Institution: Robert Gordon University

Unit of Assessment: 12 - Engineering

Title of case study: Innovations in lightweight, high performance composite materials for new products in the Oil & Gas and Construction Industries

Period when the underpinning research was undertaken: 2010 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Names	Role	Period(s) employed by submitting HEI:
Prof J Njuguna	Professor	2013 - Present
Prof J H Steel	Professor	2007– Present
Dr N Faisal	Reader	2013 - Present
Mr A McPherson	Engineering Design Technician	1992 – Present
Mr A Mohammed	Research Assistant	2018– Present
Dr S Siddique	Research Assistant	2015– Present
Dr A Mukherji	Research Fellow	2017-2020
Dr K Starost	Lecturer	2017-2019
Dr U Ekeh-Adegbotolu	Research Fellow	2017-2019

Period when the claimed impact occurred: 2013-2020

Is this case study continued from a case study submitted in 2014? No

1. Summary of the impact (indicative maximum 100 words)

This research into improving toughness of materials to enhance functional performance has driven economic growth and cost-saving innovations in engineering products worldwide. This study has led to the development of novel materials and technologies, which have since been successfully applied in new commercialized pipe and pipeline products in the Oil & Gas sector, as well as in improvements in building safety and cost-effectiveness in the Construction industry in Dubai, Singapore and Far East Asia.

2. Underpinning research

A composite material combines materials with different physical and chemical properties to create a new material with improved properties. This research in customising composite materials and improving their toughness focused on multiphase polymer-based materials and biocomposites consisting of various nanomaterials[P1]. The study enabled weight reduction and enhanced performance and durability of high-performance products. It has synthesised novel materials and designed appropriate chemical and physical characteristics by influencing nanofillers alignment, dispersion, chemical bonds and interactions between polymeric chains, securing the desired product functional performance[P2,P3].

This expertise has led to significant improvement in functional performance, impact resistance in thermoplastic and thermoset composite materials as highly desired by automotive organisations such as Nissan (UK), GIVE Srl (Greece) and Shapoorji Pallonji (India). As a result, the team was awarded InnovateUK and UKEIRI Newton Fund grants.

This research has also investigated interfacial bonds, delamination and strength of adhesively bonded joints[P4] (cold-bonding technology), and their flammability characteristics. When evaluating the role of adhesive thickness, the intrinsic properties of the materials play an important factor in

determining flexibility and load carrying capability of the adhesive joint, as well as the stress state induced in the adhesive in multi-material composite product.

Novel materials require development of optimised and often specialised manufacturing processes and knowledge in polymer matrices, cure mechanisms and pull force predictions. This research has improved materials synthesis and manufacturing process by demonstrating the physicochemical characteristics of materials, their failure envelop, failure mechanisms and damage evaluation of fibre-reinforced composites as a function of process, loading fractions and product operational conditions and requirements[P1,P2]. The study has explored thermo-mechanical behaviour of biocomposite materials[P5] and flammability when using inorganic nanofillers and degradation under various media linked to the O&G industry's high performance and safety requirements.

It has highlighted opportunities for materials improvements and reduction of manufacturing defects while improving condition monitoring techniques of new engineered materials solutions for O&G industry. The research on condition and corrosion monitoring focused on defect detection and location, stress and strain measurement and characterization of vibration. This work demonstrated specialized non-destructive testing (NDT) techniques in often inaccessible and harsh environments, developed new failure models and definitions, condition monitoring of materials, structures, pipelines, and composite products.

Further research has focused on demarcation of molecular and structural features that contribute to dynamic mechanical properties such as vibration, shock and impact resistance of multiphase composites (polymer, fibres and nanoparticles)[P1,P2,P3], important in designing hybridised composite materials for applications in shock and impact performance products. For body armour applications, new resin grades on polyamides, polyethylene and polyester fibres reinforced with glass/carbon/basalt fibres hybridised resin composite during high velocity impact were developed. Using experimental and analytical techniques, a methodology was developed for calculating Gurneisen parameter from the measured Hugoniot in shock velocity which is exploited in developing impact functionalised hybridised composites[P6] (helping design improved ballistic impact protection materials including ballistic proof beams and panels for the construction, military, and automotive sector).

