DEVELOPMENT OF GRAPHENE-HYBRID COMPOSITE HYDROGEN PRESSURE TANK FOR GAS STORAGE APPLICATION

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Abstract

This paper presents a study on the use of a graphene-carbon fibre hybrid composite in the development of compressed hydrogen pressure vessels. The study aims to minimize the materials and thickness used in the fabrication process while maintaining the pressure containment capability and structural integrity of the vessel. The research uses chemically functionalized graphene nanoplatelets as an additive reinforcement in the composite system and tensile ring test to evaluate the performance of ring tensile samples to act as a surrogate to pressure vessel walls. The study investigates the optimum percentage of graphene to be used in the pressure vessel system to make the application of graphene feasible and cost-effective.

The research methodology involves the mixing of acquired graphene in an epoxy resin and depositing it onto the filament winding line during manufacture of cylinder structures. An inline graphene coating technique is leveraged to deposit the resin-graphene mixture onto the surface of the filament prior to winding sequence. The technique involves retrofitting an automated fibre coating system with a novel mixing nozzle that allows for metering, mixing, and dispensing multi-component fluid and graphene materials for in-line dry fibre winding. This technique reduces manual handling and time for graphene dispersion, thus automating production to maintain distribution quality.

The findings indicate graphene concentration of 0.1 wt% to 0.3 wt% relative to the resin weight in the composite, the vessel can attain a burst capacity that is 35% higher compared to the unenhanced composite system. Graphene additives provide improved tensile load performance, making it a potential option to reduce utilization of carbon fibre in composite pressure vessels. However, the research argues that graphene additives must, however, be less expensive to be deposited onto composite pressure vessels than the original carbon fibre composite system for it to be a commercially viable option. For graphene to successfully be implemented in pressure vessel applications, uniform intra-tow, and inter-tow graphene distribution inside the matrix composite remains a crucial factor that affects the mechanical performance of pressure vessel. The findings of this study provide supplementary information to the existing body of literature that can benefit composite advocates and introduce graphene application in composite pressure vessel applications.

1. INTRODUCTION

Pressure vessels for hydrogen storage is one of the fastest growing sectors in the composite industry [1-3]. After the pandemic, China, Europe, and North America have all expressed a major regulatory interest in decreasing carbon emissions from mobility applications [4-7]. California has rules in place to prohibit the sale of gas-powered automobiles by 2035, and is responsible for a large portion of the decarbonization effort in the United States [5]. Considering hydrogen cost of USD 2 - 6/kg, if there is worldwide adoption of H_2 in the years ahead, up to USD 20 billion market is a reasonable estimated value of the role hydrogen will play in the race to reduce global emissions [6]. The global demand for carbon fibre experienced a decline during the pandemic era, but it is projected to increase in the coming years due to the emerging demand for pressure vessels for hydrogen storage, wind energy, and commercial air travel recovery. However, carbon fibre manufacturers may struggle to meet the new

spike in demand and will require solid commitments from their clientele and a steady tangible demand of the hydrogen supply chains. This is where graphene comes in as an additive to potentially optimize the use of virgin carbon fibres in storage vessels.

Since graphene was discovered in 2010, it has been associated with improvements in mechanical, barrier and long-term properties of Fibre Reinforced Polymer (FRP) composites for structural applications [8, 9]. Additionally, researchers have attempted to add graphene into carbon fibre materials to yield a commercially viable product [10, 11]. By adding graphene, it is possible to improve the mechanical properties of the composite material and reduce the thickness of the vessel, resulting in increased volumetric capacity. The use of graphene can also help to reduce the amount of virgin carbon fibres required to manufacture the vessel, which in turn can reduce the carbon intensity of the produced tank. Additionally, it is noted that there is increasing demand for carbon fibres for hydrogen storage applications, which may pose a challenge to manufacturers who need to expand their production capacity to meet demand while complying with emissions regulations.

Therefore, application of graphene has the potential to be expanded to include composite applications that requires service conditions in extreme temperatures, harsh climates, and high-pressure conditions. The purpose of this paper is to present findings and analysed outcomes in the development of a graphene-hybrid composite utilizing the experimental inline coating technique for compressed hydrogen pressure vessel. We studied the application of chemically functionalized graphene nanoplatelets as reinforcement in the composite system. Ring tensile test are conducted as a surrogate to burst test and preliminary findings and insights are analysed, presented, and discussed. The results provide substantive information to the existing body of literature that demonstrate the benefit of graphene as additive in composite pressure vessel application.

2. RESEARCH OBJECTIVE

The purpose of this study is to conduct a proof-of-concept utilization of graphene additives to improve the pressure containment capability of hydrogen pressure vessels.

- Optimize materials used for fabrication of pressure vessels through filament winding by graphene addition.
- Determine performance of graphene-coated pressure vessels compared to control composite pressure vessels.
- Investigate the optimum percentage of graphene and type of graphene to improve the pressure vessel system relative to the control pressure vessel in similar conditions.

