EFFECT OF MOISTURE ON THE INTERFACE OF TIMBER AND EXTERNALLY BONDED FIBRE REINFORCED POLYMERS: A REVIEW PAPER

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ABSTRACT

Timber as a structural material has been in use since the medieval period. Even today, there are many residential houses being built with timber frame in Australia. Wooden wharfs and bridges are common examples of timber structures in coastal regions of Australia. Humidity in such coastal regions is often high causing an increase in moisture level in the timber structures. Besides, over-loading, rot and decay, termites and borers, etc. cause damage to timber and presence of moisture either aggravates this or favours such causes. Hence, there has been an increased demand for repair and rehabilitation of heritage and important timber structures. Strengthening wooden structures with fibre reinforced polymers (FRPs) is becoming popular in the construction industry. The objective of this paper is to demonstrate the effect of moisture on the durability of the timber-FRP interface. After reviewing previous studies in the durability of the timber-FRP composite, it has been found that prolonged moisture exposure leads to premature debonding in the timber-FRP interface. A graphical representation of the effect of moisture on bond failure has been established through this research work after investigating the previous work of scholars. This paper also highlights the significance of applying adhesion promoter in enhancing the performance of timber-FRP interface.

KEYWORDS

Rehabilitation, Timber/FRP interface, Adhesive, Moisture

INTRODUCTION

Australia has most of its cities established around the coastal belt with over 40,000 timber wharfs and bridges which are vital for public transportation. However, most of these structures are old and approaching their end of design life. Hence, rehabilitation of these timber structures is gaining popularity to meet the rapidly increasing traffic-load demands. Another reason for the growing need for rehabilitation is to mitigate the financial risk of losing the vast amount of infrastructural resources [1].

In Australia, many residential buildings are made up of Engineering Wood Products (EWPs). Solid woods go through reconstitution and densification to produce EWPs which exhibit superior mechanical features than the original unprocessed timber. Some of the common EWPs are laminated veneer lumber (LVL), glued laminated (Glulam) and oriented strand lumber (OSL). There are some other benefits of using timber products as structural materials. They have low embodied energy and pleasant aesthetics. They are cost-effective alternatives to concrete and steel [2]. Another research carried by Wang et al. indicated that timber structures typically present good seismic performance [3]. The application of timber in the construction industry is not only popular in Australia but also all around the world. In fact, the European Union has identified the need to adopt renewable sources of energy and rebuild old structures as its important strategy to combat the global crisis of climate change [4]. The push for green energy has led to an increase in demand for timber materials as well as the rehabilitation of existing timber structures.

Factors such as damage due to over-loading, decay, etc. can lead to the need for repair. Changes to functionality, loads or changes to code can require structural retrofitting [5]. Repair and rehabilitation are two distinct terminologies. Repair can be defined as a process of restoring the original strength of an element or a section of an existing structure. It is done to a structure either as a part of maintenance activities or to correct damaged sections due to faulty construction practices. On the contrary, rehabilitation is a much broader term. It encompasses the repair process to regain the original capacity as well as the strengthening of an existing structure to accommodate the changes in the current standards and design guidelines [6]. Traditional methods of strengthening timber structures include increasing the flexural strength of an existing timber section by adding new wood elements or by using metallic cover plates tied with the help of mechanical fasteners [7]. However, there are disadvantages of the conventional strengthening techniques of timber elements. The use of mechanical fasteners creates a region of stress concentration which is vulnerable to deterioration with time. Moreover, the addition of new materials increases the labour costs as well as the dead load of the structure [8]. These problems associated with the traditional rehabilitation methods paved the way for the modern age strengthening techniques with fibre reinforced polymers (FRPs). The ease of conducting rehabilitation works in selected patches of the structures and the high strength as well as durability of FRPs have made them popular rehabilitation materials for timber structures. The most commonly used FRPs as strengthening material for timber structures are carbon fibre, glass fibre and high-strength glass fibre [9].

The motivation of strengthening timber elements with FRPs was drawn from the success of concrete-FRP composites in the construction industry. Gilfillan, Gilbert & Patrick in their research work indicated that FRP materials can easily help attain a full strength of timber elements [10]. This idea was reinforced by another scholarly work by Svecova & Eden which showed an application of glass fibre reinforced polymers as a strengthening material in timber member enhanced both the flexural and shear strength of the element by 50% [11]. Similar studies are found in the field of concrete-FRP composites where externally bonded FRPs are installed to enhance the performance of concrete structures [12]. Researchers were successful with their experiments in increasing the flexural and tensile strength of concrete sections using externally bonded FRPs [13]. Despite the remarkable achievements of scholars in the past 30 years in the domain of strengthening timber structures using FRP yet, the effect of environmental stresses on the long-term performance of the timber-FRP composites has not been properly investigated. There are many quality literature review works which highlighted the fact that there is a lack of knowledge in the bond durability of timber-FRP composites compared to concrete-FRP composites [14].