3. References to the research

[P1]Siddique, S., Smith, G. D., Yates, K., Mishra, A. K., Matthews, K., Csetenyi, L. J., & Njuguna, J. (2019). Structural and thermal degradation behaviour of reclaimed clay nano-reinforced low-density polyethylene nanocomposites. *Journal of Polymer Research,* 26(6), 1-14.

[P2]Jenkins, P., Siddique, S., Khan, S., Usman, A., Starost, K., MacPherson, A., Bari P, Mishra S., & Njuguna, J. (2019). Influence of Reduced Graphene Oxide on Epoxy/Carbon Fiber-Reinforced Hybrid Composite: Flexural and Shear Properties under Varying Temperature Conditions. *Advanced Engineering Materials*, *21*(6), 1800614.

[P3]Visco A, Yousef S, Galtieri G, Nocita D, Pistone A, Njuguna J. Thermal, mechanical and rheological behaviors of nanocomposites based on UHMWPE/paraffin oil/carbon nanofiller obtained by using different dispersion techniques. *Journal of Materials,* 2016;68(4):1078-89.

[P4]Prathuru, A. K., Faisal, N. H., Jihan, S., Steel, J. A., & Njuguna, J. (2017). Stress analysis at the interface of metal-to-metal adhesively bonded joints subjected to 4-point bending: Finite element method. *The Journal of Adhesion*, *93*(11), 855-878.

[P5]Nassiopoulos, E., & Njuguna, J. (2015). Thermo-mechanical performance of poly (lactic acid)/flax fibre-reinforced biocomposites. *Materials & Design*, *66*, 473-485.

[P6]Mukherji, A., & Njuguna, J. (2020). Shock Propagation Behaviour and Determination of Greisen State of Equation for Pultruded Polyester/Glass Fibre-Reinforced Composites. *Composite Structures*, 113444

Evidence of quality – underpinning research grants

[G1] Development of new light high-performance environmentally benign composites made of bio-materials and bio-resins for electric car application (ECOSHELL); EC FP7 Project No. 265838. **Total project value €3,880,634** (2010-2013).
[G2] EC ELife+11 ENV/ES/596. Simulation of the release of nanomaterials from consumer products for environmental exposure assessment (SIRENA). **Total value € 1,140,942** (2013 – 2015).
[G3] Nanomaterials related environmental pollution and health hazards throughout their life cycle (NEPHH), EC FP7 Project No.: 228536-2. **Total project value €3,096,159** (2009 – 2011).
[G4] Graphene Hybrid Composites for strength-after-impact performance. Funded by British High Commission/Newton Fund/DST India. UK-India collaboration (UKEIRI), (2016-2018) **Total project value: £40,000**.
[G5] Development of capability to characterise the extrusion of elastomers. Funded by Innovate UK/Rubberatkins. **Total project value: £185,100**. (2019-2022).
[G6] Honeycomb composite structures for ballistic protection. Shapoorji Pallonji, India. **Total project value: £223,500**; (2017- 2020).
[G7] Evaluating basalt fibre for high volume automotive composites manufacturing (EB-Auto). Innovate UK/ National Composites Centre/Composites Braiding/Mafic/Coats/M. Wright & Sons/Nissan/IHI Corporation. **Total project value £169,751**. (2018-2019).
[G8] Subsea 7, Subsea pipeline integrity soluble purge dams, sealing and insulation materials. **Total project value: £40,740**.
[G9] Engineering Composites Solutions Ltd, Composites wrapping repair methods in structural and pipeline integrity. **Total project value: £21,650**
[G10] Cactus Industrial Ltd; Materials evaluation for adhesive bonding technology. **Total project value £7,800**
[G11] Oil Technics Ltd; Structural integrity of chemical storage tanks in Oil and Gas facilities. **Total project value: £9,132**

