UNIVERSITI PUTRA MALAYSIA

CREEP TEST FACILITY DEVELOPMENT AND CREEP ANALYSIS OF BRACED COMPOSITE CROSS ARMS IN 132 kV TRANSMISSION TOWER

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By

MUHAMMAD ASYRAF BIN MUHAMMAD RIZAL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

To Al-Quran, the greatest source of knowledge

Bring me sheets of iron" - until, when he had leveled [them] between the two mountain walls, he said, "Blow [with bellows]," until when he had made it [like] fire, he said, "Bring me, that I may pour over it molten copper." (Al-Kahf: 96)

&

To my beloved father, Professor Dr. Muhammad Rizal Razman and my beloved mother, Professor Ts. Dr. Azrina Azlan for their invaluable sacrifices, encouragements and support throughout my life

&

To my beloved wife, Rafidah Mazlan for her love, patience and understanding

&

To my beloved siblings, Aiman Maisarah Muhammad Rizal
and Muhammad Akmal Muhammad Rizal

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

CREEP TEST FACILITY DEVELOPMENT AND CREEP ANALYSIS OF BRACED COMPOSITE CROSS ARMS IN 132 kV TRANSMISSION TOWER

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June 2021

Chairman : Mohamad Ridzwan Ishak, PhD
Faculty : Engineering

Previously, most of cross arms in 132 kV latticed suspension towers made of wood timber cross arms to sustain electrical cables and insulators above the ground. However, wood timber cross arms seemed to degrade and fail after 20 years of service due to creep, natural wood defect and attack from natural enemies. This issue has brought the urgency to replace the previous cross arms with pultruded glass fibre reinforced polymer composite (PGFRPC) cross arms due to better strength, lightweight, and low degradability. To date, no study has been conducted on the evaluation of creep properties of cross arms' material and structure for long-term service application. Moreover, the creep testing facilities specialising in cross arms are still undeveloped to conduct the creep test for outdoor use. Lastly, no research has been conducted on the enhancement of cross arm structure by retrofitting with additional braced arms to improve creep resistance performance. It is reported on the development and characterization of creep responses of PGFRPC cross arms. Initially, a hybrid TRIZ-Morphological Chart-ANP method was implemented to develop the conceptual design for both multi-operation flexural and cantilever beam creep test rigs. From the product design specifications (PDS), concept designs 3 and 5 were selected as the final design concept for multi-operation flexural and cantilever beam creep test rigs, respectively. For three-point flexural creep analysis, it started with quasi-static flexural test and found out the modulus of elasticity of PGFRP almost the same value as Balau wood. In contrast, the flexural strength of pultruded GFRP increases about 72.97 % compared to Balau wood. This finding further established that PGFRP composite permitted better creep resistance as the creep strain increases about 100% in Balau wood as compared to PGFRP composite. This is due to low creep strain and better stability of transition of elastic to viscoelastic phase. These creep results for both wood and composite cross arms were optimized with Findley model, and two general creep equations was generated. For the cantilever beam creep results, it was illustrated that both wood and composite cross arms exhibited less creep strain after retrofitting with additional braced arms. Furthermore, the creep resistance performance for both braced wood and composite cross arms improved about 15 to 21 % higher. This is due to higher structural integrity and more stable elastic transition to viscoelastic phases. Further

numerical analyses demonstrated that the stress-independent material exponent exhibited approximately the same values between right and left arms, and higher elastic, and viscoelastic performance for both braced wood and composite cross arms under long-term creep. To summarise, PGFRPC cross arms have been revealed to have better mechanical strength and creep resistance performances, which is suitable to replace wood cross arms. In addition, the enhancement of PGFRPC cross arms by incorporating bracing system contributes to significant improvement of creep resistance and mechanical performances for the current design.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN FASILITI UJIAN RAYAPAN DAN ANALISIS RAYAPAN PADA LENGAN SILANG KOMPOSIT DI 132 kV MENARA PECAWANG ELEKTRIK