This paper presents the effect of moisture on the interface of timber and externally bonded FRP by demonstrating state-of-the-art review of previous studies in the field of rehabilitation of timber using FRP composites. The paper is divided into 4 major sections comprising of the materials involved in the timber-FRP interface, factors affecting the bond durability, effect of moisture on individual components and finally, the conclusion highlighting the key outcomes of the paper and issues that can be addressed in the future research work.

TIMBER-FRP INTERFACE

The materials involved in the timber-FRP joint are timber, structural adhesives, and the FRP composites. FRPs are manufactured through a polymeric process where the fibres are fused within a matrix. The fibres impart the strength to the FRP composites. They have a low weight to density ratio, high strength, high stiffness and are resistant to corrosion. However, FRPs are anisotropic (sensitive to directions) in nature and hence, special care is required to install them in proper orientations for strengthening purposes. Moreover, FRP composites are susceptible to dimensional changes under varying moisture and temperature conditions [15]. Carbon, glass, and aramid are the common commercially available fibres. Nonetheless, carbon and glass fibres are mostly used in civil engineering projects [16]. The adhesive in the timber-FRP acts as the medium of stress transfer between the timber substrate and the externally bonded FRPs [17]. The application of adhesive in fabricating a bond is an efficient method as compared to using mechanical fasteners since it does not yield any region of stress concentration. Epoxies are the common structural adhesives used at the timber-FRP interface during the rehabilitation work of timber structures [7]. The contemporary construction industry prefers using epoxy adhesives to conventional structural adhesives. It is because epoxies are thermosetting resins which cure at ambient temperature and have superior gap-filling properties [18]. The chemical properties of epoxy adhesives make them suitable for civil engineering applications. These adhesives can cure over a wide range of outdoor temperatures and have limited shrinkage during the curing process [19]. However, previous research strongly indicated that the presence of moisture is detrimental to the durability of the timber-FRP interface [18,19]. Hence, the behaviour of individual components of the timber-FRP interface under varied service conditions is required to be studied and examined for durable rehabilitation works. Among various service conditions, moisture plays a dominant role in affecting the durability of the timber-FRP composite system. Figure 1 portrays a section of the timber-FRP interface in moisture conditions.

Fig. 1 – Shows Timber-FRP interface under moisture conditions

FACTORS AFFECTING THE BOND DURABILITY

The timber-FRP interface is composed of three dissimilar materials. Several factors affect the integrity of the interface. Environmental factors such as ultraviolet (UV) radiations, temperature variations, and moisture conditions play key roles in defining the durability of the bond. Researchers have established that the performance of the interface also depends on the surface preparation of the timber substrate. Vanerek et al. in the year 2014 highlighted the significance of the surface preparation to the long-term performance of the timber-FRP interface. The timber surface is to be suitably prepared to avoid any air bubble formations during the application of the adhesive. Air bubbles are detrimental to the durability of the bond. The adhesive should be applied within a short time interval after the surface preparation to prevent air bubble formations as well as surface contamination [18]. This philosophy is further consolidated by research work carried by Vahedian, Shrestha & Crews in the year 2017 and Cabral-Fonseca et al.in the year 2018 by outlining the requirement of surface preparation to produce a rough surface for better adhesion. Researchers recommended sanding as a cheap and efficient surface preparation method.

Cleaning the timber surface with acetone and air blasting are few other methods of surface preparation [8,20].

The main constituent of wood is cellulose. It is responsible for the wood growth and performance of the wood products. On the other hand, epoxies are made up of two components, namely hardener and base mixed at a specific ratio to produce thermosetting resins. The cellulose-epoxy bond in the timber-FRP interface is a van-der Waal's bond which is the weakest bond in nature [21]. However, a thicker adhesive bond does not circumvent the weak bonds of the interface. This essentially means the thickness of the interface needs to be carefully determined while enhancing the bond performance. This is due to the fact that thicker bond at the interface may cause increased porosity leading to failure. Hence, it is essential to reinforce the adhesion with mechanical fasteners or adhesion promoters. Commonly available classes of adhesion promoters in the market are zircoaluminate, organotitanate, organosilane, alkyl phosphate ester and metal organics. But, silane-based adhesive promoters are considered suitable for epoxies due to their high degree of chemical resistance and the ability to transfer stresses between two composite materials. This is evident from the scholarly work conducted at the National University of Ireland in 2009. A team of researchers investigated the effect of adhesion promoter on the performance of timber-FRP interface in a series of experiments. A silane-based compound in aqueous solution was used as an adhesion promoter in the experiments to evaluate the performance of the timber-FRP interface. It was found that the adhesion promoter prevented the premature failure of most of the timber-GFRP (glass fibre reinforced polymer) specimens. However, dissimilarities in moduli of elasticities in materials and coefficients of expansion raise some concerns for the dimensional stability of the bonded system [18,22].

