MODELING OF MOISTURE DIFFUSION IN CFRP STRENGTHENED CONCRETE BASED ON THERMAL-MOISTURE ANALOGY

Yunfeng Pan[1,2], Guijun Xian[1,2,*] and Hui Li[1,2]

[1] Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education (Harbin Institute of Technology), Harbin 150090, China.

[2] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China. Email: gjxian@hit.edu.cn

ABSTRACT

In this paper, the thermal-moisture analogy schemes were applied to simulate moisture diffusion in an epoxy resin and CFRP strengthened concrete system numerically. The two thermal-moisture analogy schemes were adopted for homogeneous material (e.g., epoxy adhesive) or multi-component material systems. The direct analogy (DA) is only valid for the homogeneous material system and can simulate the moisture diffusion in an epoxy adhesive accurately. The normalized analogy (NA) was proved be an effective tool for the CFRP-concrete system. In addition, based on NA, the interfacial stress and swelling stress induced by water can be simulated accurately.

Keywords

Direct analogy, normalized analogy, CFRP/adhesive interface, adhesive/concrete interface.

INTRODUCTION

Externally bonded fibre reinforced polymer (FRP) composites for civil rehabilitation has become a popular technology in recent years (Shrestha, Ueda et al. 2014). Strengthening depends highly on the integrity of the bond between FRP and concrete substrate (Lau and Büyüköztürk 2010). Some research have been conducted to investigate the long-term performance of bond property experimentally. Until now, however, the effects of the harsh environments on the bond is not yet completely understood, e.g., water immersion, high humidity exposure or freeze-thaw cycles. The durability of FRP-to-concrete system under water immersion is largely controlled by the rate at which water and deleterious ions that use water as a carrier over through the system (Ouyang and Wan 2008). The bond interface at adhesive/concrete and constitute materials are susceptible to water uptake. It is necessary to study the moisture diffusion in the FRP-to-concrete system.

As reported, for the bond between CFRP and concrete substrate, immersion into water at 23 °C and 50 °C for 8 weeks decreases the fracture toughness by 13.8% and 51%, respectively (Au and Büyüköztürk 2006). Exposure to 100% humidity for 10000hrs reduces the bonding strength by 37% for CFRP plate - concrete beam and 10% for CFRP wet layup to concrete (Grace and Grace 2005). Water molecules were found at the interface between the adhesive and concrete after 338 hrs of immersion in water at 24 °C (Nguyen, Byrd et al. 1998). The interface between adhesive and concrete substrate and the adhesive layer are susceptible to degradation significantly owing to the ingress of water. To quantify the moisture transport in the bonding zone between FRP-to-concrete system is needed to understand the effect of moisture ingress on the long term bond performance.

Absorbed moisture in a substance may bring in hygrothermal stress. Therefore, the moisture diffusion on the hygrothermal stress) was analyzed subsequently. The mass diffusion modelling results are difficult to translate into the subsequent analysis for ABAQUS (e.g., static analysis) (Systèmes 2010). In practice, thermal diffusion (heat transfer) function can be adopted to simulate the moisture diffusion by the thermal-moisture analogy scheme. Many researchers have modelled the moisture diffusion in a FRP sheet/plate, an epoxy or the bond area between FRP-concrete (Ouyang and Wan 2008). However, investigations on the moisture diffusion in a multi-component material system are very scarce. As expected, the thermal-moisture analogy can be developed for the simulation of the water diffusion in the constitute materials and interface between the components, e.g., the interface between the resin matrix and fibre.

The present study is to simulate the moisture transportation in a FRP-to-concrete system. The direct analogy and normalized analogy schemes were adopted to investigate the moisture diffusion in the resin matrix and the FRP-concrete system.

THEORETICAL BACKGROUND

THE DIRECT ANALOGY

The moisture diffusion phenomenon can be described by Fick's first law as (Ouyang and Wan 2008, Systèmes 2010).

$$\frac{\partial C}{\partial t} = \nabla(D \times \nabla C) \tag{1}$$

where D is the moisture diffusivity, C is the moisture concentration (the water content in unit volume of substrate), and t is time. Assuming that the moisture diffusivity is uniform ($\nabla D = 0$), and Eq.1 is changed to

$$\frac{\partial C}{\partial t} = D\nabla^2 C \tag{2}$$

However, it cannot apply for movement in the multi-component material system (e.g., FRP) because the moisture content is continuous at the interface.

The result of moisture diffusion is difficult for static analysis. In order to resolve this problem, a thermal analysis is introduced. Conduction heat transfer can be described by Fourier's law (Yoon, Han et al. 2007, Systèmes 2010).

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \nabla(k \times \nabla T) \tag{3}$$

where T and q are the temperature (K) and the heat flux($W\,m^{-2}$), respectively; ∇ is the gradient operator; k is the thermal conductivity ($W\,m^{-1}\,K^{-1}$) for isotropic thermal diffusion. Assuming that the thermal conductivity is uniform ($\nabla k = 0$), the Eq.3 yields the heat conduction equation as

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{4}$$

where α is the thermal diffusivity($m^2 s^{-1}$) , defined as $\alpha = k / \rho C_p$.