3. RESEARCH METHODOLOGY

3.1 Graphene and Pre-Treatment Mixing Technique

An amine-functionalized graphene, as illustrated in Figure 1, was acquired and mixed in an epoxy resin system. The acquired graphene details are as follows:

Table 1: Technical parameter of Amine-functionalized graphene

Properties	Description
Thickness (z-axis)	5 to 10 nm
Average lateral dimensions (x-y axis)	5 to 10 nm
Number of layers	5 to 10
NH_2 ratio	~ 2% to 5%
Bulk density	0.45 g/cm^3
Surface area	60 – 200 m^2/g

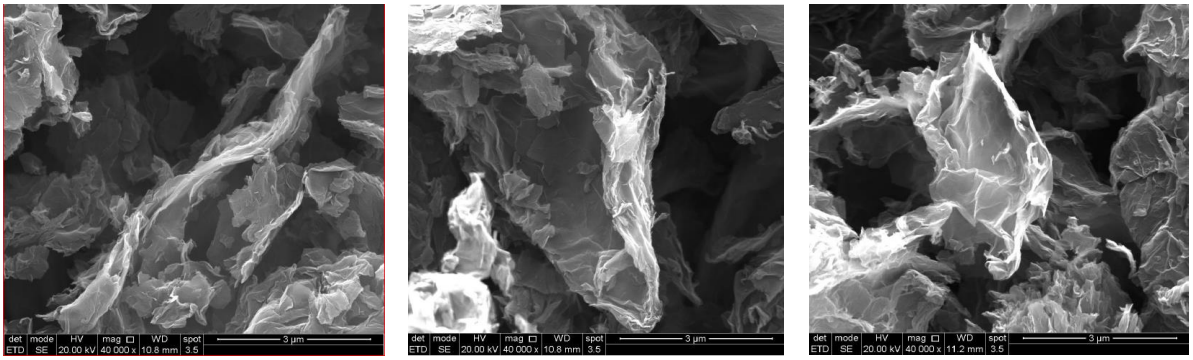

Figure 1: SEM images amine-functionalized graphene at 40,000x.

The technique of adding graphene in viscous material is based on the work of Yao et al [9] which demonstrated vacuum mixing of graphene in epoxy can uniformly distribute graphene material in the solvent. In this study, 30 g of graphene was mixed in 1 litre of acetone (depending on the concentration required). Next, the functionalized graphene-solvent mixture undergoes ultrasonication (37 kHz) for at least 30 minutes. Next, the mixture was combined with the resin and undergo high shear mixing at a rate of 400 RPM. Afterwards, the resin-solvent-graphene mixture is left overnight to enable the acetone to evaporate. After 12 hours of settling, the resin-graphene mixture again undergoes high shear mixing at 400 RPM for 15 mins followed by degassing. After all the pre-treatment to make sure distribution of graphene in the resin system, the resin with graphene additive is poured into the resin tank in the inline graphene coating (IGC) metering system. The resin is continuously stirred, and temperature is maintained at 60°C throughout the system. The IGC is connected to the filament winding machine via a mixing tee. This enables the resin epoxy system to be uniformly coated with the filament prior to the automated winding process.

3.2 Carbon Fibre Material and Epoxy System

A commercially available carbon fibre and epoxy resin system are utilized in this research. The fibre consists of unidirectional Toray T700 12K filament count combined with Araldite LY564 epoxy and Aradur 22962 hardener. The resin/hardener components are weighed, and the mix ratio of component is set at 100:32 resin-hardener ratio for all samples. The fibre volumetric ratio is calculated at 0.51 for the samples.

Table 2: Properties of procured unidirectional carbon fibre and epoxy [12, 13]

Properties	Carbon Fibre	Epoxy
Tensile strength (MPa)	4900	75-80
Tensile Modulus (GPa)	230	2.8 to 3.3
Elongation at break (%)	2.1	3.5 to 8.0
Density (g/cm^3)	1.80	1.1-1.2
Filament diameter (microns)	7	-
Flexural strength (MPa)	1670	124 to 132

3.3 Experimental Methods

Samples are manufactured at five different concentrations of graphene: 0.1%, 0.3%, 0.5%, 1.0% and 2%, alongside control samples. The percentage of graphene added in the epoxy system is calculated based on the weight of the resin utilized in the filament winding process. Subsequently, three circular specimens are prepared for each concentration from the 700 mm cylindrical pipe fabricated with the inline graphene coating machine fitted onto a laboratory filament winding apparatus by cutting the long cylindrical sample into rings of similar geometric size for ASTM D2290 [14] ring tensile test.

The graphene is encapsulated onto the carbon fibre filament via an inline graphene coating dispensing machine. This automated fibre coating system is fitted with a mixing nozzle that integrates metering, mixing, and dispensing multi-component fluid and the nanomaterial for in-line fibre winding.

This concept of automated graphene addition with minor adjustment to the filament winding process is developed utilizing tanks, pumps, mixing gun and disposable mixing tube. The technique reduces manual handling and time for spraying graphene hence automates production towards maintaining consistent product quality. Graphene that has been mixed and dispersed during pre-treatment is added to the resin tank reservoir and constantly shear mixed with a built-in mechanical stirrer. Additionally, the temperature in the reservoir and along the line to the mixing gun is kept thermally constant with an external heater and insulated tubing.

The winding process consist of several layers in the hoop direction of winding to generate thickness of the cylinder. A 30 mm diameter cylindrical tube functions as a mandrel of the winding process. The winding sequence are repeated until ten layers of graphene infused filaments are formed on the cylindrical body. The ten layers of the cylindrical has an average diameter of 35.3 mm with average thickness of 1.85 mm. Subsequently, the cured cylindrical body is then proceeded to vacuum infusion before curing for 2 hours at 80°C continued by 8 hours in oven at 140°C post curing. Next, the completed composite cylinder is extracted and sliced into 25 mm width ring samples. Five ring tensile samples of corresponding concentration are generated for each graphene concentration. For comparison, a control sample without graphene is fabricated and tested under the same condition and apparatus. Ring tensile test were conducted, and the results were analysed and reported in the results section.

