

Effectiveness of vacuum consolidation in bonding fibre reinforced polymer (FRP) composites onto concrete surfaces

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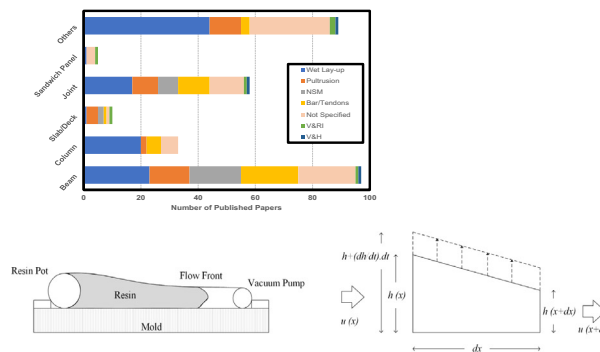
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HIGHLIGHTS

- The effectiveness of FRP automated processing methods in improving bond behaviour is studied.
- This paper will discuss interfacial behaviour of various FRP-concrete connections.
- Quantitative and qualitative analyses of local and global bond characteristics are performed.
- The formulation of governing equations for vacuum pressure and resin flow are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

With the growing popularity of fibre reinforced polymer (FRP) composites in strengthening of structures, new FRP processing methods are required to achieve reliable repairing systems. Application of vacuum resulted in production of components with sound mechanical properties, lower porosity level and accurate fibre management. While the application of automated composite processing techniques is fairly well developed in the aeronautics and marine industry for production of high performance composites, review of the literature reveals that civil infrastructure has still not been benefitted well from the advantages of these methods. This highlights the potential for a comprehensive research program to evaluate efficiency of automated processing techniques in strengthening of infrastructures. This paper will examine interface behaviour of various FRP-concrete connections processed with automated vacuum consolidated techniques as well as wet lay-up and pultrusion. Local and global interfacial characteristics of connections are investigated through series of single lap shear tests and the analytical formulation of governing equations are presented. In addition, the morphology of the composites is examined through scanning electron microscope (SEM). This research reveals the potential of automated FRP processing methods in achieving high level of bond characteristics for structural applications and provides recommendations for future research.

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1. Introduction

Fibre Reinforced Polymeric (FRP) materials have been used in the construction industry over the last two decades. Based on damages caused by several factors such as, environmental effects and/

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or structural changes, the need for strengthening of existing structures is inevitable. Since introduction of FRP application in structural engineering, a variety of strengthening strategies have been proposed for reinforced concrete elements such as beams, columns, joints, walls and slabs [1–5]. For many years, wet lay-up and pultrusion techniques have been widely recognised as common FRP installation methods in civil engineering applications due to their simplicity and lower capital cost. However, advances in epoxy manufacturing, need for high quality composites, and environmental concerns about exposure to hazardous liquids and vapours obliged construction industry to introduce and apply alternative methods in FRP installation.

In the wet lay-up method, impregnation of fibres and curing are carried out manually under ambient temperature which require intensive labour work. This can slow down the production rate and makes it hard to maintain composite uniformity (e.g. alignment of the fibres, proper resin impregnation, sufficient compaction of fibres) and the thickness steady [6]. The quality of lay-ups highly depend on the operator's skill and possibility of entrapped air voids inside the composite is high that can result in deterioration and reduction of durability [7]. In addition, there are environmental and safety concerns since the processing technique occurs without isolation of the resin and volatiles. In pultrusion, the final quality of the profile is dependent on several variables, such as pulling speed, pulling force, die length, heating die system [8], and prediction of temperature and curing of the resin within the material [9]. These interdependent variables lay constraints on the quality control of the pultrusion. Extrusion of profiles through die and heater as part of fabrication can generate residual stresses and initiate pre-mature failure during service life. In addition, since pultruded sections are pre-fabricated, limitations exist in relation to their size.

Subject to individual site safety procedures, manual repair in wet lay-up or pultrusion requires scaffolding and site closure during curing. In some cases, the need for shut down imposes social and economic costs. In more controlled methods, repair can be undertaken while structure is still in operation and there is no need for scaffolding. Amongst automated techniques, the vacuum and resin infusion (V&RI) and the vacuum and heat (V&H) can be employed as alternatives for the contemporary fabrication methods due to their simplicity in moulding and cost effectiveness. These automated techniques have been used in aeronautics, marine, and automotive industries for production of high performance composites. Impregnation of the fibres in the V&RI is carried out by injection of the resin through a vacuum consolidated chamber while the V&H involves application of heat over pre-impregnated fibres in the presence of the vacuum. Vacuum evacuates bonded surface from the air and provides a safe and reliable source of power for distribution of the resin over the fibre. These two mechanisms lower porosity level and subsequently improve mechanical properties of composite [10,11]. Curing takes place under vacuum condition for both methods, while in the V&H curing is also accompanied with an elevated temperature.

