SHEAR PERFORMANCE OF YELLOW MERANTI SOLID TIMBER BEAM STRENGTHENED USING FIBRE REINFORCED POLYMER

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DEDICATION

To my beloved husband, Jalil bin Siroon who always sacrifice and make me believe in myself throughout this journey. To my lovely mother, Hajah Rahmah binti Kassim who always love me, give an inspiration and provide continually of moral, spiritual and emotional support. To my lovely father, Haji Mokhtar bin Bachek thanks for your sacrifice, meaningful advice and patiently wait for my success. To my beautiful children, Muhammad Jamil Hariz and Dhia Jamilah Ammara, thanks for your unconditional love and understanding. To my siblings, who shared their words of advice and encouragement.

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ABSTRACT

Yellow Meranti timber has relatively lower shear strength than other softwood species due to its shorter fibre length and larger pores. As a result, it suffers lower fibre strength, more brittle and lower load carrying capacity. In some cases the timber beams experience shear failure that occurs suddenly right before bending. Thus, shear strengthening for Yellow Meranti by using Fibre Reinforced Polymer (FRP) is crucial to solve the aforementioned problems for the structural application. This research was conducted to improve the shear performance of Yellow Meranti beam by strengthening it with carbon fibre reinforced polymer (CFRP) plates, CFRP laminate and glass laminate (GFRP) using Sikadur-30 and Sikadur-330 as bonding agents and for laminating. Firstly, materials characterization was conducted for the timber, FRP and adhesives, to determine their mechanical properties on shear, tensile and compression. The bonding between the FRPs to the timber using epoxy adhesives was examined and the effective bond length was determined. Thirty-six beams with dimension 100 mm x 200 mm x 1475 mm were tested, where three of the beams were un-strengthened and used as the control beam. The remaining beams were strengthened with various configurations and tested under four-point loading up to failure. The results showed that all the strengthened beams perform better than the control beam in terms of ultimate load, shear strength, stiffness and ductility. The performance enhancement by FRP to timber beam for load carrying capacity and shear capacity was ranged from 11.0% to 41.0%, while for stiffness; the range was 26.61% to 62.05%. The ductility index for strengthened beams ranged between 2.0 to 3.7 and 3.7 to 8.4 based on deflection and energy method respectively. The optimum number of FRP is 5 strips which was equivalent to 0.45 strengthened area ratio (A_f / A_{shear}). The optimum type of FRP was GFRP. However types of FRP did not give significant difference in shear strengthening. FRP orientation angle of 45° was found to be the optimum angle in this study. The optimum wrapping schemes were by fully wrapped (FW) with addition of FRP overlapping at the bottom of the beam. Strengthening at the shear zone of the beam could change the mode of failure from shear failure to combination of compression and tensile fracture with no shear failure at shear zone. All the predicted shear capacities computed in this study have good agreement with the experimental value where the percentage difference ranged from 0.5% to 18.3%. As a conclusion, the shear performance of solid beam of Yellow Meranti timber was successfully improved by external strengthening using FRP, where the optimum design parameter for shear strengthening was proposed. As a result, the modification factors formula for shear strength and stiffness were proposed. The result of this study is also able to assist both researchers and engineers in the field of timber engineering technology in the tropical countries to perform strengthening work on timber beams.

