PERFORMANCE OF PULTRUDED GFRP COMPOSITES UNDER TROPICAL CLIMATE

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To my beloved mother – ***Robiah Ibrahim****, late father –* ***Mohamad Yatim Manap****, wife –* ***Azmahani Abdul Aziz*** *and children –* ***Siti Nadiah****,* ***Muhammad Syahir****,* ***Nurulaina****,* ***Anis Hazwani*** and ***Nur Asilah***.

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ABSTRACT

Glass fibre reinforced polymer (GFRP) is a composite material, which consists of polyester thermosetting resin as matrix and glass fibres as reinforcement. GFRP is mainly used as structural sections and as structural rehabilitation and repair material. It is observed that the current required technical and design data of pultruded GFRP sections is rather limited especially with regard to material properties and its performance in the tropical climate. Therefore, this study is conducted experimentally to investigate the engineering properties of the GFRP material and sections, and its performance to the local tropical climate. Special observations on the effects of the fibre orientations and stacking sequences in laminates are also made. Testing procedures are basically in accordance with the requirements of the American Standard of Testing and Materials (ASTM), and the British Standards (BS). There are six different fibre orientations of GFRP plates and two different fibre orientations of GFRP box sections of 6.35 mm nominal thickness with different stacking sequence selected for the test samples. They were fabricated by local manufacturer according to the commercial quality requirements. A total of 2304 GFRP samples were tested, 1152 of the samples were exposed to the outdoor environment, while the other 1152 samples were kept in the laboratory environment as control samples. The samples were tested for physical and mechanical performance. Among the visual observations made were the surface appearance, thickness variation and weight gain. Samples were also tested for tension, compression and in-plane shear to indicate the mechanical performance. Measurements were taken at 3, 6, 12 and 24 months period of exposure to weathering. Four point bending tests were also conducted on 900 mm span of GFRP box section beams to investigate the structural performance under tropical weather. Twenty-four beams were tested for this purpose after being exposed to the outdoor environment and the other twenty-four beams were tested under controlled environment. The statistical test data were analysed using Weibull distribution. The test results showed that the GFRP material is significantly affected by tropical weather conditions. In general, surface degradation was significant after 12 months exposure due to fungal attack. Surface roughness and discoloration on the top surface of the samples were also observed with the bottom surface not affected by the exposure at all. The effect of tropical weather conditions on mechanical performance of the exposed GFRP samples was significant, but varied with fibre quantity. The reduction in flexural capacity of GFRP box beams was also observed due to weathering after a period of 24 months. Ultimately, the mechanical properties and structural beam performance with respect to the period of exposure under tropical weather was formulated and presented at the end of this study.