3.4 Testing

The testing conducted based on ASTM D2290-19a [14] which uses a split disc test fixture to compare the apparent tensile strengths of cylindrical geometry when tested under specific circumstances. For the test, a 600 kN universal tensile machine is utilized for this research. The force and displacement experimental data was extracted from the tensile machine and recorded for analysis.

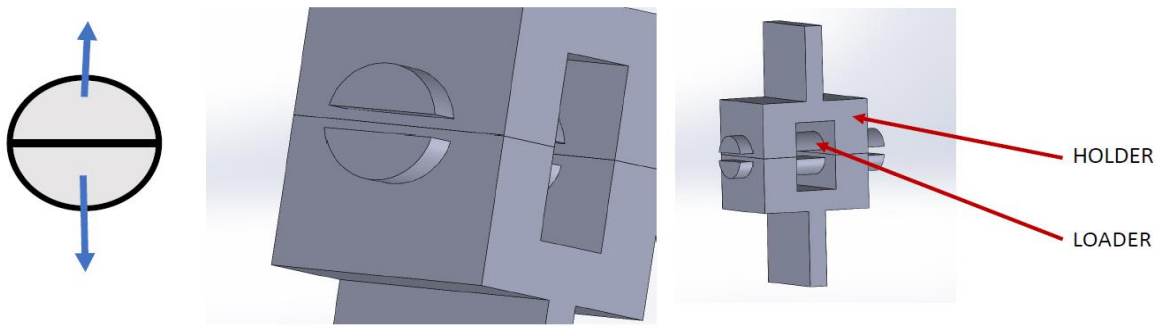

Figure 2: Test Fixture for Tensile Test as per ASTM D2290

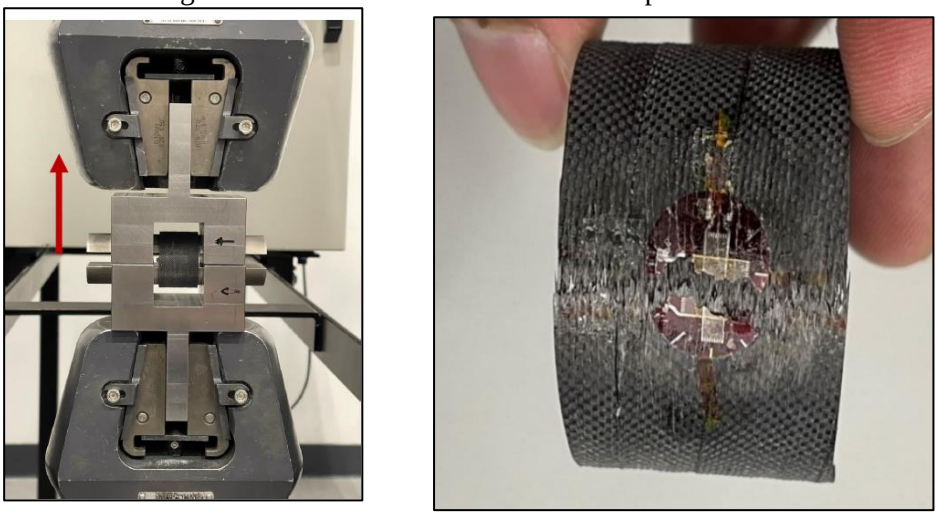

Figure 3: Illustration of test (left) and outcome on the sample tensile machine (right)

Prior to the start of the test, the width and thickness of the sample is measured utilizing a digital calliper and recorded to two significant figures. Next, the sample is mounted onto the rig being supported by the loader as shown in Figure 2. Once, the sample is securely mounted, the ring sample is ensured to aligned to the test fixture on the loader so that it is centred on the line joining the loader. Afterwards, the displacement speed of the tensile machine is set at 0.2 mm/s to exert vertical uniaxial load as depicted in Figure 3. The yield point, maximum load prior to failure, and maximum elongation at break is recorded. The test is repeated five times each for control, 0.1%, 0.3%, 0.5%, 1% and 2% graphene concentration samples.

All tensile tests were conducted until failure. The failure cross-section area occurred at the 3 o'clock and 9 o'clock position relative to the axial load direction. Therefore, the test samples result is considered acceptable and meaningful. Overall, sample with graphene indicated higher ability to withstand higher load compared to the control sample.

4. RESULTS

4.1 Tensile Test

Overall, there are 30 samples of 35 mm outer diameter of varying graphene concentration that are tested. The tensile failure load of each specimen and the maximum displacement extension are recorded, tabulated, and analysed. In the fabrication, it was observed that thickness of the composite under similar fabrication technique linearly increased with the percentage of graphene added in the resin. For example, the 2% graphene concentration sample is 12% thicker than the control sample thickness.