Oleh

MUHAMMAD ASYRAF BIN MUHAMMAD RIZAL

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Pada sebelum ini, menara pencawang untuk 132 kV talian penghantaran mempunyai silang lengan yang diperbuat daripada kayu untuk menanggung beban daripada kabel elektrik dan penebat yang di atas dari paras permukaan bumi. Walau bagaimanapun, silang lengan kayu kelihatan merosot dan gagal setelah 20 tahun berkhidmat disebabkan oleh rayapan, serangan serangga perosak dan kecacatan semulajadi. Isu ini telah membangkitkan keperluan untuk menggantikan silang lengan terdahulu kepada silang lengan yang diperbuat daripada gentian kaca diperkuat polimer komposit (PGFRPC) kerana ia mempunyai kekuatan yang lebih baik, ringan dan sukar diurai. Sehingga kini, tiada lagi kajian dibuat mengenai penilaian sifat rayapan bagi silang lengan dari segi bahan dan struktur untuk aplikasi perkhidmatan jangka panjang. Selain itu, kemudahan ujian rayapan khusus untuk silang lengan masih belum dikembangkan untuk kegunaan persekitaran luar. Akhir sekali, tidak ada kajian yang dilakukan mengenai penambahbaikan struktur silang lengan dari sudut pemasangan tambahan lengan pendakap bagi meningkatkan prestasi ketahanan rayapan. Oleh itu, kajian ini melaporkan mengenai pengembangan dan pencirian tindak balas rayapan pada silang lengan PGFRPC. Pada awalnya, kaedah TRIZ-*Morphological Chart*-ANP hibrid telah digunapakai bagi menghasilkan reka bentuk konsep bagi kedua-dua pelantar ujian lenturan dan kantilever. Daripada sudut spesifikasi reka bentuk produk (PDS), reka bentuk konsep 3 dan 5 telah dipilih sebagai konsep reka bentuk terakhir untuk pelantar ujian rayapan lenturan dan kantilever. Untuk analisis lipatan lentur, ia bermula dengan ujian lentur kuasi-statik dan mendapati kekakuan untuk composite PGFRP hampir sama dengan kayu Balau. Sebaliknya, kekuatan lenturan komposit PGFRP lebih tinggi sekitar 72.97% berbanding kayu Balau. Penemuan ini seterusnya membuktikan bahawa komposit PGFRP mempunyai ketahanan rayapan yang lebih baik kerana regangan merayap meningkat sebanyak 100% pada kayu Balau berbanding komposit PGFRP. Hal ini kerana regangan merayap yang rendah dan kestabilan pada peralihan fasa elastik ke viskoelastik. Hasil rayapan ini untuk kedua-dua lengan silangan kayu dan komposit menunjukkan hasil yang optimum dengan model Findley. Oleh itu, dua persamaan creep

umum dihasilkan daripada model tersebut. Bagi hasil kajian rayapan kantilever, digambarkan bahawa kedua-dua struktur lengan silang kayu dan komposit menunjukkan regangan rayapan lebih rendah apabila dipasang dengan lengan pendakap tambahan. Tambahan itu, prestasi rintangan rayapan untuk kedua-dua lengan silang kayu dan komposit yang disokong meningkat sekitar 15 hingga 21% lebih tinggi. Ini disebabkan oleh integriti struktur dan peralihan elastik yang lebih stabil ke fasa viskoelastik yang lebih baik. Analisis berangka lebih lanjut, hasil kajian menunjukkan bahawa eksponen bahan bebas tekanan menunjukkan nilai yang hampir sama antara lengan kanan dan kiri bagi struktur lengan silang. Prestasi elastic serta viskoelastik untuk kedua-dua lengan silang kayu dan komposit yang berpendakap lebih stabil dan baik dalam ujian rayapan dalam jangka masa yang panjang. Ringkasnya, struktur lengan silang komposit telah terbukti mempunyai kekuatan mekanik and prestasi daya tahan rayapan yang tinggi dan sesuai untuk menggantikan lengan silang kayu. Dalam pada itu, kemajuan lengan silang komposit dengan tambahan sistem pendakap menyumbang kepada peningkatan ketahanan rayapan dan prestasi mekanikal secara ketara bagi reka bentuk semasa.