UV rays, changes in temperature and moisture exposure can cause deterioration to the timber-FRP bonded system. It was found that UV rays caused photo-degradation of the top surface of the FRP strips. This led to the decolorisation of the FRP strips and eventually a reduction in shear and tensile strengths of the FRP material [20]. Temperature also plays an important role when it comes to the long-term performance of the timber-FRP interface. The epoxies are tolerant to a wide range of operating temperature and do not show many deteriorating mechanical properties under the effect of temperature. On the contrary, FRPs are susceptible to heat and temperature changes. The matrix holding the fibres tend to crack under high temperature [23]. Another environmental factor that plays an important role in influencing the durability of the timber-FRP interface is the moisture condition. Researchers agree to the fact that the effect of moisture is unavoidable. It affects the mechanical properties of all the individual components involved in the timber-FRP. Timber composites are susceptible to changes in the moisture content. Any change in moisture content can cause a drastic effect on the dimension and strength of timber products. Moreover, researchers claim that the adhesive strength also reduces under continuous wet and dry cycles throughout the design life of the structure [8,18,20,21,24].

Overall, this section summarizes the critical factors that can affect the success of the rehabilitation work of timber structures using externally bonded FRPs. Further, a tabular matrix has been developed showing both the positive and negative relationships between the effect of environmental, cost, mechanical and visual factors respectively on the individual components of the timber-FRP interface. The matrix has been represented in a tabular format as shown in Table 1.

Tab. 1 - Shows the analysis of material properties

TIMBER - FRP INTERFACE: ANALYSIS OF MATERIAL PROPERTIES				
Categories	**Wood / Timber**		**Epoxy Adhesives**	
	Positive features	**Negative features**	**Positive features**	**Negative Features**
Environmental factor	Renewable	Degrades	No gaseous emission	Dimensionally unstable under moisture exposure
Cost factor	Low cost	Added surface treatment cost	Increase in demand leading to competitive prices	High manufacturing cost
Mechanical parameters	High Strength - Weight ratio	Low load carrying capacity and brittle failure	Limited Shrinkage during curing and transfer stresses	Susceptible to mechanical damage
Visual appearance	Pleasant aesthetic	Surface defects such as splits and knots	Clear liquid	May require mechanical faster
Categories	**EWPs**		**FRPs**	
	Positive features	**Negative features**	**Positive features**	**Negative Features**
Environmental factor	Low embodied energy	Degrades	Durable	Deteriorates under UV rays
Cost factor	Economic alternative to steel and concrete	High manufacturing cost	Strength and stiffness	Expensive
Mechanical parameters	Aseismic property	Brittle failure	High capacity	Premature debonding
Visual appearance	Pleasant aesthetic	Finger joint	Tidy installation	Painting needed

MOISTURE CONDITIONS

The success of the rehabilitation work depends largely on the integrity of the timber-FRP interface. The review of past scholarly articles indicates moisture as the most important parameter affecting the performance of the timber-FRP interface. Hence, a critical understanding of the effect of continuous wet/dry cycles on the timber-FRP interface is essential to fabricate a durable joint. The following sections elaborately review the effect of moisture on the individual components of the timber-FRP system.

Effect of moisture on timber

Wood, being a natural material, is very much prone to environmental deterioration. Moisture is one of the most important factors impacting the strength as well as the dimensional stability of timber element [18]. Continuous exposure to moisture cycles at varied temperature causes the development of hygrothermal stresses in the wood elements. These stresses affect the bond between dissimilar materials and are detrimental to the timber-FRP interface. There were many experiments that recorded and demonstrated the effect of moisture in timber structures. One of such experiments was highlighted by Björngrim, Hagman & Wang in the year 2016 where sensors were used to assess the health of timber bridge subjected to aggressive moisture attacks. The purpose of setting up sensors was to check the moisture levels at various sections of the bridge. It was found that if the moisture content was above 20%, the wood section was at high risk of rotting. Further, frequent inspections of moisture levels helped to identify locations of high moisture content and hence, reducing the risk of biological degradation leading to failure of the bridge elements [25]. Nonetheless, researchers are still trying to develop efficient and effective methods to protect and rehabilitate timber members from moisture attacks.