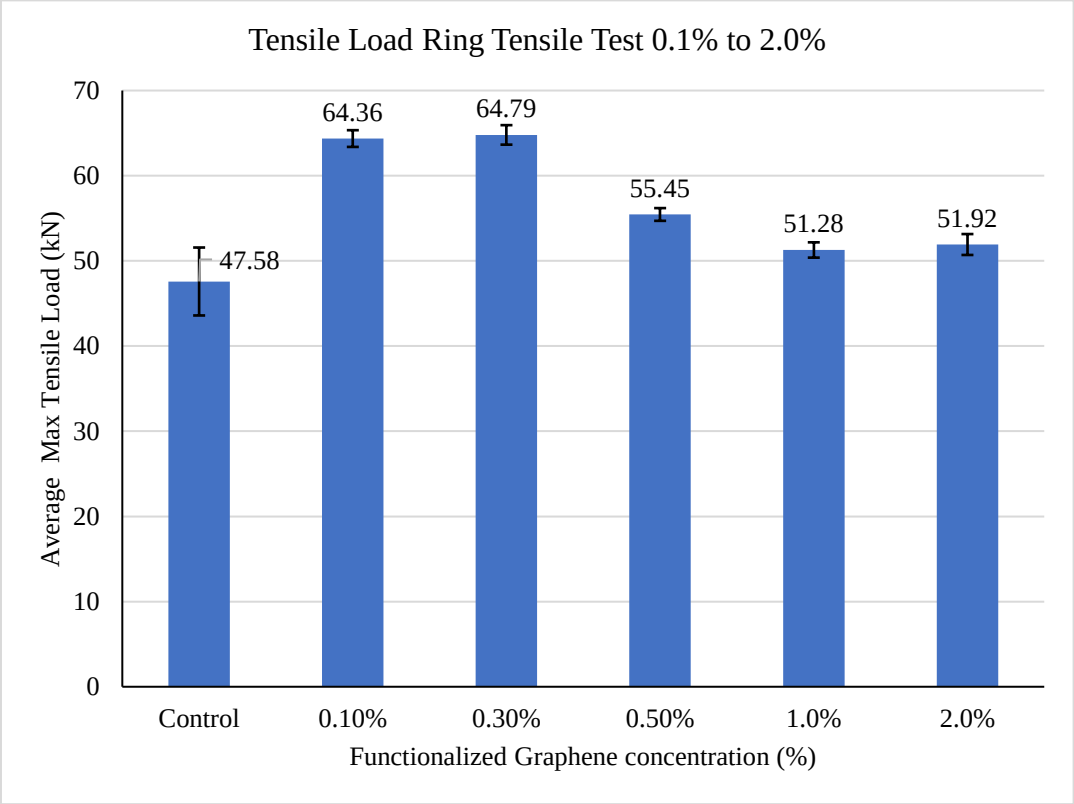

Figure 4: Tensile Ring Test of Graphene 0.5% to 2.0%

The ring tensile tests were conducted and results of tensile load over different graphene weight concentration are shown in Figure 4. The tensile load of the control sample was 47.58 kN. Meanwhile the loads undertaken by 0.1% and 0.3% are 64.36kN and 64.79kN respectively. Meanwhile, the load of 0.5% graphene translates to max tensile load of 55.45 kN, 1.0% of graphene is 51.28 kN and for 2.0% graphene is 51.92 kN respectively. In general, incorporation of graphene in the resin matrix produced

improvement in the composite performance were better than the control sample. The most significant improvement in tensile performance is seen in 0.1% to 0.3% graphene concentration by 35% compared to unmodified composite sample. However, increasing the additive content does not necessarily increase the materials ability to withstand more load. This is observed in reduction of tensile load in graphene concentration 0.5% and higher. This reduction in performance may be attributed to the uneven dispersion of graphene in the matrix system. The inhomogeneous distribution leads to localized stress concentration area within the composite matrix that leads to recorded failure at lower loads. Additionally, the dispersion of graphene in between the tows and within the tows needs further investigation as well as refinement of the dispersion technique during the mixture of the additive in the resin and hardener system.

In essence, the total performance of composites is determined by the qualities of the optimal additive-to-epoxy ratio and its interfacial bonding. Strong covalent and non-covalent bonding between the fibre and the polymer matrix is critical for achieving excellent load transmission from the resin to the composite fibres [8, 15]. In this case, it can be inferred that, with uniform distribution at a certain concentration, the deposition of graphene in the matrix aided in improvement of the composite to withstand additional deformation prior to break. This effect can be linked to graphene's enhancement of interfacial shear strength of fibre composites by boosting adhesive strength at the interface and limiting the fracture propagation pathways [8, 16].

