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HYGROTHERMAL DURABILITY OF ADHESIVELY BONDED FRP/STEEL JOINTS

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The use of fiber reinforce polymer, FRP, bonding to strengthen and repair deteriorated steel structures is increasing owing to its unique advantages over traditional strengthening and repair techniques. However, the lack of knowledge regarding environmental durability of adhesively bonded FRP/steel joints still hinders the widespread application of this method in steel structures. A number of studies have reported significant degradation of mechanical properties of these joints in hot and wet environments. In addition to that, the mechanisms of failure have been observed empirically to change from cohesive failure in the adhesive to apparent interfacial failure with increasing amount of moisture. This study presents the results of an experimental and numerical investigation to predict the mechanical behavior of FRP/steel joints after hygrothermal aging. First, moisture diffusion kinetics and mechanical degradation of a two-part commercially available epoxy adhesive and Carbon FRP material were experimentally characterized over a wide range of temperature and humidity conditions. These parameters were then incorporated in a coupled 3D diffusion-mechanical finite element, FE, model. In addition, bonded double-lap shear joints of CFRP/steel were aged for up to a year and tested to failure. It is found that the presence of moisture for less than a critical period can increase the joint strength. However, prolonged exposure to the same moisture content degrades the load-carrying capacity of the joint.

Keywords: Long-term performance, FE simulation, Fiber reinforced polymer, Adhesive joints, Moisture diffusion, Coupled FE analysis, Double lap shear joint.

1 INTRODUCTION

Fiber reinforced polymer (FRP) composites offer remarkable mechanical properties, such as high specific strength and stiffness, corrosion resistance and light weight. Due to these superior characteristics, compared with conventional building materials such as steel and concrete, FRPs are being used increasingly in civil engineering applications. Carbon fiber reinforced polymer (CFRP) laminates were first used during the 1970s for strengthening and repair purposes (Hollaway 2010). During the past ten years, there has been a trend towards using FRP composites to manufacture whole/hybrid FRP bridge structures (Hollaway 2010). In these applications, adhesive bonding is usually the preferred joining technique due to its distinct advantages compared with mechanical fastening techniques, such as easier assembly, rapid installation and cost efficiency.

One major drawback when it comes to using FRP composites in steel bridges is the lack of knowledge relating to the long-term performance and durability properties of

FRP/steel bonded joints. In spite of the fact that no major problems associated with adhesive joints have been reported in FRP-bonded steel structures, it is very important to research this subject scientifically, as the decision-making process relating to the selection of FRP solutions is based on life cycle cost analyses which are highly dependent on an accurate service-life prediction for the FRP system.

A review of the literature reveals that of the many different environmental factors influencing the durability of adhesive joints with FRP and metallic adherents, moisture, which can take the form of humidity, liquid water or de-icing salt solutions, is the most problematic substance (Karbhari 2014). Moisture penetrates into the FRP/steel joint through diffusion into adhesive layer, porous FRP adherent and, wicking along the interfaces. The penetrated moisture affects the mechanical properties of the joint through two principal mechanisms; the degradation of the adhesive and/or adherents and the degradation of the adherent/adhesive interface(s). It is therefore very important to have accurate estimations of moisture-diffusion in different joint constituents.

With recent improvements in computational possibilities, advanced numerical methods, such as the finite element (FE) method, can be used to simulate moisture diffusion and investigate its effect on mechanical response of bonded assemblies. However, due to the complexity of numerical multiphysics simulations, very few scientists have addressed the effects of moisture on the structural performance of joints of this kind. The aim of this paper is to shed some light on the effects of hygrothermal aging (combined moisture and temperature effects) on adhesively bonded CFRP/steel joints. This research deals with a crucial step in implementing durability aspects in the design of FRP joints in steel bridges.

