FLEXURAL STRENGTH OF PLAIN CONCRETE BEAM STRENGTHENED WITH WOVEN KENAF FRP PLATE: EXPERIMENTAL WORKS AND NUMERICAL MODELLING

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DEDICATION

For my beloved parents Omar bin Othman and Rusnah binti Jaafar,
family Al Faiz, Al Arif, and Al Rais,
My Love
Supervisors Assoc. Prof Dr Hilton, Dr Mustafasanie and Prof Sugiman,
and all my beloved friends.
Thanks for everything.
For all the support and encouragement to finish my PhD journey.

"It's not about easy going, analysis requires calm."

"Success may be achieved by setting clear targets and determination along with patience. Those who can acknowledge their true self, eventually succeed."
- Zaim Omar

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ABSTRACT

A strengthening technique using externally-bonded synthetic Fibre Reinforced Polymer (FRP) has been reported to improve flexural resistance on concrete beams. To this end, limited research work was reported to investigate natural FRP as a strengthening material. Woven fabric kenaf composites (KFRP) have good specific strength and sustainability than synthetic FRP counterparts. This research aims to conduct experimental work to study the parametric effects of KFRP plates on flexural strength in concrete beams, later validated with strength predictions from FEA modelling. Four-point bending of 100 x 100 x 400 mm concrete beam were tested in two phases, i.e., Phase 1 investigates the effects of externally bonded KFRP plates variations such as woven architecture arrangements and KFRP geometries (lengths, widths, and thickness) on concrete beam, and Phase 2 investigates the flexural resistance of various notch depths, a_0 in concrete beams repaired with/without KFRP plate. The flexural resistance improvement is between 18% to 84% where the former is given with shortest overlap length and latter with thickest KFRP plates. The presence of interfacial stress between adjacent layers offers better resistance in thickest plates. In phase 2, flexural resistance of notched beam improved by up to 48% KFRP strengthening is readily seen due to larger bending in notched beam. Finite element analysis (FEA) requires incorporation of constitutive models, and most reported literature adopts extensive experimental datasets. The proposed physically-based traction-separation relationship requires two material properties, which were independently determined from a small-scale experimental set-up. XFEM techniques offer visual tracking of crack initiation and propagation by using ABAQUS CAE software. It was found that post-processing discrepancies of lesser than 12 % in both phases, as validated to experimental datasets. Additionally, both experimental and modelling approaches showed incorporation of KFRP plates can increase appreciably the flexural resistance of plain concrete beams.

ABSTRAK

Teknik penguatan tampalan luaran menggunakan Polimer diperkuat serat (FRP) sintetik dilaporkan dapat meningkatkan kerintangan lentur untuk rasuk konkrit. Didapati kajian penyelidikan untuk FRP semulajadi sebagai bahan pengukuhan sangat terhad. Komposit kenaf fabrik (KFRP) mempunyai kekuatan spesifik yang baik dan mengekalkan kelestarian dibandingkan FRP sintetik. Matlamat projek ini mengkaji kesan parametrik plat KFRP terhadap kekuatan lenturan rasuk konkrit, kemudian ramalan kekuatan dijalankan dengan memodelkan analisis unsur terhingga (FEA). Lenturan empat-titik pada rasuk konkrit bersaiz 100 x 100 x 400 mm dijalankan dua fasa, iaitu, Fasa 1 mengkaji variasi KFRP, iaitu corak tenunan dan dimensi (panjang, lebar dan ketebalan KFRP) terikat luaran pada rasuk konkrit, dan Fasa 2 menyiasat rintangan lenturan dalam kedalaman takuk berbeza, a_0 dalam rasuk konkrit dengan/tanpa plat KFRP. Rintangan lenturan meningkat antara 18% hingga 84%, di mana merujuk kepada sambungan ikatan terpendek dan plat KFRP paling tebal. Kehadiran tegasan antara-lapisan menawarkan rintangan yang terbaik untuk plat paling tebal. Dalam Fasa 2, rintangan lenturan rasuk bertakuk meningkat sehingga 48% disebabkan lenturan yang lebih signifikan dalam rasuk bertakuk. Analisis unsur terhingga (FEA) memerlukan pendekatan model bahan di mana kebanyakan kajian lepas melaporkan pelaksanaan data eksperimen yang besar. Hubungan daya tarikan-pemisahan yang diusulkan hanya memerlukan dua nilai bahan, dan ditentukan secara bebas daripada eksperimen berskala kecil. Teknik XFEM menawarkan visual grafik permulaan dan perambakan retak menggunakan perisian ABAQUS CAE. Didapati bahawa percanggahan pasca-pemprosesan adalah kurang daripada 12% untuk dua fasa kajian, dibandingkan data eksperimen sebelumnya. Selain itu, kedua-dua pendekatan eksperimen dan pemodelan menunjukkan tampalan luaran plat KFRP dapat meningkatkan dengan kerintangan lenturan rasuk konkrit biasa dengan ketara.