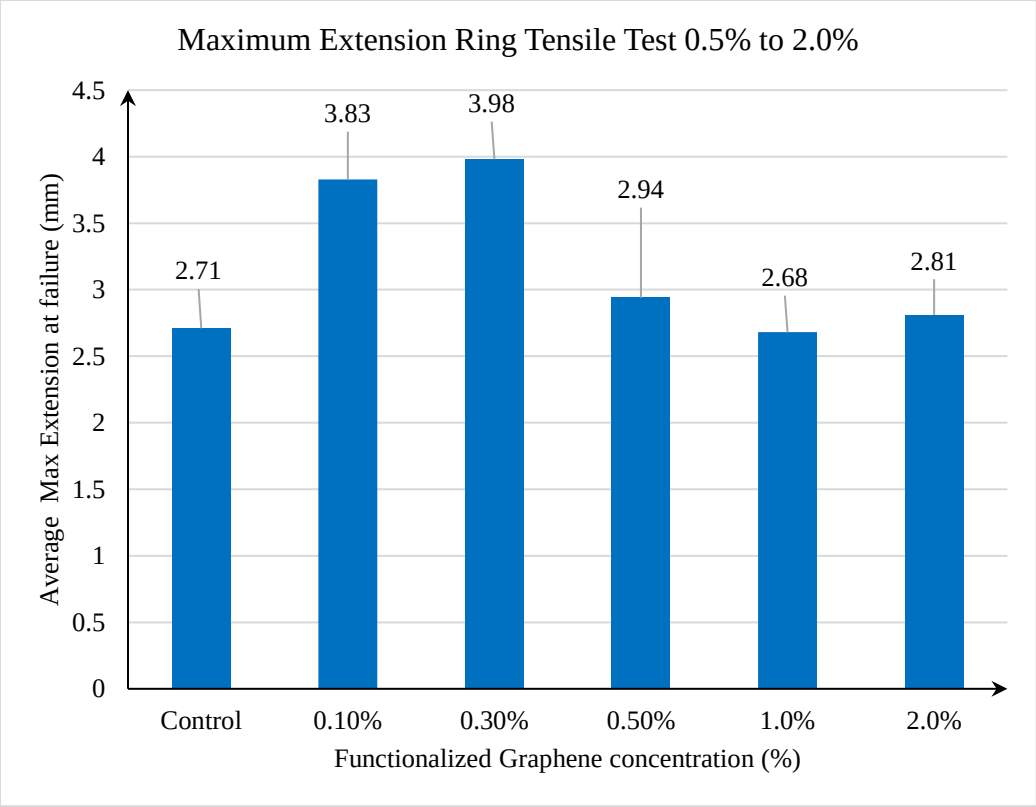

Figure 5: Maximum Extension Ring Tensile Test

On the other hand, Figure 5 describes the maximum extension (crosshead displacement) of the samples prior to failure. The samples with 0.3 wt% graphene recorded 46% higher maximum extension prior to failure compared to control samples. Meanwhile, 1.0% graphene exhibited a reduction of maximum extension by 1% and 2% graphene recorded a 2.81 mm extension compared to the composite sample without any graphene. The failure of the ring due to extension is correlated to the tensile load due to graphene addition. Similarly, distribution of graphene within the composite matrix is a crucial factor to increase the mechanical performance of the pressure tank walls under loads.

4.2 Electron Microscope Images

The analysis proceeded with Spectro-Electron Microscopy (SEM) images to determine the distribution of amine-functionalized graphene within the composite matrix of the manufactured composite cylinder. SEM depicts high-resolution images of graphene distribution in 2.0% wt distribution of graphene magnified from 500x to 6000x in the axial section in the composite system. At 500x, the carbon fibre filament is represented by near spherical shape. Furthermore, there are air bubbles in several pockets/trapped air orifice detected representing defects in manufacturing. Graphene nanoplatelets can be seen at 6000x magnification in between the filament indicating that graphene is disperse in the resin matrix. Amine functionalized graphene appear to behave like a membrane in the resin

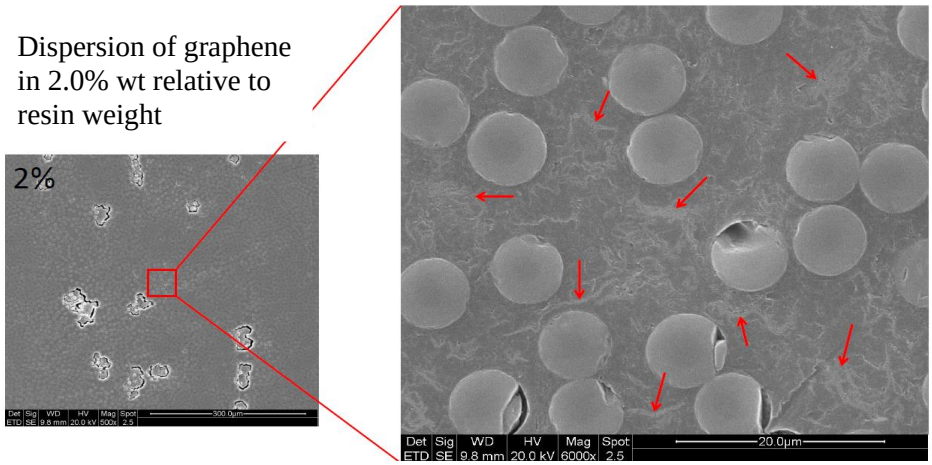

Figure 6: SEM images of functionalized Graphene in composite matrix in 2.0% wt

Based on the SEM images, dispersion of graphene is relatively requiring further improvement. It is observed thar graphene material is distributed in the inter-tow region rather than intra-tow. Figure 7 illustrates the comparison of graphene within the inter-tow rather which several platelets noticeable in between the carbon fibre filament. Meanwhile, no graphene is observed available in the intra-tow area in the filament boundary. This is the result of the inline coating technique which externally applies the resin to cover the filament surface prior to winding process rather than in between the filament. As a result, graphene in resin adheres to the surface instead of between the filaments in the tows. Further modification for improving graphene intra-tow penetration is the next step towards uniform distribution in both inter-tows and intra tows area.