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This thesis was submitted to Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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- the research conducted and the writing of this thesis was under our supervision;
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4. RESULTS AND DISCUSSIONS

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LIST OF ABBREVIATIONS

3D	Three-dimensional
ANP	Analytic Network Process
AHP	Analytic Hierarchy Process
ASTM	American Society for Testing and Materials
CAD	Computer aided drawing
MCDM	Multiple-Criteria Decision-Making
kV	Kilo-volt
PGFRP	Pultruded glass fibre reinforced polymer
PGFRPC	Pultruded glass fibre reinforced polymer composite
TNB	Tenaga Nasional Berhad
TRIZ	Theory of The Resolution of Invention-Related Tasks
TL	Transmission line
UPE	Unsaturated polyester
VIKOR	*VIseKriterijumska Optimizacija I Kompromisno Resenje*
WOB	Without bracing configuration cross arm
WB	With bracing configuration cross arm

LIST OF SYMBOLS

w	Priority vector
a_{ij}	Important scale
n	Number of criteria
F	Cross-head motion
L	Support span length
D	Depth of beam
z	Magnitude of 0.01
ε	Maximum strain
d	Depth of specimen
b	Width of specimen
D_c	Maximum deflection at mid-span
σ	Maximum stress
P	Applied load
y	Deflection of member beam
L_b	Member beam’s length
I	Moment of inertia
b_b	Width of member beam
h_b	Thickness of member beam
ε_n	Specific strain
σ_n	Specific stress
x	Location of shear stress
ε_e	Elastic strain

ε_k	Viscoelastic strain
ε_d	Viscous strain
E_e	Modulus of elasticity
E_d	Modulus of elasticity of relaxation response
η_d	Modulus of viscoelasticity of relaxation response
η_k	Modulus of viscoelasticity
A	Stress-dependent coefficient
n	Stress-independent material exponent

CHAPTER 1

INTRODUCTION

1.1 Background of study

A cross arm structure is the key component in a latticed steel transmission tower where the extended arm member aids to grasp the power conductor and insulator. This structure component is essential to be stiff and strong enough to sustain the electrical wires as well as to withstand the dynamic wind loads in any conditions (normal and stormy days).

Previously, Chengal wood timber was chosen to make up the cross arm in 132 kV transmission line (TL) tower due to its outstanding mechanical performance and better electrical strike arc quenching behaviour during lightning attack (Bakar et al., 2018). However, a tremendous reduction amount of wood timber in the forest every year due to logging activity has been raised by environmental societies and scientists throughout the world. Although most developed countries have obtained net forest gains domestically, they have also increased the deforestation embodied in their imports, of which tropical forests are the most threatened ecosystem. For instance, consumption patterns of the developing country have been grown to an average loss of 3.9 trees per person every year (Hoang & Kanemoto, 2021). Furthermore, several hotspots of deforestation embodied in international trade are also biodiversity hotspots, such as Malaysia, Indonesia, and Brazil. Subsequently, many government agencies restrict and gazette many forest areas as natural conservation areas to control the deforestation rates (Bou, 2019; Wicke et al., 2011).

Due to some reasons, large quantities of good quality wood are limited since it is difficult to find adequate suppliers, especially in Malaysia (Omran & Schwarz-Herion, 2020). Besides that, the wood cross arm is problematic to transport as it is heavy. Other than that, Tenaga Nasional Berhad (TNB) engineering department established that a troublesome wood cross arm could only withstand its operation up to 24 years (Rawi et al., 2017). They demonstrate that a failed cross arm happens due to natural wood defects, exposure to the extreme tropical climate and biological attacks such as termites, woodpeckers, and fungi. Another significant contribution of a failed cross arm is the creep phenomenon that degrades the cross arm structure after serving for around 20 years. This has brought an urgency to replace the wood cross arm with pultruded glass fibre reinforced polymer (PGFRP) composite.