Effect of moisture on FRP

It is important to study the effects of moisture on the FRPs where they are used as externally bonded materials. The externally bonded FRPs are the first point of contact for the environmental stresses and the knowledge of their behaviour under moisture attacks would provide valuable insights on the durability of the timber-FRP interface. It is now established that moisture plays an important role in affecting the long-term performance of FRPs. It is the epoxy matrix in FRP that might get affected due to diffusion of water through the various layers of FRPs. In general, there is no definite relationship between moisture content and the durability of FRP. However, it has been found that glass fibres are more prone to moisture degradation than carbon fibres. The surface microcracks give way for the ingress of water molecules in glass fibres leading to crack propagation and deterioration [23]. FRPs are generally immune to moisture attacks. But, researchers provide evidence of cases where wet and dry cycles over an extended period of time have led to a reduction of strength in FRPs [20].

Effect of moisture on epoxy adhesives

In 2003, Charles R. Frihart, one of the pioneer scholars in the field of Timber-FRP analysis, indicated that the failure of adhesive to transfer stress effectively across timber substrate to the FRP was responsible for the debonding of timber-FRP under moisture conditions. In the subsequent years, researchers were able to establish the fact that the decrease of bond strength of timber-FRP composites was witnessed due to exposure to wet cycles over an extended period [24]. Hence, moisture is an important factor to consider while fabricating a bonded system using adhesive.

An epoxy adhesive is a structural adhesive used in the timber-FRP interface for its many benefits. Although the production cost of epoxy adhesive is high, it does not cause stress concentration, unlike mechanical fasteners. Moreover, there are certain epoxies that could be used to fabricate a stronger timber-FRP interface. Hence, suitable selection and application of adhesives could lead to durable bonded systems [22]. Epoxy adhesive has gap-filling properties which can treat micro-cracks in the timber substrate producing durable bond. However, application of epoxy adhesives in moisture conditions resulted in loss of nearly 50% of the bond strength [18]. Vulnerability of epoxy adhesives to moisture attack is due to their molecular affinity to water molecules [20]. Although researchers have established significant theories around the role of adhesives in debonding under moisture conditions yet, there is a scope of further research and development of adhesive suitable for durable timber-FRP composites to be used in rehabilitated timber structures.

Effect of moisture on Timber-FRP interface

The application process of adhesive while fabricating the timber-FRP bond should be done extremely cautiously. Any development of air bubbles will lead to failure of the bond [27]. In a significant research work published in 2015, Zhou, Tam, Yu and Lau explained their experiments which were intended to understand the correlation of moisture development and failure behaviour of the timber-FRP joint. They found that development of air bubbles may lead to premature failure of the timber-FRP interface if the moisture content is more than 20%. Conversely, under low moisture condition (moisture content < 15%), the timber-FRP composite may also fail. However, the failure under low moisture conditions would be brittle. This implies that the presence of a failure plane within the timber substrate of the timber-FRP system in case of brittle failure. With the increase in moisture content from less than 15% to more than 20% over 8 weeks' time, the debonding failure plane demonstrated movement from within the timber substrate to the timber-FRP interface. The failure under moisture conditions (moisture content > 20%) was progressive in nature as compared to sudden failure in low moisture conditions (moisture content <15%). It was found that the timber-FRP interface failed prematurely at higher moisture content. The experiment also revealed the failure behaviour of seasoned timber in normal environmental conditions. Seasoned timber at normal room conditions has a moisture content less than 15% [21]. However, in case of marine wooden structures in the context of Australian coastal regions, seasoned timber used for structural purposes may also experience high moisture content and could lead to premature debonding failure. Interestingly, another recent development in concrete-FRP composites suggested that the failure plane shifted from within the concrete substrate towards the timber-FRP interface when exposed to moisture [20]. This study reinstated the outcomes of the aforesaid experiment which indicated the movement of failure plane from within the timber section to the timber-FRP joint when subjected to moisture content greater than 20%. Such similarities and patterns in concrete-FRP composites and timber-FRP composites can help researchers to drawn more conclusions from the already established earlier system to consolidate durability studies for the latter one.

Hence, it is evident from the studies that the failure plane moves from within the timber towards the interface under moisture exposure and fails prematurely [8,20,21,22]. Figure 2 gives a representation of the load versus deflection graph depicting the premature failure of the timber-FRP interface under different moisture conditions.