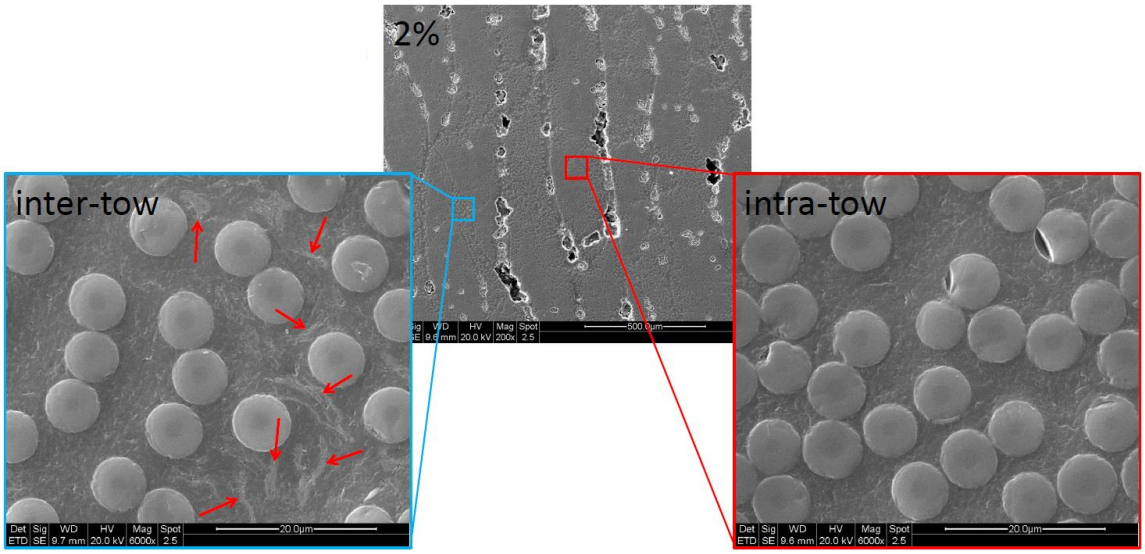

Figure 7: Dispersion of graphene in inter-tow vs intra-tow of the composite

5. ANALYSIS & DISCUSSION

5.1 Composite Thickness

According to thickness data, the control sample has the lowest thickness, and the 2% graphene concentration sample has the greatest thickness, with others falling linearly somewhere in between. Furthermore, in the graphene-loaded samples, it is discovered that tows are becoming rounder. This could be owing to graphene's lubricating effect. Furthermore, graphene agglomeration on the tow surface, as well as graphene penetration within tows, may have resulted in enhanced tow thickness and compaction resistance during vacuum infusion. To investigate this phenomenon in the future, the research needs to investigate on improved tow spreading and tension control with the inline graphene coating technique.

5.2 Equivalent Burst Pressure

The ring tensile test shows indicative results of how the pressure distribution occurs on the inner surface of the cylinder subject to internal pressure. The ring tensile test provides uniaxial test in comparison to full burst test with minor difference in how load is distributed. Firstly, the tensile test generates axial load unidirectionally which will tear on the 3 o'clock and 9 o'clock of the sample. As a result, the ring tensile failure occurs in the region mentioned and depicted in Figure 3. Pressurised gas in a tank will exert force uniformly on the inner surface area of the pressure vessel. Failure occurrence of the material ranges from pin-hole failure to catastrophic loss of primary containment mechanism which leads to the pressure tank to burst.

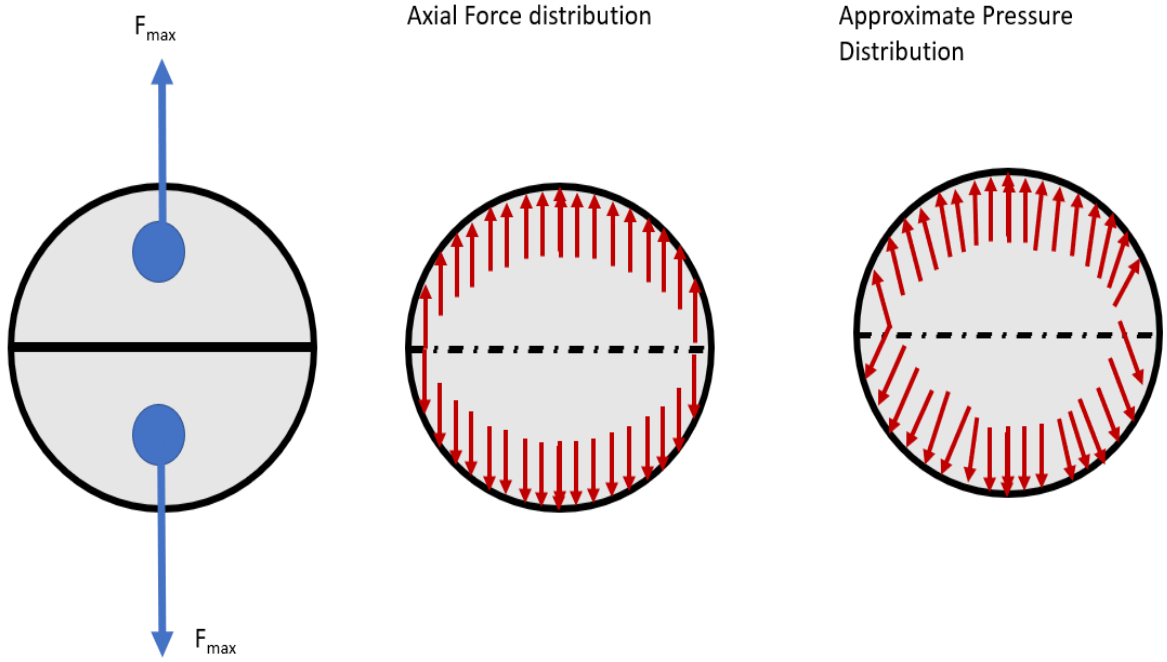

Figure 8: Axial loading as a surrogate to approximate pressure distribution on the inner surface of the cylinder.