Globally, glass fibre composite is well-known material used in several structural industries such as automobile, construction and energy transmission due to its reasonable cost factors since the material composed of fine fibre with strong, robust and lightweight. Sanjay & Yogesha (2017) reported that GFRP has less stiffness and strength than carbon fibre. Nevertheless, glass fibre composite is far less brittle, and the raw materials are much less expensive. GFRP composite has been chosen due to its high mechanical strength, dimensional stability, durability, and low thermal and electrical conductivity (Wazery et al., 2017; Sanjay & Yogesha, 2017). The glass fibre composites are easily produced by using the pultrusion method and other moulding techniques. This has led various researchers to implement PGFRP composite as an alternative material for cross arm applications due to its good potential and well-known advantages. However, since it is new and recently used in cross arm application, no studies have yet been established on the principle of long-term creep properties of PGFRPC cross arm assembly.

Creep is a phenomenon where a solid material deforms, which is permanently influenced by continuous mechanical stresses in long period of time. The creep properties of a material evaluate the long-term durability along its service. It is divided into three stages: primary (rapid rate), secondary (steady-state) and tertiary (rapid rate to rupture) creeps (Jorik et al., 2019). The creep properties can commonly be explained using creep strain-time principle and creep compliance. These experimental data are further analysed using creep numerical models to understand the steady-state creep, elastic, and viscoelastic properties (Fu et al., 2020). Creep behaviour is fundamental for the composite structure to withstand loads in a maximum period. A potential problem that may arise due to extreme creep deformation of the cross arm is sudden structural failure after years of service (Beddu et al., 2018). This would potentially disrupt electrical supply to residential and industrial areas, which subsequently inhibit the economic growth for locals and the whole country. Besides that, the occurrence of extreme creep deformation also incur the maintenance cost along the transmission line and cause a period of electrical downtime. This would jeopardize the daily routine and activity for industry and household.

No studies have been reported on creep response for PGFRPC cross arm in a 132 kV transmission tower. The study on effect of retrofitting of bracing system in cross arm is also still unexplored. Thus, the objective of the current study is to develop and characterize the creep response of wood and PGFRPC cross arm in both coupon-scale and full-scale sizes. Moreover, an improvement of cross arm by incorporating braced members is implemented to study the effects on creep resistant performance.

1.2 Problem statements

Most of the literature focuses on creep performance of PGFRP composite and wood samples in coupon-scale size, either in tensile (D’Antino & Pisani, 2019; Peng et al., 2017), four-point bending (Loni et al., 2013a) or three-point bending (Anand et al., 2018) creep tests in laboratory environment. The creep properties for wood timber and PGFRPC cross arms are reported in a very limited amount in the literature. In order to address the matter, a comparison study has to be developed to analyse creep properties of the previous wood and PGFRPC cross arms in coupon-scale. No specific study on creep model has gained global acceptance among majority of structural industries. Each sector evaluates the creep model prediction in accordance to the application. The primary issue in the prediction on any material depends on the contribution of creep. In order to comprehend this issue, this prediction study of the structure under long-term continuous loading in actual tropical climate conditions has to be conducted. This provides a baseline work and prediction formulation for the long-term creep properties under bending effect. However, the creep data produced from coupon scale experiment and numerical analysis may lead to numerous exaggerated factors, especially in terms of geometrical, profile and shape of the structure. The geometry and profile of the material could be neglected when the test is conducted in coupon-scale samples. Thus, more reliable data collection would be achieved when a full-scale cross arm is used to carry out a creep test to understand the mechanical behaviour during long-term loading conditions. The investigation of the long-term behaviour of the main member for the cross arm structure could provide a more holistic perspective to evaluate the whole structure's behaviour. Thus, it is expected to conduct a creep test in actual cantilever beam mode for full-scale sized cross arms and a three-point bending test for coupon-scale sized to explore the actual strain-time behaviour for each member of cross arm structure. However, there is no creep facility available to accommodate the creep test for coupon-scale and full-scale sized cross arms in outdoor environment. This is due to the complex assemblage of member structure without proper testing facilities in order to conduct the experiment. In this case, it will be more dangerous if the creep performance and service life are over predicted by carrying out the study in coupon-scale size. Moreover, the current available creep test rig for coupon scale limited for the use in laboratory environment. Hence, two new creep test rigs have to be developed to accommodate the coupon-scale and full-scale sized cross arms to study the creep properties of the structure in the open area environment. To the best of our knowledge, no study has been carried out on the effect of incorporation of braced arms in the existing designs of cross arms on long-term creep properties. The retrofitting of bracing system in cross arm would probably increase the overall structural and mechanical performances, which would contribute to the reduction of maintenance cost and any potential casualties. Thus, a research on the influence of the addition of braced arms on cross arm’s creep properties has to be carried out to justify the addressed matter.