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LIST OF SYMBOLS AND ABBREVIATIONS PAGE

ABS	-	Acrylonitrile Butadiene Styrene plastic mould
ACI	-	American Concrete Institute
AFRP	-	Aramid Fibre Reinforced Polymer
ASTM	-	American Society for Testing and Material
BK	-	Benzeggagh-Kenane failure criterion
BS	-	British Standard
CEB	-	Euro-International Committee for Concrete
CDP	-	Concrete Damage Plasticity
CFRP	-	Carbon Fibre Reinforced Polymer
CS	-	Continuous Supported beam
CSC	-	Concrete Smear Crack
CZM	-	Cohesive zone model
EB	-	Externally Bonded
EN	-	European Standard
FFRP	-	Flax Fibre Reinforced Polymer
FEA	-	Finite Element Analysis
FEM	-	Finite Element Method
FIP	-	International Federation for Pre-stressing
FKAAB	-	Faculty of Civil Engineering and Built Environment
F	-	Flexural failure of concrete beam
FPZ	-	Fracture Process Zone
FR	-	Flexural failure of beam with KFRP Ruptured failure mode
FRP	-	Fibre Reinforced Polymer
GFRP	-	Glass Fibre Reinforced Polymer
KFRP	-	Kenaf Fibre Reinforced Polymer
LVDT	-	Linear Vertical Displacement Transducer
ND	-	Notch Depth

OPC	-	Ordinary Portland Cement
RILEM	-	The International Union of Laboratories and Experts in Construction Materials, Systems and Structures
SS	-	Simply Supported
SSD	-	Saturated-Surface-Dry
ST	-	Shear failure of beam at the KFRP plate Tip
TSL	-	Traction Separation Laws
UTHM	-	Universiti Tun Hussein Onn Malaysia
VCCT	-	Virtual Crack Closure Technique
XFEM	-	Extended Finite Element Method
mm	-	millimetre
pts/s	-	points per second
w/c	-	Water to cement ratio
3-D	-	Three-dimensional
3PB	-	Three-point bending
4PB	-	Four-point bending
B	-	Beam breadth
D	-	Beam depth
E	-	Elastic modulus
G	-	Shear modulus
L	-	Beam length
P	-	Point load
S	-	Beam span
TEX	-	Textile measurement of fibre gram over km
N.A.	-	Natural axis
e.p.c.	-	end per cm
p.p.c.	-	pick per cm
G_c	-	Cohesive fracture energy
L_f	-	FRP length
t_f	-	FRP thickness
V_f	-	Kenaf volume fraction
V_m	-	Matrix (epoxy resin) volume fraction
W_f	-	FRP width

S_L	-	Beam span load
m_1	-	Initial beam mass
m_2	-	Final beam mass
m_f	-	Kenaf mass
m_m	-	matrix (epoxy resin) mass
ρ	-	Density
λ	-	Wavelength
δ	-	Displacement
a_0	-	Notch depth
a_v	-	Notch depth to beam depth
w/c	-	Water cement ratio
ν	-	Poisson's ratio
σ_o	-	Unnotched strength
σ_c	-	Compression cube strength

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LIST OF PUBLICATION

Journal Papers

1. Ahmad, H., Sugiman, S., Jaini, Z. M. & Omar, A. Z. (2021). Numerical Modelling of Foamed Concrete Beam under Flexural Using Traction-Separation Relationship. – Co-author.
   (Submitted to Latin American Journal of Solids and Structures with IF = 1.52/Q3)
2. Omar, Z., Sugiman, S., Yussof, M. M. & Ahmad, H. (2022). Predicting the Flexural Behaviour of CFRP-Strengthened Concrete Beam using Combined XFEM and Cohesive Zone Model. – Main author.
   (Submitted to Journal of Applied Science and Engineering Tamkang with IF = 0.82/Q3)
3. Omar, Z., Sugiman, S., Yussof, M. M. & Ahmad, H. (2022). The Effects of Woven Kenaf FRP Plates Strengthened on Plain Concrete Beam Under a Four-Point Bending Test. – Main author
   (Submitted to Case Studies in Construction Materials, Elsevier with IF = 5.06/Q1)
4. Omar, Z., Sugiman, S., Yussof, M. M. & Ahmad, H. (2022). Utilizing XFEM Model to Predict the Flexural Strength of Woven Fabric Kenaf FRP Plate Strengthened on Plain Concrete Beam. – Main author (Under review)
   (Submitted to Case Studies in Construction Materials, Elsevier)

Proceeding Papers

1. Omar, Z., Sugiman, S., Yussof, M. M. & Ahmad, H. (2022). Material and Independent Properties of Kenaf FRP Composites, – Main author
   (Proceedings of the First Mandalika International Multi-Conference on Science and Engineering 2022, MIMSE 2022 (Civil and Architecture), Mataram, Nusa Tenggara Barat, Indonesia; Journal: Advances in Engineering Research, Vol. 215- Scopus index.)

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