ABSTRAK

Polimer bertetulang gentian kaca (GFRP) ialah bahan komposit yang terdiri daripada resin polyester termoset sebagai matriks dan gentian kaca sebagai tetulang. GFRP digunakan terutama sebagai anggota struktur dan pemuliharaan struktur dan bahan baikpulih. Berdasarkan perkembangan terkini, keperluan data teknikal dan reka bentuk bagi keratan GFRP telah dikenalpasti amat terhad terutama daripada segi sifat bahan dan keupayaan terhadap iklim tropika. Oleh yang demikian, kajian secara ujikaji makmal ini dijalankan untuk mengkaji sifat-sifat kejuruteraan bahan dan keratan GFRP, dan keupayaan terhadap iklim tropika. Pemerhatian khusus juga dilakukan ke atas pengaruh orientasi dan susun atur gentian di dalam laminat. Tatacara ujikaji merujuk kepada kaedah yang disyorkan dalam piawaian-piawaian Amerika (ASTM) dan British (BS). Enam reka bentuk keratan plat GFRP dan dua reka bentuk keratan kekotak GFRP dengan ketebalan nominal 6.35 mm yang berbeza daripada segi orientasi dan susun atur gentian telah dipilih sebagai sampel ujian. Keratan GFRP telah difabrikasi dan dibekalkan oleh pengeluar tempatan berpandukan kehendak kualiti pasaran. Sejumlah 2304 sampel GFRP telah diuji, yang mana 1152 sampel dikenakan dedahan luar manakala 1152 sampel lagi untuk dedahan normal dalam makmal sebagai kawalan. Semua sampel diuji untuk prestasi fizikal dan mekanikal. Kajian tinjauan visual dijalankan termasuk perubahan rupa bentuk permukaan, ketebalan dan capaian berat sampel. Sampel juga diuji untuk sifat-sifat tegangan, mampatan dan ricih satah untuk mengkaji pengaruh dedahan luar ke atas prestasi mekanikal bahan. Pemantauan dilakukan ke atas sampel untuk tempoh dedahan selepas 3, 6, 12, dan 24 bulan. Ujian lenturan empat titik juga dijalankan ke atas rasuk keratan kekotak GFRP dengan rentang 900 mm untuk mengkaji pengaruh dedahan cuaca tropika terhadap keupayaan rasuk. Untuk tujuan ini, dua puluh empat sampel rasuk telah diuji untuk dedahan luar manakala dua puluh empat sampel rasuk lagi diuji sebagai kawalan. Data ujian dianalisis menggunakan kaedah statistik Weibull. Keputusan ujian telah menunjukkan bahawa bahan GFRP mengalami kesan yang ketara disebabkan dedahan cuaca tropika. Secara umum, kesan degradasi yang ketara ke atas permukaan sampel telah dikenalpasti berlaku selepas 12 bulan disebabkan serangan kulat. Terdapat juga kesan kekasaran permukaan dan ubah rupa warna pada permukaan atas sampel, tetapi tidak ketara pada permukaan bawah sampel. Kesan ke atas prestasi mekanikal sampel dedahan luar didapati amat ketara, tetapi berubah-ubah dengan kuantiti gentian. Pengurangan dalam keupayaan lentur rasuk kekotak GFRP juga dikenalpasti berlaku selepas tempoh dedahan 24 bulan. Rumusan bagi sifat-sifat mekanikal bahan dan prestasi rasuk GFRP terhadap tempoh dedahan kepada iklim tropika telah diterbitkan dan diperincikan di peringkat akhir kajian.

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LIST OF SYMBOLS

ρ_c - Density of GFRP laminate

ρ_m - Density of matrix (cured polyester resin)

ρ_f - Density of fibres

V_f - Fibre volume ratio

V_r - Resin volume ratio

V_v - Void volume ratio

V - Total volume or volume of composite laminate

W_f - Fibre weight ratio

W_r - Resin weight ratio

W - Total weight or weight of composite laminate

T - Time in year(s)

σ_{TLo} - Longitudinal tensile strength at initial ($T = 0$)

σ_{TTo} - Transverse tensile strength at initial ($T = 0$)

σ_{TL} - Longitudinal tensile strength after periodic exposure

σ_{TT} - Transverse tensile strength after periodic exposure

E_{TLo} - Longitudinal tensile modulus at initial ($T = 0$)

E_{TTo} - Transverse tensile modulus at initial ($T = 0$)

E_{TL} - Longitudinal tensile modulus after periodic exposure

E_{TT} - Transverse tensile modulus after periodic exposure

$\varepsilon_{\mathrm{TLo}}$ - Longitudinal tensile strain at failure at initial ($T = 0$)

$\varepsilon_{\mathrm{TTo}}$ - Transverse tensile strain at failure at initial ($T = 0$)

$\varepsilon_{\mathrm{TL}}$ - Longitudinal tensile strain at failure after periodic exposure

$\varepsilon_{\mathrm{TT}}$ - Transverse tensile strain at failure after periodic exposure

σ_{CLo} - Longitudinal compressive strength at initial ($T = 0$)

σ_{CTo} - Transverse compressive strength at initial ($T = 0$)

σ_{CL} - Longitudinal compressive strength after periodic exposure

σ_{CT} - Transverse compressive strength after periodic exposure

E_{CLo} - Longitudinal compressive modulus at initial ($T = 0$)

E_{CTo} - Transverse compressive modulus at initial ($T = 0$)