ABSTRAK

Kayu Meranti Kuning mempunyai kekuatan ricih yang rendah berbanding spesis kayu lembut yang lain disebabkan panjang serat yang pendek dan poros yang besar. Hal ini menyebabkan ia mempunyai kekuatan serat yang lebih rendah, lebih rapuh dan kebolehan menanggung beban yang lebih rendah. Banyak kejadian kayu jenis ini mengalami kegagalan ricih yang berlaku tiba-tiba sebelum kegagalan lenturan. Oleh itu, memperkuatkan kayu Meranti Kuning dalam ricih menggunakan polimer bertetulang gentian (FRP) dilihat sangat kritikal untuk menyelesaikan masalah kegunaan struktur secara ricih. Kajian ini dijalankan untuk mempertingkatkan kelakunan ricih pada kayu Meranti Kuning melalui cara diperkuat dengan plat polimer bertetulang gentian karbon (CFRP), lamina CFRP dan lamina kaca (GFRP) dengan Sikadur-30 dan Sikadur-330 sebagai ejen ikatan dan untuk melamina. Pada permulaan kajian, pencirian kayu, FRP dan pelekat dijalankan untuk menentukan sifat mekanikal terhadap ricih, tegangan dan mampatan. Ikatan semua jenis FRP kepada kayu menggunakan pelekat epoksi telah diperiksa dan panjang ikatan berkesan ditentukan. Tiga puluh enam rasuk dengan dimensi 100 mm x 200 mm x 1475 mm diuji di mana tiga daripada rasuk tersebut tidak diperkuat sebagai rasuk kawalan. Rasuk selebihnya diperkuatkan dengan pelbagai konfigurasi dan diuji di bawah pembebanan empat titik sehingga gagal. Keputusan menunjukkan bahawa semua rasuk diperkuatkan memberikan prestasi yang lebih baik daripada rasuk kawalan dari segi beban muktamad, kekuatan ricih, kekukuhan dan kemuluran. Peningkatan prestasi oleh FRP terhadap rasuk kayu untuk kapasiti menanggung beban dan kapasiti ricih adalah 11.0 % hingga 41.0 %, manakala untuk kekukuhan adalah 26.61 % hingga 62.05 %. Indeks kemuluran untuk rasuk diperkuat adalah 2.0 hingga 3.7 dan 3.7 hingga 8.4 berdasarkan kaedah lenturan dan tenaga. Bilangan FRP optima ialah lima jalur yang bersamaan dengan nisbah luas diperkuat 0.45 (A_f / A_{shear}). Jenis FRP optima adalah GFRP. Walau bagaimanapun jenis FRP tidak memberikan perbezaan yang ketara di dalam penguatan ricih di dalam kajian ini. Sudut orientasi FRP daripada 45° didapati sebagai optima. Skim pembalut optima ialah balutan penuh (FW) dengan tambahan FRP bertindih di bawah rasuk. Memperkuat rasuk kayu pada zon ricih rasuk boleh mengubah mod kegagalan daripada kegagalan ricih kepada kombinasi kegagalan mampatan dan tegangan dengan tiada kegagalan ricih di zon ricih. Semua jangkaan kapasiti ricih yang dikira hampir menyamai keputusan eksperimen di mana perbezaan peratus adalah di antara 0.5 % hingga 18.3 %. Sebagai kesimpulan, kelakunan ricih rasuk kayu Meranti Kuning berjaya dipertingkatkan dengan menggunakan FRP secara lekatan luaran, di mana parameter reka bentuk optima untuk memperkuat ricih pada rasuk kayu padu telah dicadangkan. Hasilnya formula faktor modifikasi untuk kekuatan ricih dan kekukuhan telah dicadangkan. Hasil kajian ini juga boleh digunakan untuk membimbing penyelidik dan jurutera di dalam bidang teknologi kejuruteraan kayu di negara tropika untuk melakukan kerja pengukuhan ke atas rasuk kayu.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
ASTM	-	American Standard Testing Method
BMD	-	Bending Moment Diagram
BS	-	British Standard
BSI	-	British Standards Institution
CACM	-	Centre for Advanced Composite Materials
CFF	-	Carbon Fibre Fabric
CFRP	-	Carbon Fibre Reinforced Polymer
CFS	-	Carbon Fibre Sheet
CIDB	-	Construction Industry Development Board
CLT	-	Cross Laminated Timber
DLS	-	Double-Lap Shear
EN	-	European Standard
ETTF	-	European Timber Trade Federation
FBD	-	Free Body Diagram
FEA	-	Finite Element Analysis
FRIM	-	Forest Research Institute Malaysia
FRP	-	Fibre Reinforced Polymer
FW	-	Fully Wrapped
GFF	-	Glass Fibre Fabric
GFRP	-	Glass Fibre Reinforced Polymer
Glulam	-	Glulaminated Timber
ID	-	Identification Number
ISO	-	International Organization for Standardization
ITTO	-	International Tropical Timber Organisation
LVDT	-	Linear Displacement Transmission Transducers
LVL	-	Laminated Veneer Lumber
MC	-	Moisture Content
MOE	-	Modulus of Elasticity
MS	-	Malaysian Standard