The equivalent burst pressure relates the force exerted by the tensile loading onto the ring tensile cross-sectional area. For the ring tensile test, the axial loading, as illustrated in Figure 8, approximates pressure distribution and function as a surrogate to the uniform pressure that occurs when the pressure tank is filled with compressed gas.

Generally, hoop stress operates perpendicular to the axial direction. When pressure is applied to a cylindrical body, hoop stress develops along its circumference. Tensile stresses are created in hoop structures to withstand the bursting action caused by pressure. The hoop stress, σ is described as the maximum load, F_{max}, divided over the wall cross-sectional area (2 x length x thickness) as shown in

Equation (1). Subsequently, the burst pressure is derived by substituting Eq. (1) into Eq. (2) which result in Eq (3). The equivalent burst pressure equation in (3) infers that the burst pressure is related to the load, width, and radius of the ring tensile sample.

$$\sigma_{hoop} = \frac{F_{max}}{2lt} \quad (1)$$

$$P = \frac{\sigma_{hoop} t}{r} \quad (2)$$

Where:

t= thickness, mm
l = width, mm
r = radius, mm
P = burst pressure
Fmax= Tensile load at failure, kN
σ_{hoop} *= hoop stress, MPa*

$$P = \frac{F_{max}}{2lr} \quad (3)$$

Based on the result in Figure 4, the burst pressure calculated from the Eq (3) is tabulated in Table 3. The result shows the calculated burst pressure derived from tensile ring tests. From the table below, the vessel can achieve 35% more burst capacity at 0.3% graphene concentration. The result of the tensile strength directly corresponds to improvement in burst capacity. Subsequently, at higher graphene composition, burst pressure performance of the vessel have slight improvement compared to pressure vessel with no graphene additives.

Table 3: Calculated burst pressure based on F_{max} of tensile ring test

% Graphene	Max Tensile Load (kN)	Burst Pressure (bar)
Control	47.58	601
0.1%	64.36	812
0.3%	64.79	818
0.5%	55.45	700
1.0%	51.28	647
2.0%	51.92	655

Analysis of the axial loading as a surrogate burst test indicates addition of graphene additives in matrix of composite system will potentially enable higher burst capacity with similar geometric dimensions. Ultimately, potential material reduction could only be confirmed after studying additional testing such as impact response, cyclic gas test, and full scale burst test on graphene-added hydrogen storage pressure vessel. Given that there are additional parameters that needs to be addressed to reduce the materials used for hydrogen pressure vessels, this first steps to demonstrate that material used for bursting pressure can be optimized using graphene indicates that there is potential to further study. This will create more understanding of how graphene can contribute to the pervasive use of hydrogen energy storage system in the future.

Importantly, the cost of adding graphene additives needs to be less than the cost of virgin carbon fibre composite system that is being reduced. This will generate sufficient value creation of graphene additives in composite pressure vessels for it to be a worthwhile endeavour. Additionally, graphene addition would also be benefit considering the awareness of carbon-emission intensity by the industry. The use of graphene from environmentally responsible sources will be complement carbon storage in the form of graphene in composite structures. Given that carbon fibre production is generally a carbon intensive process, the use of graphene will optimize the carbon fibre utilization.

5.3 Materials Selection

The Ashby plots for material selection provides a qualitative guide for choosing suitable materials for engineering applications. In the analysis of hydrogen pressure vessel, the Ashby's material selection concept [17, 18] is utilized to determine the most suitable material for hydrogen compressed storage vessel. In the application, the design needs to determine the lightest, pressure-sustaining and fracture resistant storage vessel for compressed hydrogen storage.

The key target of graphene addition in the research is to be able to minimize the weight and to withstand the internal pressure with lower thickness. The study focus on the mechanical properties of materials in ambient temperature hence thermo-mechanical design consideration is not covered in this analysis. The design requirements are summarized as per the table below:

Table 4: Design Requirements for the Hydrogen Pressure Vessel

Function	Hydrogen Storage Vessel Pressure vessel = contain pressure, p
Objective	Minimize the mass. Maximize Safety
Constraints	Length l is specified. Radius, r is specified. Thickness, t is specified. Must not fracture if accidentally struck. Support bending load without deflecting too much

Based on the design prerequisite, the objective functions are derived and updated from earlier analysis of non-metallic pressure containers [19] and tabulated in Table 5. A pressure vessel is a confined container that needs to withstand compressed internal gas loads via tensile strength and fracture toughness.

Table 5: Calculated objective function extracted from Thiyahuddin et. al [19].

(a) The best materials for light weighting are those with large values of the material index	$M_1 = \frac{E^{1/3}}{\rho}$	E = Youngs modulus ρ = Density
(b) Maximum pressure is carried most safely by the material with the greatest value of:	$M_2 = \frac{\sigma_f}{K_{Ic}^2}$ $M_3 = \sigma_f$	K_{IC} = Fracture Toughness σ_f = Strength

As shown in Table 6, the mass of the pressure vessel can be reduced with the used of carbon fibre reinforced plastics (CFRP) based on the highest value of 3.48. The target of development is to design a vessel that can store pressurized hydrogen with increased volumetric capacity. While the ideal qualitative geometry features of pressure vessel are subjective depending on the application and requirement, the application of additives such as graphene can improve tensile properties will aid in reducing the thickness of the pressure vessel and provide incremental volumetric improvement.