E_{CL} - Longitudinal compressive modulus after periodic exposure

E_{CT} - Transverse compressive modulus after periodic exposure

$\varepsilon_{\mathrm{CLo}}$ - Longitudinal compressive strain at failure at initial ($T = 0$)

$\varepsilon_{\mathrm{CTo}}$ - Transverse compressive strain at failure at initial ($T = 0$)

$\varepsilon_{\mathrm{CL}}$ - Longitudinal compressive strain at failure after periodic exposure

$\varepsilon_{\mathrm{CT}}$ - Transverse compressive strain at failure after periodic exposure

τ_{SLo} - Longitudinal in-plane shear strength at initial ($T = 0$)

τ_{STo} - Transverse in-plane shear strength at initial ($T = 0$)

τ_{SL} - Longitudinal in-plane shear strength after periodic exposure

τ_{ST} - Transverse in-plane shear strength after periodic exposure

G_{SLo} - Longitudinal in-plane shear modulus at initial ($T = 0$)

G_{STo} - Transverse in-plane shear modulus at initial ($T = 0$)

G_{SL} - Longitudinal in-plane shear modulus after periodic exposure

G_{ST} - Transverse in-plane shear modulus after periodic exposure

γ_{SLo} - Longitudinal in-plane shear strain at failure at initial ($T = 0$)

γ_{STo} - Transverse in-plane shear strain at failure at initial ($T = 0$)

γ_{SL} - Longitudinal in-plane shear strain at failure after periodic exposure

γ_{ST} - Transverse in-plane shear strain at failure after periodic exposure

σ_{tl} - Longitudinal tensile stress

σ_{tt} - Transverse tensile stress

σ_{cl} - Longitudinal compressive stress

σ_{ct} - Transverse compressive stress

τ_{sl} - Longitudinal in-plane shear stress

τ_{st} - Transverse in-plane shear stress

ε_{tl} - Longitudinal tensile strain

ε_{tt} - Transverse tensile strain

ε_{cl} - Longitudinal compressive strain

ε_{ct} - Transverse compressive strain

γ_{sl} - Longitudinal in-plane shear strain

γ_{st} - Transverse in-plane shear strain

λ_T - Property retention ratio at time, T

K_t - Weathering coefficient of tensile properties

K_c - Weathering coefficient of compressive properties

K_s - Weathering coefficient of in-plane shear properties

b_f - Width of flange

b_w - Depth of web

t_f - Thickness of flange

t_w - Thickness of web

A - Total cross sectional area

A_w - Area of web element (s)

f_s - Shape factor

D - Bending stiffness of beam

F - Shear stiffness of beam

σ_c - Maximum compressive stress at top flange of beam

δ_{mid} - Deflection at the mid span of beam

$P_{ult}^{bending}$ - Ultimate failure load due to bending (theoretical)

P_{ult}^{shear} - Ultimate failure load due to shear (theoretical)

P_{act} - Actual ultimate failure load obtained from the test

P_{pred} - Calculated ultimate failure load from theory

CHAPTER I

INTRODUCTION

1.1 General

Since 1990s, the use of the glass fibre reinforced polymeric composites in the construction industry has grown very rapidly especially in developed countries. The applications of the composite material are mainly in building structures, bridges, offshore structures, etc.

The development of the material in the construction industry in Malaysia is still at its infancy. In local current applications, the use of the material is only visible in marine and aircraft technology, and chemical industries where fabrication process are employed mainly by close- and open-moulded techniques. But, in the construction industry, the existing fabrication technology can also be employed to fabricate structural components. The material has been used for secondary structures such as water tanks, light poles, platform gratings, beams, cladding and piping.

The composite material has been slowly being accepted locally as an alternative construction material due to its ability to sustain structural loads comparable to the existing conventional materials such as concrete, steel and timber. Generally, the composite material is non-corrosive and dimensionally stable; it has an advantage that fulfils the durability aspects for the applications. However, study on the durability of GFRP materials is still new and more data are required from a wide range of weather conditions especially the tropical climate. Previous studies on the GFRP composite materials indicated that there were some basic understandings on the variations of material properties as a guide for in-depth studies. The material properties depend on several factors, such as:

i) the fabrication process or method of manufacturing,
ii) the type of reinforcement fibre,
iii) the fibre orientation and stacking sequence,
iv) the type of resin used as a matrix,
v) the environmental conditions, and
vi) the method of testing.