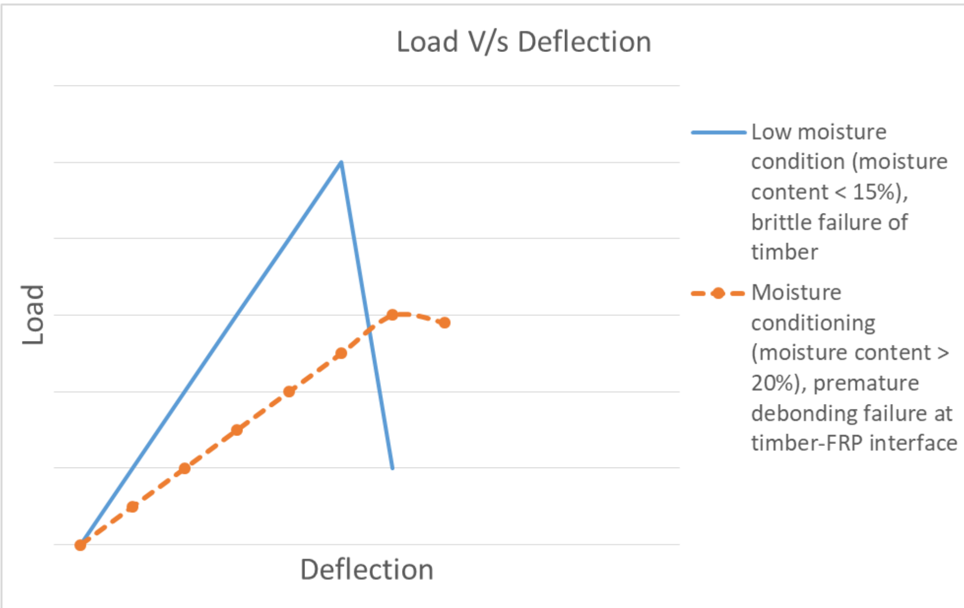

Fig. 2 – Illustration of premature failure of Timber-FRP interface under the effect of moisture

CONCLUSION

The paper encourages engineers and building practitioners in Australia to take into account the effect of moisture on bond durability of timber-FRP interface. Consideration of moisture variations is crucial while strengthening the timber elements (eg. timber decks of bridges) using externally bonded FRPs. The paper also highlighted the application of adhesion promoter in enhancing the performance of the timber-FRP interface. Adhesion promoters, or commonly known as coupling agents, are brush-applied materials used as a priming coat to increase the adhesive strength of a substance to bind two dissimilar materials. Among the many variants of coupling agents in the market, authors recommend silane-based coupling agents for epoxy adhesives because of their unique characteristic of transferring stresses from resin-based substance (epoxy adhesive) to the substrate (timber composite). In addition, it is important to note that the effectiveness of the adhesion promoter, and subsequently the durability of the timber-FRP interface depends on the surface preparation of the timber substrate. This preparation is necessary to avoid any air bubble formation as well as the inclusion of dust and contamination during the application of the adhesive.

Such a reconstruction procedure is of great consequence to the construction industry of Australia because it has a number of timber structures that are approaching the end of their life and are in need of immediate rehabilitation works, especially heritage bridges close to a marine region like the Hampden Bridge built during the 1890s in Kangaroo Valley. Many of these structures are in the coastal belt which makes it difficult for the engineers to carry out long-lasting repair and rehabilitation works.

In conclusion, the paper establishes the fact that timber composites, as well as epoxy adhesives, are prone to detrimental changes due to variations in moisture level over the service period of a structure. It is the view of the authors that thicker bondline may be more likely to result in increased porosity and micro-cracking resulting in low bond strength. Therefore, this paper attempts to provide modest guidance to the future scholars for developing a proper design guideline or a design handbook with definite specifications on the bond length and bond-line thickness for fabricating durable and economic timber-FRP interface. The paper also came up with a unique comprehensive table that summarizes the characteristics of different components of the timber-FRP interface under the effect of various factors. The summary table is very convenient for any engineer or academician to have a look and get initial views of the merits and demerits of different materials involved in the rehabilitation of timber structures. It is evident from the review work that among various service conditions, moisture plays a dominant role in affecting the durability of the timber-FRP composite system. High moisture content (greater than 20%) shifts the failure plane from within the timber substrate towards the interface of the timber-FRP bond causing pre-mature debonding and failure of the repaired section. This failure pattern is analogous to the failure model of concrete-FRP composites. As a result, the authors suggest proven and established theories of concrete-FRP composites should be used as a baseline reference for carrying future research in the field of timber-FRP composites. Finally, the authors support further work in this field to produce valuable insights not only in developing a durable timber-FRP interface, but also to have a sustainable balance between the construction of new structures and rehabilitation of old structures.

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