1.3 Research objectives

The aim of this study are to evaluate the creep properties of cross arms made of Balau wood and PGFRP composite in 132 kV transmission tower using experimental and numerical approaches. The specific objectives of this study are listed as follows:

1. To develop, design, and fabricate a flexural creep test rig for coupon-scale sized cross arm used in transmission tower.
2. To develop, design, and fabricate cantilever beam creep test rig for full-scale sized cross arm applied in transmission tower.
3. To compare flexural creep properties of wood and composite cross arms in coupon scale using both experimental and numerical approaches.
4. To examine the effect of bracing in Balau wood cross arm in 132kV transmission tower on its creep strain, steady state creep, elastic and viscoelastic moduli.
5. To analyse the influence of braced arms addition in PGFRP composite cross arm on its long-term creep properties.

1.4 Significance of study

The significance of this research work is listed as follows:

1. The findings from the current study are expected to enrich the knowledge in enhancing the current PGFRP composite cross arm towards longer service life and better durable structure in transmission tower application.
2. The development of creep test rigs for coupon-scale and full-scale sized cross arms in this research is likely to provide long-term mechanical testing facilities specialized for cross arms in actual environment.
3. The study of creep responses and general creep equations of previous (wood timber) and current (PGFRP composite) cross arms are expected to aid in creating a baseline for engineers and researchers to forecast cross arms for longer service time.
4. The problems and issues associated with structural failures of cross arms during the service can be comprehended earlier by retrofitting the structure with additional braced arms to provide better strength and stiffness.
5. The successful application of braced arms would also contribute to reduce the maintenance cost, safety risk to workers, and also any potential casualties which may occur.

1.5 Scope and limitation of research

The main novelty of the study is credited to the development and characterization of creep responses of PGFRP composite cross arms with bracing through experimental and numerical approaches. Two cross arm configurations, which are braced and current designs, were implemented in two creep tests; three-point flexural creep test (coupon-scale) and cantilever beam creep test (full-scale size) following ASTM D2990-17 (2017). These creep tests were subjected to two newly developed creep test rigs using hybrid TRIZ-Morphological Chart-ANP approach, as creep testing facilities specialise in cross arm structures. They were placed at an outdoor environment, situated at the Aerospace Hanger, Universiti Putra Malaysia. Many researchers (Fu et al., 2020; Loni et al., 2013a) have conducted creep tests in laboratory with controlled environment (temperature and humidity). Thus, this creep study would simulate the long-term behaviours of these cross arms in actual conditions. The creep test was taken within 1000 h because the minimum required time for creep was 1000 h to observe trends from instantaneous strain followed by primary creep and secondary creep stages. Moreover, since the creep study for the cross arm is the exploratory research phase, several limitations such as lack of specimens from and limitation of test rig can run one sample at a time and lack of samples in industrial suppliers as one cross arm set per material. In addition, this study is focusing on material engineering rather than structural evaluation.

The creep test implement in this study was normal creep test, which is also called a load-based creep test. The flexural creep test is chosen in this study due to it reflects the actual cross arm experience bending deformation by shear stress during its operation in transmission tower. In the study, the dial gauges with magnetic holders were used as strain measuring instrument in both coupon and full-scale creep tests. These instruments were used since both creep tests were conducted in outdoor environment, which expose to uncontrolled humidity and temperature. However, the operation of strain gauge with data loggers requires special tools and facilities (conducive environment and work space). In terms of data replication, the three-point flexural tests were carried out with four replications for each material, which showed almost similar creep trends. This showed that the cantilever beam creep test for full-scale cross arm could be done only once. The cantilever beam creep test was carried out once due to limitation of test rig which can run only once at a time, the safety issues of handling large structure on the operator, and both cross arms were obtained directly from manufacturers.