4. Details of the impact

The research on resin matrix cure mechanism, pull force predictions and polymer nanocomposites hybridization enabled Shapoorji Pallonji (US$25.7 billion Indian multinational) to develop new products using pultrusion process, including composite bulletproof panels, skyscraper I and H composite beams, and construction foundations layering panels now used in construction buildings in Singapore and Dubai, ~15% of Far East Asia construction business[C1] creating new jobs both in India and Far East Asia. RGU research continues to support these products to diversify and evaluate life cycle prediction (cyclic loads and surface behaviour). Shapoorji Pallonji have also employed a material grade developed into a new generation of ballistic proof vest (Indian Patent App. No 201821031691) as military/security protection gear and vehicle armor in passive safety vehicle body structures.

Engineered Composites Solutions Ltd (ECS) also benefited from this study, generating 15% new business in composites repair technology[C2]. The organisation focused on the impact behaviour of composites pipe wraps and their long-term integrity in offshore Oil & Gas production risers and pipelines, where it is mandatory to extend pipelines lifespan. This method averts costly production shutdown cost (>US$125,000/hr), typically 30% cheaper than welded steel sleeve repair and 75% cheaper than replacing defected pipe section while reducing maintenance burden. This provided ECS with an edge over other suppliers bearing 15% new market growth.

These novel materials were also applied in servicing pipelines by Subsea 7 (global Engineering Services Company) to address the challenges related to connecting and assembling multi-bore structures and systems in subsea waters, such as pipeline bundles and riser structures used in subsea Oil & Gas industry[C3] (U.S. Patent No. 10,774,971). Consequently, RGU input to Subsea 7 on thermo-mechanical (combined pressure and temperature) ageing of insulation materials in subsea pipes successfully demonstrated the applicability of insulation types to the new technique for subsea pipe-in-pipe design. This novel insulation method is anticipated to secure projects worth £50m in oilfields with specific fluid temperature problems.

RGU research on adhesives bonding technology and expertise in material behaviour under extreme thermo-mechanical loads was employed by Cactus Industrial Ltd and supported by global manufacturer Chesterton ARC (Germany), successfully providing a solution for rehabilitation of overlaying decks and roofs as an alternative to traditional method of plating and welding in pressured habitat[C4]. The treacherous offshore conditions in sealing assembly result in heavy shear loads on axial movement (up and down) conditions for adhesively bonded joints used in high temperature and flammable environments, which can have major safety implications. This research demonstrated the capability of composite-metal system to endure harsh environments and cost-savings of ~£250,000/unit platform flooring. Cactus Ltd has since achieved significant business growth (CAGR 10%) in its Oil & Gas onshore and offshore operations, where the cold process technique is growing and has safeguarded jobs[C4].

Further RGU research was utilised by Oil Technics Ltd (fire extinguishing foam grade producer) which was facing concerns about increased capital expenditures from leaking storage vessels worldwide storing over 100,000 litres of fire extinguishing foams[C5]. This problem was especially persistent in hot climate regions in Australia, Middle East and Brazil. The research focused on materials compositions and foam additives in these locations, to devise a solution capitalizing on materials behaviour at given temperature conditions. This resulted in substantial cost-savings for Oil Technics and storage tanks manufacturer SEMCO MARITIME (Australia), while ensuring fire safety for Oil & Gas operators, safeguarding 20% Oil Technics business. This in turn created new jobs in the UK, secured large scale contract from Australia and acted as a gateway to new market for OilTechnics [C5].

5. Sources to corroborate the impact

[C1] Letter of support, N.D. Tarapore, Shapoorji & Pallonji co Pvt Ltd.
[C2] Letter of Support, Prof Simon Frost, Engineered Composites Solutions Ltd (ECS).
[C3] Letter of Support, Mr Harvey Jamieson, Engineering Project Manager, Subsea7.
[C4] Letter of Support, Mr Gordon Cairns, Managing Director, Cactus Industrial limited.
[C5] Letter of Support, Mr David Evans, Managing Director, Oil Technics.