MTC	-	Malaysian Timber Council
MTIB	-	Malaysian Timber Industry Board
NA	-	Not Available
NSM	-	Near Surface Mounted
RC	-	Reinforced Concrete
SB	-	Side Bonded
SD	-	Standard Deviation
SFD	-	Shear Force Diagram
SGF	-	Strain Gauge for FRP
SGT	-	Strain Gauge for Timber
SLS	-	Serviceability Limit States
UD	-	Unidirectional
UJ	-	U-Jacket
UK	-	United Kingdom
ULS	-	Ultimate Limit States
UM	-	Univeristi Malaya
UPC	-	Unbonded Post Tensioned
UPM	-	Universiti Putra Malaysia
USA	-	Unites States of America
UTHM	-	Universiti Tun Hussein Onn Malaysia
UTM	-	Universiti Teknologi Malaysia
YM	-	Yellow Meranti

LIST OF SYMBOLS

A	-	cross-sectional area
A_f/A_{shear}	-	strengthened area ratio
a_v	-	shear span length
b	-	width
b_c	-	FRP section width
b_s	-	length of significant section
b_t	-	section width
b_w	-	timber section width
C_{MOE}	-	modification factor of stiffness
$C_{MOE,\ CP}$	-	modification factor of stiffness using CFRP
$C_{MOE,\ GF}$	-	modification factor of stiffness using GFRP
$C\tau$	-	modification factor for shear capacity
$C\tau_{CFRP}$	-	modification factor for shear capacity using CFRP
$C\tau_{GFRP}$	-	modification factor for shear capacity using GFRP
d	-	depth of beam
e_r	-	percentage different
E	-	Young's Modulus
E_c	-	modulus of FRP
E_f	-	FRP types
E_i	-	inner plate stiffness
E_o	-	outer plate stiffness
E_w	-	modulus of timber
f'_c	-	concrete compressive strength
F_e	-	elastic limit load
F_{th}	-	theoretical shear capacity
F_y	-	yield limit load
G	-	shear modulus
G_a	-	adhesive shear modulus
GA_s	-	shear stiffness
h	-	height

h_c	-	FRP section height
h_w	-	timber section height
I	-	moment of inertia
I_t	-	section moment of inertia
K	-	modification factors
l	-	length
L	-	total span
L_b	-	bond length
M	-	bending moment
m_1	-	the mass of the test sample before drying in grams
m_2	-	the mass of the test sample after drying in grams
P	-	applied load
P_u	-	ultimate load
Q	-	first moment of area
t	-	width of beam cross-section
t_a	-	adhesive thickness,
t_i	-	inner plate thickness.
t_o	-	outer plate thickness,
t_s	-	thickness of significant section
V	-	shear force
w	-	width
w	-	width of bonding sample
W_e	-	elastic energy
W_{tot}	-	total energy
γ_e	-	elastic adhesive shear strain,
γ_p	-	plastic adhesive shear strain,
ε_{fe}	-	concrete effective strain
ε_{fc}	-	compression strain of FRP at failure
ε_{ft}	-	tensile strain of FRP at failure
ε_{tc}	-	compression strain of timber at failure
ε_{tt}	-	tensile strain of timber at failure
ε_u	-	ultimate strain
ρ_f	-	amount of FRP
σ_u	-	average tensile strength

$\sigma\|$	-	bending parallel to grain grade stress
σ_{adm}	-	permissible bending grade stress
σ_p	-	stress at proportionality
σ_u	-	ultimate stress
τ	-	shear strength
τ_{ap}	-	plastic adhesive shear stress,
τ_{adm}	-	permissible shear grade stress
τ_b	-	bond strength
τ_{d}.	-	shear strength of the timber in horizontal shear
$\tau_{w,\ max}$	-	maximum shear stress
τ_v	-	shear parallel to grain grade stress
Δ	-	deflection
Δ_e	-	deflection at elastic load
Δ_u	-	deflection at ultimate load
Δ_y	-	deflection at yield load
ΔF	-	difference between load of 20% and 50% of maximum tensile force
$\Delta\varepsilon$	-	strain difference between ΔF (%)
κ	-	form factor
μ_E	-	ductility index based on energy
μ_Δ	-	ductility index based on deflection
α	-	angle from x-axis to the applied load
η	-	modular ratio
θ	-	angle from fibre direction
v	-	poisson’s ratio
v_{xy}	-	poisson’s ratio parallel to the grain direction in *xy* plane