This study on the cross arm was applying the cantilever beam principle due to previously published work by Tian et al. (2016). The assumption of the cross arm can be simplified as a cantilever beam due to downward force and transverse deflection. In this work, Balau wood and PGFRP composite cross arms for 132 kV transmission tower have the same original geometry and dimensions used by TNB. The cross arms for 132 kV transmission tower studied as the structural sizes were comparatively small compared to 275 kV and 500 kV, and the 132kV cables were widely available in many transmission lines. In the meantime, Balau wood timber was chosen instead of Chengal wood in this project since both woods exhibited the same mechanical and physical properties with wide availability, but less costly for Balau wood timber. Both Balau wood and PGFRP composite cross arms were fabricated from industrial timber and composite manufacturers which followed the exact industrial quality. The bracing in cross arm structure was implemented based on the design developed by Sharaf et al. (2020). From the bracing design, it was embedded in the cross arm to evaluate the influence of bracing on creep properties of both wood and composite cross arms. Thus, the main focus of this work focus involve the development of creep test rig specialized for cross arm and study of creep behaviour of cross arm in latticed transmission tower.

1.6 Structure of thesis

This thesis is composed of five chapters starting from Chapter 1 (Introduction), and ends with Chapter 5 (Conclusion and Recommendation). For the first chapter, it describes the overall introduction for this research, which mainly consists of research background, problem statement, research objectives, research scopes, significance of study, and overall thesis structure. Chapter 2 demonstrates the literature review relevant to the research conducted, focusing on recent studies and issues related to cross arms, product developments, current creep experiments and numerical analyses. For Chapter 3, it elaborates the overall research methodology and specific methods used to execute this research, including the product development process, materials used, fabrication and creep characterisation processes involving cross arm structure. Chapter 4 narrows the results and analyses obtained from the experiments along with their discussions. Lastly, Chapter 5 delivers the overall and specific conclusion of this research as well as future work recommendations.

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BIODATA OF STUDENT

Muhammad Asyraf bin Muhammad Rizal was born on the 2nd December 1996 at Ampang, Selangor. He received his high school education at Sekolah Menengah Islam Al-Amin Bangi, Selangor from 2009 to 2013. Later, he continued his study in Foundation of Agricultural Science at Universiti Putra Malaysia from 2013 to 2014. In 2014, he was awarded the JPA *Program Ijazah Dalam Negara* (PIDN) scholarship to pursue his Bachelor's Degree (BEng) in Mechanical Engineering at Universiti Putra Malaysia. He has been awarded with first class honors in his Bachelor of Engineering (Mechanical) and *Anugerah Pelajaran Diraja* (Royal Education Award) from *Majlis Raja-Raja Malaysia* (Conference of Rulers). After his finishing BEng program in 2018, he proceeded to undertake Doctorate (PhD) degree in Material Engineering at Faculty of Engineering, UPM. In 2019, he was again awarded the JPA *Program Pelajar Cemerlang* (PPC) to aid and support his doctorate studies. Along his doctorate study, he has been awarded with Best Speaker Award and Best Paper Award in Seminar Enau Kebangsaan 2019 by Persatuan Pembangunan dan Industri Enau Malaysia (PPIEM). His main interests are: (1) Composite material (Polymers, Fibers, Polymeric composites); (2) Creep characterization and analysis (Cantilever beam creep, Flexural creep, and Creep numerical modelling) and (3) Concurrent Engineering (Conceptual design, problem solving technique, MCDM, CAD). He has authored and published more than 40 citation indexed journals on design developments, composite materials and material characterizations. He was also authored and co-authored 1 book, 5 book chapters and 12 conference proceedings/seminar papers/research bulletin.

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