2 MOISTURE DIFFUSION THEORY

Fickian diffusion model is often used to simulate moisture diffusion in polymeric materials. The solution to a one-dimensional Fickian diffusion is:

$$M_t = M_\infty \left\{ 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[\frac{-(2n+1)^2 \pi^2 D t}{h^2} \right] \right\} \tag{1}$$

where h is the plate thickness, D the diffusion coefficient, M the moisture content and the subscripts t and ∞ represent the condition at the time of interest and at saturation, respectively. Although Fickian model is valid in many cases, non-Fickian diffusion behavior has been observed for some polymers for long exposure durations at high temperatures (Bordes *et al.* 2009, Jiang *et al.* 2013). In this respect, Placette *et al.* (2012) proposed a dual-stage Fickian model, based on the assumption that Fickian and non-Fickian diffusion (relaxation) occur simultaneously:

$$M_t = M_{\infty,1} \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \mathrm{e}^{\frac{-(2n+1)^2 \pi^2 D_1 t}{h^2}} \right] + M_{\infty,2} \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \mathrm{e}^{\frac{-(2n+1)^2 \pi^2 D_2 t}{h^2}} \right] \tag{2}$$

where $M_{\infty,1}$ is the maximum absorption due to initial Fickian process, $M_{\infty,2}$ the maximum absorption due to relaxation process, and D_1 and D_2 represent diffusion coefficients for initial and relaxation processes, respectively.

3 EXPERIMENTAL PROGRAMME

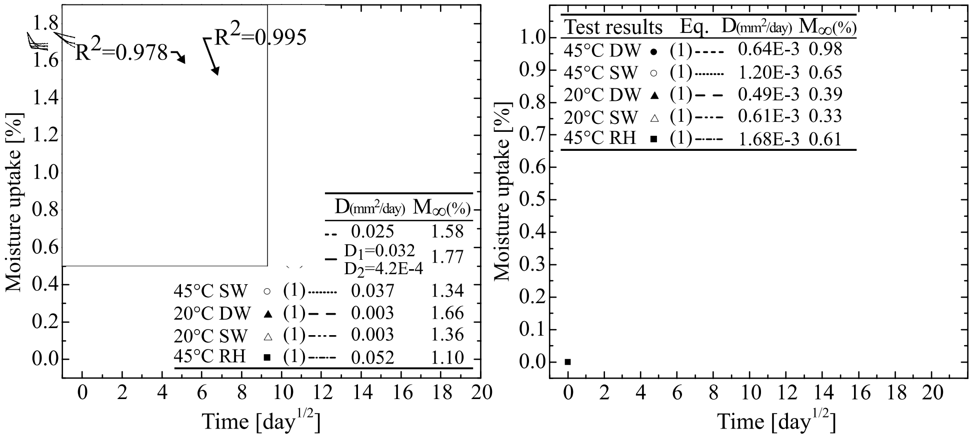
The experimental study includes: (i) gravimetric measurements to characterize moisture diffusion properties, (ii) dog-bone tests to obtain moisture-dependent mechanical properties of adhesive, and (iii) double-lap shear joints to evaluate the effects of hygrothermal aging on adhesively bonded CFRP/steel joints.

Three materials, epoxy adhesive, CFRP laminate and steel S355 (E=210 GPa), were used to manufacture the specimens. The used adhesive is a commercial two-part structural epoxy adhesive, STO® BPE Lim 567, with a glass transition temperature of 55°C. Unidirectional CFRP laminates (E=156 GPa) with nominal thickness of 1.25 mm and a width of 50 mm were provided by Mostostal®.

3.1 Moisture Diffusion Characterization

Five environmental ageing conditions were selected: 20°C deionized water (DW), 20°C 5% NaCl salt water (SW), 45°C 95% relative humidity (RH), 45°C deionized water and 45°C salt water. Ageing was performed on square-shape bulk adhesive, 60×60×1.0 (mm), and CFRP specimens, 50×50×1.25 (mm), for up to a year. To ensure one-dimensional moisture diffusion, the specimens were designed to yield very low ratio for the edge surface area to the total area. The weight gain of the specimens is periodically measured and the results are plotted in Figure 1.

As can be seen, the diffusion rate (initial slope) is increased at higher temperature, while it is not affected by the solution type. Moisture saturation content, however, exhibits a direct relation with solution type where lower values are obtained for salt-water compared with distilled water solution. In addition, much slower diffusion rate and permeability is found for CFRP compared with adhesive specimens, which can be due to different resin and manufacturing methods. The simple Fickian model fits well the measured data with the exception of adhesive specimens conditioned at 45°C DW which exhibit the dual Fickian response.



(a) (b)

Figure 1. Moisture absorption results: (a) adhesive, (b) CFRP material.