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Research

The building trend in world construction industry based on sustainable and environmental friendly resources had lead to increase awareness to substitute material of construction to renewable resources such as timber. The development of forest and production of timber product in a tropical country like Malaysia is undeniable as the Malaysian government, which is also a member of the International Tropical Timber Organisation (ITTO), an establishment committed to sustainable forest management, has been ranked among the world's top exporters of logs, plywood and sawn timber which produce abundant of production or resources of timber as a building material. Figure 1.1 presents the export market of major timber products from January to December of 2015 from Malaysia. The Malaysian timber trade was around RM22 billion in 2015 which position timber as a big prospective to be promoted as a product to increase Malaysia’s profit. From the exported market, 23% was invented from logs and sawn timber that is potentially be endorsed as a structural element in construction industry.

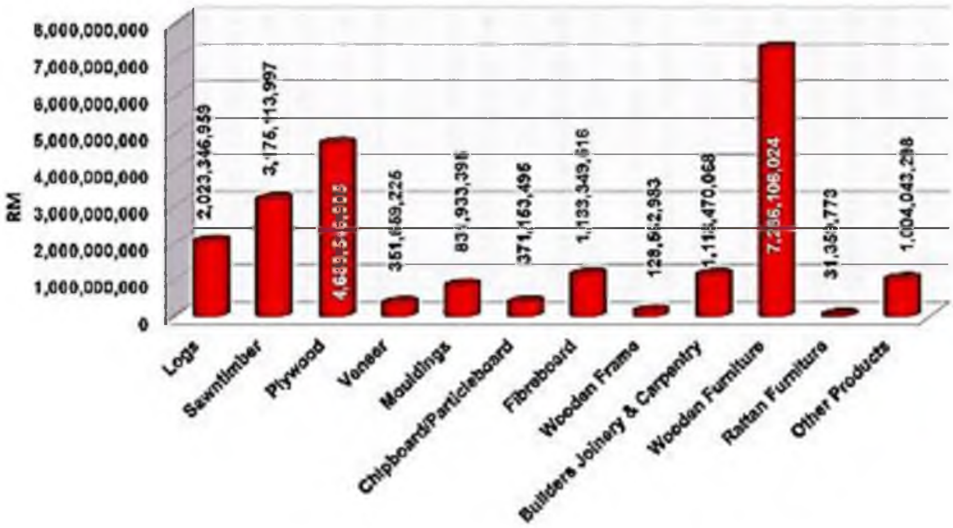

Figure 1.1 Export of major timber products from January to December of 2015 (Malaysian Timber Industry Board)

Timber is a unique and excellent building material that has been used for centuries. It have been used for centuries for framing, lining, cladding, flooring and roofing in both domestic and industrial constructions, as well as used for bridges, wharves and railway sleepers. In Malaysia, there are a wide variety of timbers with over four thousand species. According to European Timber Trade Federation (ETTF), among those species, the commonly harvested species from natural forests include Meranti (Shorea spp.), Keruing (Dipterocarpus spp.), and Merbau (Intsia spp.), although there are other species are harvested, these are the top threes.

Currently, a range of alternative materials such as steel, aluminium and concrete have been successfully introduced into the construction industry. But the trend of extensively used of these materials had drawn to the decreasing of the supply source and this contributes to the prices soaring. Many catalysts presume that the industrial supply of steel and concrete will discontinue one day if the trends remain unchanged (Ahmad, 2010). Therefore, as a renewable and environmental friendly material, timber becomes a marginal material to replace steel and concrete. Moreover, sustainable technology in structural construction is the current main interest to establish by the construction industries.

Despite the fact that steel and concrete are now become more popular than timber and have been used commonly as building material, these materials have several drawbacks. For example, concrete have low tensile strength, low toughness, and low specific strength, with long curing time and it demands strict quality control. Even the innovation of concrete, which is a reinforced concrete, made from a combination of concrete and steel to cater the low tensile strength, the steel itself could corrode over time. Construction using steel and concrete also require heavy lifting machine. Moreover, those materials were made up majorly by cement that primarily produced carbon dioxide, a potent greenhouse gas and harmful to living creature.

