assumed materials properties did not represent the actual wood tested in the laboratory. Meanwhile, the fit dowel assumed in the modelling might also affect the obtained results since a fit dowel is imposible to get in the laboratory. In the modelling, a square dowel was adopted in stead of circle dowel as it may also influence the results.

The stiffness from finite element model is 1.6 kN/mm which is low as compared to the experimental value of 3.6 KN/mm obtained by Rohana [6]. The maximum displacement is 5.1 mm with maximum loading of 8.5 kN. The yield load in the laboratory test was 8.1 kN. Therefore, the results obtained from the FEM were acceptable. Figure 5 shows the comprison of load–displacement curve from experiment and FEM.

7 Conclusion and Recommendation

The results from this study enhance the understanding of performance of mortise and tenon fastened with wood dowel. The behavior of the joints was studied by utilizing finite element model (FEM). The results from the finite element model had been compared with the experimental results obtained by Rohana [6]. A similar shape of load–displacement curve was found between the FEM results and the experimental results.

However, FEM underestimate the stiffness of the connection. Therefore, further improvement can be done for future studies. It is recommended that researchers must conduct laboratory works to find out the mechanical properties of the tested wood rather than relying on published data. Advanced FEM software is suggested to cater for limitation on modeling higher order meshing types and joints element.

Finite element model had shown that it is capable of predicting the behavior of mortise and tenon joint under tensile loads. Therefore, it is very useful to use FEM in research to reduce cost and time and also as a method to validate the findings in the experimental works.

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