3.2 Adhesive Tensile Coupon Tests

The adhesive is often regarded as the weak link in adhesively bonded assemblies. Therefore, a total of 30 dog-bone adhesive specimens were manufactured according to ASTM D638-10. Five specimens were tested directly in the dry state, while all the other specimens were tested after exposure to the aforementioned ageing conditions for 260 days. The results in terms of elastic modulus versus moisture content at the time of testing are plotted in Figure. 2. As shown, the elastic modulus decreases considerably with increasing moisture content. The reduction rate is, however, slightly lower for the salt solution compared with distilled water or vapor. In both cases, linear equations that best represent the experiments are established and are used in numerical analyses.

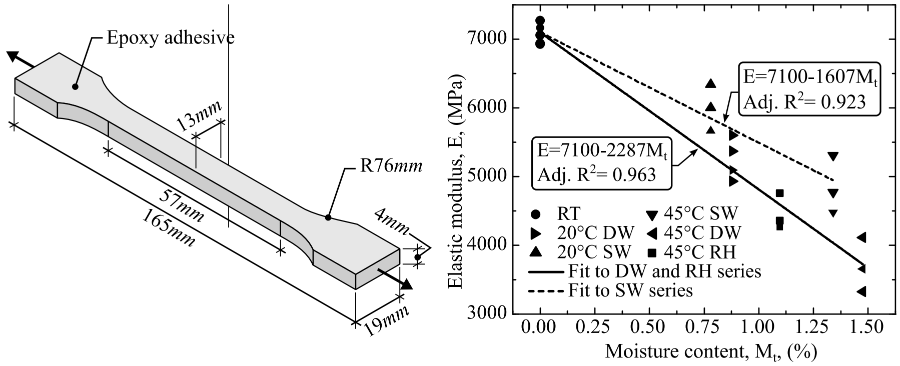


Figure 2. Changes in the elastic modulus of the adhesive versus moisture content.

3.3 Double-lap Shear (DLS) Joints

A total of nine DLS specimens were manufactured, see Figure. 3. Three specimens were directly tested in the dry state and six specimens were exposed to the 45DW ageing condition for up to a year. Of the six aged specimens, three were tested after eight months of exposure, whereas the rest were tested after one year. Monitoring the specimens during tensile tests showed that the failure always initiated from the center of the joint close to the gap location. The relationship between exposure time and residual strength as well as the triggering failure mode are illustrated in Figure. 3.

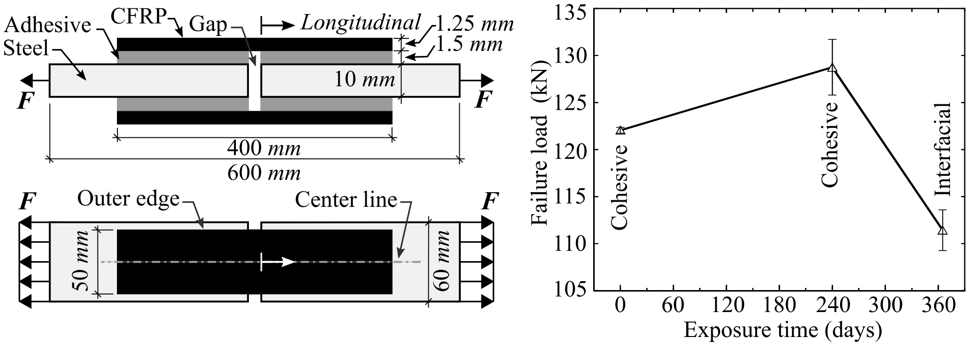


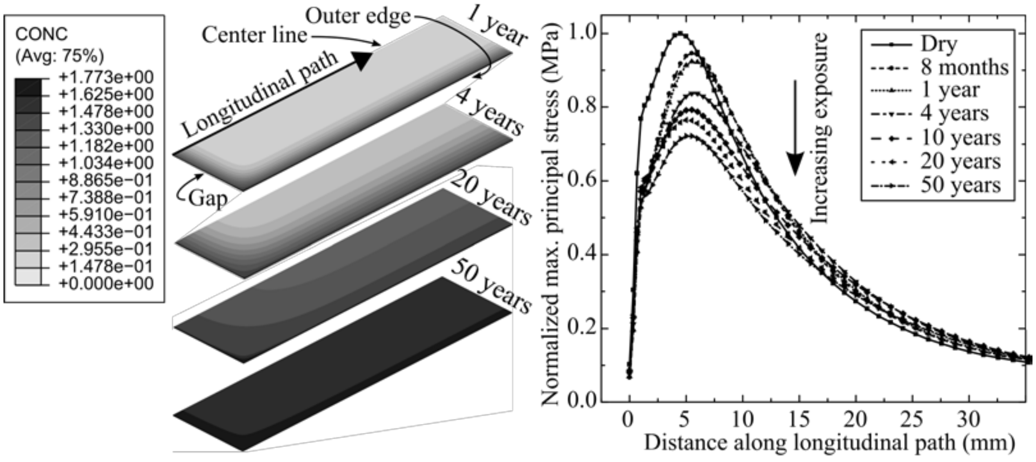
Figure 3. Configuration of DLS specimens and plot of load vs. time of exposure to 45°C DW.