Timber is originated from wood, which is the only renewable building material that naturally grown and that removes carbon dioxide from the atmosphere. The production of wood for construction industry uses much less energy than most other living materials, giving wood products a significantly lower carbon footprint and safer for health and ecology. Using timber as a building material may speed up the construction since it requires less machining and labour, easy to process such as cutting, drilling and repair. This non-corrosive material will boost wood industry as timber are less pollutant, with biodegradable residues and allows aesthetic and elegant finishing.

On the other hand, lack of knowledge regarding design of timber may attribute to lack of confidence among engineers to use timber as building material and consequently lower the application of timber structures in Malaysia. Timber most popular limitations that constrained the usage are durability that deals with the resistance against insects (such as termites), decay, fire and water damage. But such durability problems may be solved if the respective timber is treated properly.

Other reason that limits the usage of timber as building material is that timber has lower strength than steel or reinforced concrete. Timber-based structure could also encounter problems due to overload, design failure and infestation by termites. In the field of structural engineering, structure with high strength is the most crucial concerns. However, timber strength is much rely on its moisture content and the orientation of the timber's grain; despite the strength varies by the same log of timbers. Therefore, method of repairing and strengthening should be applied for the purpose to enhance the strength and load capacity of these timbers structure. One of the methods employed is by strengthening timber structure with steel rods/plates or fibre reinforced polymer (FRP) rods/plates/fabrics bounded by resin.

FRP is the current preferred material to strengthen timber structures either in construction or for rehabilitation purposes due to its high potential to improve mechanical performances. FRP is a composite made from fibre reinforcement in a plastic (polymer) matrix. FRP had been used widely in building, bridges, timber and other construction due to this composite has desirable properties that enhance its performance. The advantages of using FRP are anti-corrosion, lightweight, high durability, high elastic modulus and high resistance to environmental degradation. These factors enhance the mechanical performance of timber and is choice for researchers to use in their study. Due to adhesive ability, FRP composite sheet had been used in about thirty recent years in concrete or timber.

In normal practice, any structural members are primarily design for flexural strength and shear strength. Beam are structural member designed to carry loads in which flexure is usually considered first, prior to shear design. Shear failure always occur without hesitation or warning. Therefore, the design for shear must ensure that the shear strength for every member in the structure exceeds the flexural strength. The shear capacity of concrete structure that is a common building material often unable to meet current standards requirements is a reason timber material rarely used in construction as building material.

In addition, some of timber beams fail in shear before bending. This may be attributable to increased load requirements, inadequate shear provisions in the original design, deterioration of materials or an increased demand in shear capacity owing to flexural strengthening. Providing proper shear reinforcement along the beam will reduce the possibility of shear failure along the beam.

For a typical concrete beams, the shear reinforcement was provided by internal shear link. Solid timber beams had neither internal reinforcement for flexural nor shear. Existing timber beams potentially be strengthened externally and give comparable load carrying capacity with considerable bigger size of beams. There are various approaches to repair and strengthened the beam in shear using FRP. Typical shear strengthening techniques are steel plate bonding system or section enlargement. Instead of using bigger size of timber which considerably increase the overall cost of constructing building, strengthening smaller timber is seen as an alternative way to the shear problem in beam as addressed earlier. Techniques used in repairing and strengthening of concrete structures in shear using FRP to be applied to the timber beam are used in this study since there are small numbers of researches conducted on the behaviour of the timber beam against shear resistance.

Research has been conducted on strengthening of solid and glulam beam using tropical timber such as Yellow Meranti, Kempas and Keruing in bending but shear strengthening of these solid tropical timber beam has not been conducted yet. Yellow Meranti is one of the major species available and widely distributed in Malaysia for light construction and furniture manufacturing industry. Due to its availability and low in cost, research on utilizing of low grade Yellow Meranti timber to be used as structural member are required. Most of the application of FRP in strengthening timber structure were bonded externally by adhesive which make surface preparation is also an interesting area to be researched.

Generally, the cellular structure of hardwood species like Yellow Meranti is more complex where they tend to have a short fibre length and very large vessels (pores). Whilst, softwood is relatively has longer fibre length and present uniform appearance free from large pores. Literature proved that smaller hardwood fibre in terms of fibre length and fibre diameter which was one third on average from the size of softwood fibre would result in less capability in carrying load and consequently have lower shear strength and stiffness (Coutts, 1987). Therefore, strengthening of solid timber beam from hardwood species was seen crucial to enhance the shear performance of the timber for structural usage.