Table 6: Objective Function Calculated Result for Material Selection in Hydrogen Pressure Vessel

Material	$M_1 = \frac{E^{1/3}}{\rho}$	$M_2 = \frac{E^{1/3}}{C_m \rho}$	$M_3 = \frac{K_{Ic}^2}{\sigma_f}$	$M_4 = \sigma_f$	Comment
	$(GPa)^{1/3}$ m^3/Mg	$(GPa)^{1/3}$ $/(k\$/m^3)$	$(m^{1/2})$	(MPa)	
34CrMo4 Alloy Steel	0.76	0.32	0.085	980	Benchmark
Carbon Fibre (CFRP)	3.48	0.16	0.010	4900	T700S Carbon Fibre
Glass Fibre (GFRP)	1.01	1.56	0.001	3445	E-glass Glass Fibre

5.4 Carbon Fibre Supply-Demand in Industry

Globally, carbon fibre demand experienced a decline during the pandemic era of 2020–2021. Consequently, it is projected that demand will increase between 2022 and 2027. This is supported by the emerging demand for filament-wound pressure vessels for hydrogen storage and other markets such as wind energy and commercial air travel recovery. In the development of hydrogen storage vessel, an industry guideline used is that 10 kg of carbon fibre is needed for every 1 kilogram of hydrogen kept at 70 MPa, depending on the tank's volume and pressure rating [4]. Hence, 50 kilograms of carbon fibre are required to manufacture a tank that can hold 5 kilograms of hydrogen at 700 bar.

Additionally, it most often requires approximately two years for carbon fibre manufacturers to build and commission new carbon fibre line production to meet their customer need. Hence, the carbon fibre manufacturers are in challenging situation to meet the new spike of demand of carbon fibre in hydrogen storage pressure tanks. Moreover, these lines will require consistent supply of polyacrylonitrile precursor feedstocks and stringent production line that generates specific quality for a given application. To support the additional capacity expansion and high capital investments, the manufacturers will require solid commitments from their clientele and a steady tangible demand of the hydrogen supply chains from the industry. Combination of glass fibre, carbon fibre and graphene additives in composite storage tanks will enable composite users to optimize the usage of virgin feedstock fibre materials while maintain the quality and pressure containment requirement.

With Environmental, Social and Corporate governance (ESG) framework in place to curb the increase of global temperature within 2°C, majority of countries have begun imposing regulations on their local industries the requirement to monitor as well as curb emission of CO_2. Hence, another challenge that may dissuade carbon fibre manufacturer from increasing their production capacity is the emission intensity generated from their carbon fibre production. The high-temperature heat treatment for carbonisation and oxidation used in the carbon fibre fabrication process is energy-intensive and results in significant carbon emissions. According to a study, each metric tonne (MT) of virgin carbon fibre produces emissions of 29.45 MT of carbon dioxide [20, 21]. Hence, reduction of carbon fibre feedstock used to manufacture composite hydrogen pressure tanks will reduce the carbon intensity of the produced tank. Moreover, graphene material that is synthesized from recyclable materials will also provide additional carbon dioxide storage function within the matrix structure of the pressure tank as a form of carbon capture and storage.

Therefore, based on the outcome of the test in this research, utilization of graphene as additives potentially optimizes the use of virgin carbon fibres in storage vessel by up to 35%. This reduction translates to up to 5 kg of carbon fibre materials reduction for a 700 MPa pressure storage vessel produced.

6. CONCLUSION

Adding graphene to the composite matrix enhances the material's capacity to sustain further strain prior to breaking. The ring tensile test revealed that, compared to the control sample, the composite's tensile load capability increased by 35% at 0.1 wt% to 0.3 wt% graphene. However, results also show that adding more graphene may not produce an increase in the material's capacity to withstand additional load. The observed improvement in performance may be attributable to graphene's improvement in the interfacial shear strength of fibre composites by increasing adhesive strength at the interface and restricting the fracture propagation pathways. With higher graphene concentrations, the samples' maximum extension before failing was not made better. Ultimately, uniform intra-tow and inter-tow distribution technique of graphene inside the matrix composite remains a crucial factor that affects the mechanical performance of pressure vessel to sustain higher pressure loadings.

In general, the result from the ring tensile test is consistent with the outcome result previously reported in literature [8, 11]. The calculated burst pressure shows a direct correlation between tensile strength and burst capacity. The results show that the vessel can achieve 16% more burst capacity at 0.5% graphene concentration. Therefore, the addition of graphene additives in the composite matrix improves its tensile load capability and burst pressure, making it a potential candidate for various applications. On the other hand, it is crucial that the cost of incorporating graphene additives into composite pressure vessels is lower than the cost of the original carbon fibre composite system. This is necessary to ensure that using graphene additives is economically viable.

Moreover, the addition of graphene in composite pressure vessels would be advantageous as the industry is currently placing greater emphasis on reducing carbon emissions. By utilizing graphene from sustainable sources, carbon can be stored in the form of graphene in composite structures. This will help to optimize the use of carbon fibre PAN precursor production, which is known to be a carbon-intensive manufacturing process.

In conclusion, the application of graphene additives in composite pressure vessels presents a favourable solution to reduce the cost, feedstock materials and carbon emissions of carbon fibre composites pressure vessels production. Several challenges such as distribution of additive within the matrix inter-tow and intra-tow needs to be addressed to maximize the potential of graphene in the hydrogen pressure vessel application. With further research and development, graphene could become a key material in the future of sustainable and cost-effective composite materials.

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