The V&RI and the V&H are closed mould procedures that can provide low cost FRP application for structural strengthening of large scale components. Previous studies [10] showed that complex geometries can be efficiently constructed by the V&RI or the V&H. In addition, a composite with high quality, in terms of the mechanical and microstructural properties, is achievable. These techniques are repeatable and are able to achieve high fibre-to-resin ratio. Since in V&RI or V&H process the whole system is confined, the release of the volatile organic compounds (VOCs) or contact with composite is minimized.

The application of vacuum and resin infusion/heat has not been fully investigated in structural strengthening. For instance, number of studies using various FRP fabrication/processing techniques

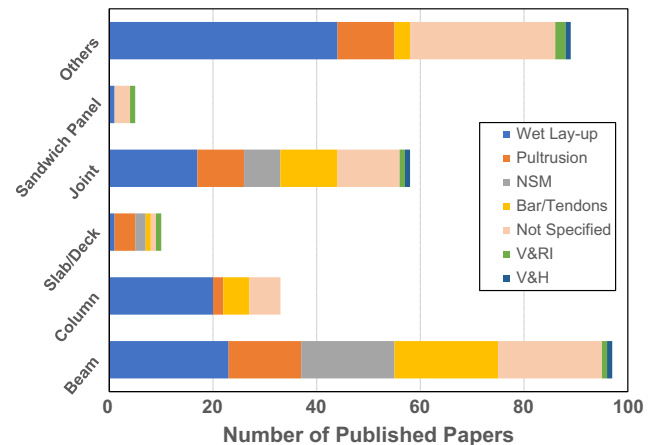


Fig. 1. Application distribution of different FPTs in published studies during year 2016. Where papers are silent about exercised FPT, processing technique is categorised as Not Specified or further information were collected for determination of FPT. If various FPTs were used in a research, just dominant method was used in data analysis. "Others" on y-axis refers to any other structure's element rather than those mentioned on the graph (e.g. FRP tubes, concrete cylinders, confined concrete, FRP frameworks, shear connectors, masonry, timber, walls, and etc). Both analytical and experimental studies were considered in this figure.

(from now on, *FPTs*) in structural applications is collected and shown in Fig. 1. In fact, these studies (around 292 articles) were extracted from ScienceDirect database for those papers published in one year, and then distribution of each FRP processing technique was added up. Wet lay-up and pultrusion methods were used in more than 50 per cent of the studies while just 3 per cent of research exercised the V&RI or the V&H. This figure indicates the lack of published data on the use of automated techniques in structural engineering.

The vacuum resin infusion is used in fabrication of FRP bridges for replacement of deteriorated structures, e.g. Bennett's Creek in US [12] and West Mill Bridge in Oxfordshire, UK. Significant strength was achieved for the replaced bridge through prototype and field proof tests applying a full-scale load as well as less construction time and cost effectiveness [13,14]. The successful application of the vacuum assisted resin transfer moulding in enhancing the punching resistance of GFRP composite sandwich panels has been reported [15]. Vacuum and resin infusion/heat technique has recently been used to investigate the performance of steel-FRP shear walls made by pre-pregs [16], patch repair of steel I-beams with pre-pregs [17], the repair of damaged reinforced concrete columns with pre-pregs [18], bond performance between FRP and concrete [19], flexural behaviour of concrete beams strengthened with prestressed carbon-basalt fibre sheets using vacuum assisted resin transfer moulding (VARTM) [20].

2. Research significance

Although the performance of FRP composites in strengthening of structures have been studied in many researches, very limited data is available on the effectiveness of automated FPTs in the context of structural application. It is clear that FRP installation is of great importance to attain a proper strengthening strategy. As a matter of fact, mechanical and physical properties of composites depend on the design as well as fabrication method [21]. FRP strengthening is efficient if immature debonding prior to the ultimate strength is prevented. Hence, the interfacial behaviour between the FRP and the substrate is one of the most influential factors which has to be carefully considered. This paper presents experimental results on the bond performance of several

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