1.2 Problem Statement

Yellow Meranti has relatively lower shear strength than softwood species due to its shorter fibre length and larger pores compares to most softwood species that present uniform appearance free from large pores. These wood anatomy of hardwood species of Yellow Meranti allow it to have lower fibre strength, be more brittle and able to carry lower load when under stress. In addition to that, some of timber beam experience shear failure that always occurs suddenly before bending. Thus, shear strengthening of Yellow Meranti by using Fibre Reinforced Polymer (FRP) is seen to be crucial to solve the aforementioned problem for the structural application. Afterward, comprehensive design and guideline of the strengthening system for tropical timber are established to the construction industry. Consequently, the mechanical properties of the non-structural applicant of timber are greatly enhanced likewise it is capable to be convert to structural timber beam with fully utilized of bending capacity.

1.3 Research Question

Some modifications in terms of techniques in strengthening are developed to enhance the timber capacity. There are four main research questions in this study:

(a) How the bonding of FRP behave when externally bonded to timber and what are the effective bond length between these materials?

(b) What is the shear strength, stiffness and ductility enrichment provided by FRP to timber beam and their respective modification factor?

(c) What is the most suitable design parameter that contribute well in strengthen timber in shear by using composite material?

(d) How the strengthened timber beams performed structurally from the failure mode?

(e) How efficient the mathematical model to accurately predict the shear capacity of the strengthened timber beam?

1.4 Research Objectives

The aim of this study is to improve the shear properties of Yellow Meranti by strengthening the solid timber beam externally by using Fibre Reinforced Polymer (FRP). The mechanical properties of solid timber, FRP and adhesive were firstly determined and the results were compared with the existing data as a supplementary step in order to achieve the aim of this study. Therefore the objectives set up in this research are:-

(a) To determine the bonding properties of FRP to timber beam using epoxy adhesives.

(b) To determine the shear capacity, stiffness and ductility of strengthened solid timber beams under four point loading.

(c) To determine the design parameter for strengthening of composite material to timber beam (number of FRP strips; types of FRP; FRP stripping angle and wrapping schemes).

(d) To investigate the structural performance from failure mode of solid timber beams strengthened with FRP

(e) To develop mathematical model of the strengthened timber beam.

1.5 Research Scopes

The scope of this research covers the selection of materials, types of testing and analysis involved. In this research, untreated seasoned Yellow Meranti timber which is randomly selected is used as the main structure which their moisture content is limited to be below and equal to 23%. Carbon fibre reinforced polymer (CFRP) pultruded plate, carbon fibre fabric (CFF) and glass fibre fabric (GFF) were selected as the strengthening material for timber beam. Sikadur-30 was used as bonding agent for CFRP pultruded and Sikadur-330 was used as laminating and as well as bonding agent for CFF and GFF to the timber. The material properties measured in this study was limited to shear, tensile, compression and bonding strength by double strap joint configuration between FRP and timber with three different bond length (50 mm, 75 mm and 100 mm). The beams were tested under four point loading. The strengthening work was limited to externally bonded and employed on shear zone of the timber beam. Number of strips (n=2 to 7), type of FRP (CFRP, CFF and GFF), FRP stripping angle (90° and 45°) and FRP wrapping schemes (Side bonded (SB), U-Jacket (UJ) and Fully wrapped (FW)) were used as experimental parameter. Analytical analysis modified from Morales-Conde et al. (2015) was developed and used as comparison to the experimental results.

1.6 Research Significance

This research expectation to come out with a novel findings where the finding should be beneficial to the construction industry and their respective communities. Environmental awareness could be highly promoted to the society through revival of natural building material with low carbon footprint that also help conserve resources. The designers are encouraged for the strengthening techniques of Yellow Meranti which is low in strength (commonly used for furniture and plywood industry) for structural usage and thus utilize the capacity and performance of timber. Fabricators and engineers are assisted in improving the strengthening works in field and established guideline for design works and fabrication works on site in the future. This study also facilitates the introduction of environmental friendly materials with proven performance to contractor and Aid in providing economic advantage of material utilization by efficiently compositing low cost timber with minimum but sufficient amount of FRP in construction works. Lastly, researcher(s) are guided to uncover critical areas in structural engineering that other researches unable to explore thus develop new knowledge particularly in strengthening timber structure.

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