It should be noted that the joint strength increases by 5.5% on average after eight months of exposure compared with dry specimens, whereas, after 12 months, the failure load drops by 8.7%. This observation can be justified by the change in failure mode after 12 months of exposure, which does not allow the adhesive to plasticize.

4 FINITE ELEMENT MODELING

The commercial FE analysis software Abaqus® 6.13 was used for the FE analyses. 3D transient mass-diffusion analyses were conducted in which the moisture concentration of all the surfaces of permeable materials that are in contact with moisture were set to be fully saturated as the boundary conditions. It should be noted that in composite joints with permeable adherends, the moisture concentration profile becomes discontinuous across the joint thickness as the moisture-saturation content is different for the composite and the adhesive. This issue is resolved by using the normalized concentration, $\varphi=C_t/C_\infty$, as the degree of freedom at the nodes. First, to verify the FE analyses, the gravimetric tests were modelled and the results were found to be in very good agreement with experimental data. Next, the verified analysis procedure was used to model moisture diffusion in dog-bone and DLS specimens. Figure. 4(a) shows contour plots of the predicted moisture-concentration profiles in the adhesive mid-layer of the DLS joints immersed in distilled water at 45°C. As can be seen, due to the low permeability of the CFRP, the diffusion through the adhesive edges is dominant. However, as moisture diffusion path from the adhesive edges to the center of the joint is longer, full saturation is not achieved even after 50 years of immersion.

Having obtained the moisture-concentration profile in the DLS joint, the mechanical properties of adhesive are defined as a function of moisture content derived from the tests on dog-bone specimens. Therefore, a sequentially coupled static analysis was defined in which a tensile load was applied to one end of the specimen.



(a) (b)

Figure 4. FE predictions of moisture profile and consequent stress redistribution in DLS joints.

The plots of the maximum principal stress in the adhesive mid-layer along the marked longitudinal path are shown in Figure. 4(b). After eight months of exposure, the peak stress drops by around 5%, which is approximately equivalent to the observed increase in the strength of the tested DLS specimens. Despite almost identical moisture-concentration profiles and stress distributions for specimens aged for eight months and one year, the failure load of the latter series was found experimentally to drop (see Figure. 3). This can be explained by the observed change in the triggering failure mode from cohesive to interfacial, which suggests that the presence of moisture at the interface of steel/adhesive for a critical time can cause localized interfacial damage. In this case, the critical time is exceeded by extending the exposure from eight months to one year, even though the moisture content is very low (less than 1.6%). Thus, although the maximum principal stresses plotted in Figure. 4(b) drop by approximately 30% after 50 years of exposure, the failure load would not be expected to increase.

5 CONCLUSIONS

This study presents the results of ageing tests and coupled finite element analysis of adhesively bonded FRP/steel joints used in civil engineering applications. The CFRP material exhibited very slow diffusion and relatively lower moisture uptake. The elastic modulus of adhesive was found to decrease considerably with increasing moisture content. The reduction was slightly less for salt water than distilled water. Adhesively bonded CFRP/steel DLS joints were also aged in distilled water at 45°C for up to a year. The strength was found to increase by 5.5% after eight months of exposure, while the failure mode remained cohesive. The failure locus of the one-year-exposed series shifted to the interface with steel, which caused the failure load to drop by 8.7%. In addition, FE mass-diffusion analysis was used to simulate moisture ingression into the bonded joints for 50 years. Thereafter, the obtained moisture concentration profile was set as the boundary condition for sequential mechanical analysis. Based on the results, it is anticipated that the presence of moisture at the interface of steel/adhesive for a critical time could cause localized interfacial damage even at low moisture concentrations.

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