These parameters affect the properties of end products and must be carefully selected to ensure suitability of the final applications.

1.2 Background and Rationale of the Project

Glass fibre reinforced polyester (GFRP) pultruded composite consists of polyester resin (thermosetting polymer) as a matrix and glass fibre as reinforcement. It is manufactured through a continuous pultrusion process to form structural sections. During the manufacturing process, the form(s) of continuous glass fibres are pulled from one end of the line into a resin bath that contains liquid polyester resin, curing agent (initiator), and other ingredients. The fibre-resin is then passed through in the heated die for curing to form a hard, solid and continuous structural section.

In structural applications, pultrusion process is considered the most practical and economical manufacturing method for producing structural sections, as compared to other methods because it is able to produce sections in continuous uniform shapes. The process can also produce prefabricated components in various shapes such as hollow sections, I-sections, H-sections and many more according to the requirement of the consumers. Prefabrication of components is a key feature of the present dominant technologies; thus the pultrusion process offers greater scope to prefabricated components.

Pultruded GFRP is categorised as a high-performance composite material due to its ability to sustain structural loading. In addition, it has the advantages of high strength-weight ratio, dimensional stability, and with the right selection of resin formulation, will give good weathering properties, chemical resistance, electrical properties, fire and heat resistance.

Presently, due to the rapid development of fibre systems in continuous forms, the desired property data of pultruded GFRP sections must be concurrently developed. The properties of pultruded GFRP materials would largely depend on process parameters such as resin viscosity, running speed and thermal application on the die during the process. Thus, manufacturers must decide the adequate process parameters to ensure a good quality of material and compliance with consumer's requirements. At this stage, the technical know-how and experience of manufacturers on the processing system are often played the important roles.

In present applications of GFRP, the use of gel coat as a finished layer on the hand-laid up products have been applied successfully to improve the durability of the materials. But for pultruded GFRP sections, the employment of gel coat as a finished layer is impractical since it would cause non-uniformity in shapes and dimensions. Therefore, as an alternative solution, manufacturers usually apply a modified resin to improve sustainability to the environmental. However, the effectiveness of the modified resin ingredient is questionable since the exposed surface is still unprotected. Instead, besides applying the modified resin system, the contribution of fibres in terms of quantity or volume ratio and arrangement systems in the GFRP materials has also to be considered. With the optimum quantity and proper arrangement system of fibres in the material will probably improve sustainability to the environment or weather. The fibres may act as filler in the material to minimise deterioration effects due to environmental factors or weathering. Since, it is still as a hypothesis, an in-depth study has to be conducted to collect adequate data to support the argument.

It is understood that environmental factors such as temperature, humidity and ultraviolet rays may have some influence on the durability of GFRP. The common features of tropical hot-wet weather in Malaysia are high humidity and frequent sunlight. As the sections are exposed to this weather, their properties may change with time. Thus, this phenomenon will adversely affect the overall performance of GFRP. To utilise the full potential of GFRP sections their response to the weather must be observed. This is conducted experimentally under indoor and outdoor laboratory studies.

For the purpose of this study, it is essential to assume that some climatic factor will affect the physical and mechanical properties of GFRP. The total variation in the properties may be due to the integrated effect from these factors. The physical features of the sections may change due to chemical reactions between the constituents and factors such as moisture, temperature, solar radiation (ultra violet), acid rain and some gases that exist in atmosphere. Consequently, the changes in physical properties will cause variation in mechanical properties of the material considered in structural design such as tension, compression and shear. As a result, the changes in properties of weathered GFRP will affect their long-term performance.

Insufficient test data is observed and reported by the previous researchers. There are some important issues that need to be addressed and studied in depth with regard to the durability particularly of the pultruded GFRP materials and sections for future applications, such as:

i) The material properties in both principal directions, longitudinal and transverse,
ii) The properties of multilayer fibre laminates of pultruded GFRP,
iii) The material performance to the tropical climate in order to establish the durability of material,
iv) The overall material and structural performance under exposed tropical climate, and
v) Establishing the appropriate test methods.

1.3 Overall Objectives and Scope of the Study

1.3.1 Objectives of the Study

The main objectives of the study are:

1) to characterise the engineering properties of pultruded GFRP sections produced by a local manufacturer, and establish structural design data of pultruded GFRP sections with regard to continuous glass fibres for structural applications,

2) to study the effect of continuous glass fibres and orientations on the physical and mechanical properties of pultruded GFRP sections,

3) to investigate the long-term durability of pultruded GFRP sections exposed to tropical climate,

4) to study the structural performance of pultruded GFRP box beams exposed to tropical climate in association to the material performance,

5) to propose and validate empirical models in GFRP structural design with regard to continuous glass fibres and its applications in tropical climate.

1.3.2 Scope of the Study

The scope of the study was established to fit into the desired objectives and the period of weathering exposure. The study was mainly focussed on experimental work in laboratory. All testing activities were subject to actual tropical climate except for the certain procedures already specified by referred standards of practice.

For the purpose of study, the isopthalic polyester resin, Crystic 491E produced by Scott Bader Comp. Ltd., UK was employed. The continuous E-glass type fibres, which were compatible with the polyester resin, were used as reinforcements. The pultruded GFRP plate bars of 76.2 mm width and 6.35 mm thickness, and square hollow sections of 76.2 mm depth by 76.2 mm width and 6.35 mm thickness (3 in. by 3 in. by 0.25 in.) were manufactured and supplied by a local fabricator.

The pultruded GFRP plate bars were fabricated in six-laminate systems consisting of three different single oriented fibre laminates (or single layer fibre laminates) and three different combined oriented fibre laminates (or multilayer fibre laminates) as follows:

i) unidirectional roving,
ii) continuous filament mat,
iii) woven roving,
iv) the multilayered fibres of continuous filament mat and unidirectional roving laminate,
v) the multilayered fibres of woven roving and unidirectional roving laminate,
vi) the multilayered fibres of continuous filament mat with unidirectional and woven roving laminate.

All the multilayer fibre laminates were of balance laminate. The samples were prepared in specified sizes to test their physical and mechanical properties according to the existing standards of practice, such as American Standard of Testing and Materials, British Standard BS 2782, and some other recommended test procedures proposed by previous researchers.

The experimental program was briefly divided into two major parts. In the first part, the study on initial performance of pultruded GFRP was established by conducting elementary tests on physical and mechanical properties of the GFRP. The physical property tests included density, constituent content, dimensional tolerances and variation, water absorption and hardness were carried out. The mechanical property tests included strength and elastic properties in tension, compression, and in-plane shear. The second part of the experimental program was exposure tests of the GFRP samples under out-door tropical climate, which was set up after the first part had been completed. Another group of GFRP samples was subject to room environment as a control. The samples were exposed for 3, 6, 12 and 24 months and tested for physical and mechanical properties. In order to verify the effects of tropical climate on the structural performance of GFRP section, flexural test was conducted on GFRP box beams under four-point loading system. Only two laminate systems of GFRP beams were employed for the test. They were continuous filament mat to represent single layer fibre laminate, and multilayer fibre laminate consisting of continuous filament mat with unidirectional roving and woven roving fibres.

1.4 Conclusion

The current development of GFRP materials in the construction industry has tremendously grown especially in the developed countries since 1990s. But their use in Malaysian industries is still at infancy due to insufficient database on the material properties and durability aspects. Environmental factors have significant effects on the physical and mechanical properties of GFRP materials; normally reducing the properties on long term exposure.

For structural applications, the pultruded GFRP sections are most practical since the system are produced in uniform prefabricated sections with various shapes and sizes. The materials have been developed to increase their ability to sustain primary loads by improving on the production technology from time to time. In addition, their durability to sustain environmental factors must also be simultaneously improved in various weather conditions. There are many specific areas, in facts that require proper in-depth studies on the durability of GFRP pultruded materials. This may assist the fabricator and engineers to improve the material quality and provide established database for design works in the future.

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