In comparison of Eq. 2 and Eq. 4, the temperature (T) and the diffusion coefficient (α) can be equal to the concentration(C) and the moisture diffusion (D), respectively. The direct analogy can be expressed as

Temperature (T) = Concentration (C) (5)

Diffusion coefficient (α) = Moisture diffusion (D) (6)

THE NORMALIZED ANALOGY

Eqs 5 and 6 are valid for the uniform within a homogenous material. In order to be applied for the multi-component materials, the normalized concentration was introduced by Samson Yoon et al. (Yoon, Han et al. 2007). The new variable field can be defined as

$$\phi = \frac{\mathrm{C}}{\mathrm{S}} \tag{7}$$

ϕ is referred to as the "activity" of the material (Systèmes 2010). In this case, the variable is continuous at the interface. The Eq.7 is submitted into Eq.2, it can be expressed as

$$\frac{\partial C}{\partial t} = DS\nabla\phi + D\phi\nabla S \tag{8}$$

It can be assumed that the S is a constant under the given temperature. The Eq.8 can be simplified as

$$\frac{\partial C}{\partial t} = DS\nabla\phi \tag{9}$$

Eq.9 is independent on the S and is only valid when $\frac{\partial S}{\partial t} = 0$. The normalized concentration analogy can be expressed as

Temperature (T) = Normalized concentration (ϕ) (10)

$$k = DS \tag{11}$$

$$\rho C_p = S \tag{12}$$

FINITE ELEMENT MODEL

In the present study, a finite element analysis using ABAQUS software was employed to simulate the moisture diffusion in a substance. The DC2D8 was used for the implementation of the thermal-moisture analogies. It was assumed that the moisture diffusion was driven by the concentration gradient and a two-dimensional model was adopted. The nodes at the interface for the multi-component material are shared. FEM was used to model the changes of the water content based on Eqs 5 and 6 and Eqs 10 - 12, respectively.

The water ingress in a short period is dependent on the capillary action. However, the long-term moisture movement in concrete is generally controlled by the moisture transportation through the gel pores, which is driven by concentration gradient (Ouyang and Wan 2008). Therefore, the water transportation through the concrete, adhesive and CFRP plates are assumed to follow the Fickian law (Yoon, Han et al. 2007, Ouyang and Wan 2008).

DIFFUSION MODELING IN AN EPOXY ADHESIVE

At room temperature, the specimens (25 x 25 x 2 mm) were used for water absorption test. The moisture uptake was determined by periodically weighing the samples taken from the water bath. Due to the symmetric geometry, only half of the epoxy was considered in the finite element analysis. It was assumed that the moisture flux only translate into the epoxy adhesive along the thickness direction of the specimens. Fig.1 shows the specimens geometry and typical results for finite element analysis.

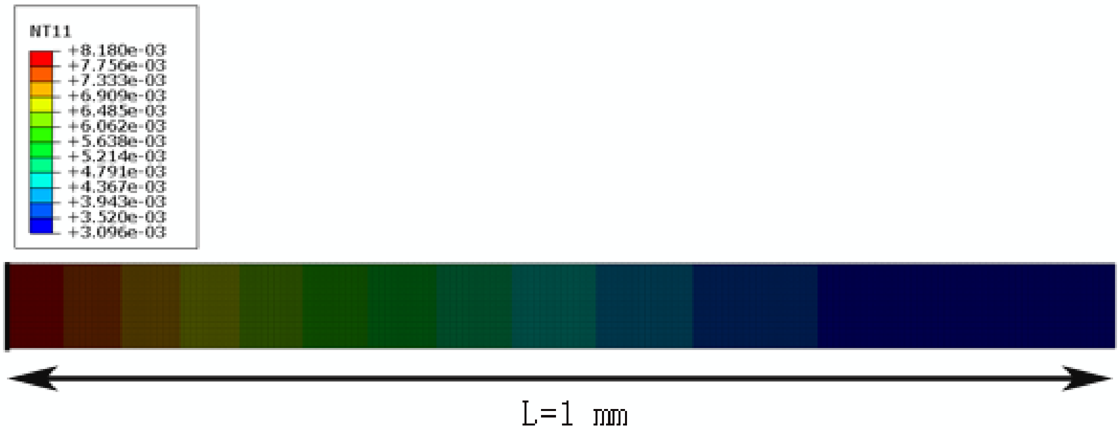


Figure 1 The geometry and typical results of an epoxy adhesive plate sample at 39.32 hrs.

The left boundary condition (black line) was exposed to 100% RH at room temperature. To ensure a high level of numerical accuracy, the element size is set as 0.002 mm. Table 1 shows the properties of the epoxy samples in the simulation.

Table 1 The properties of epoxy adhesive.

		Direct analogy(DA)	Normalized analogy(NA)
	Field variable	Moisture concentration (C)	Normalized concentration (ϕ)
Epoxy Adhesive	Density	1	1
	Conductivity	2.17 x 10^{-6}	1.8 x 10^{-7}
	Specific heat	1	0.818

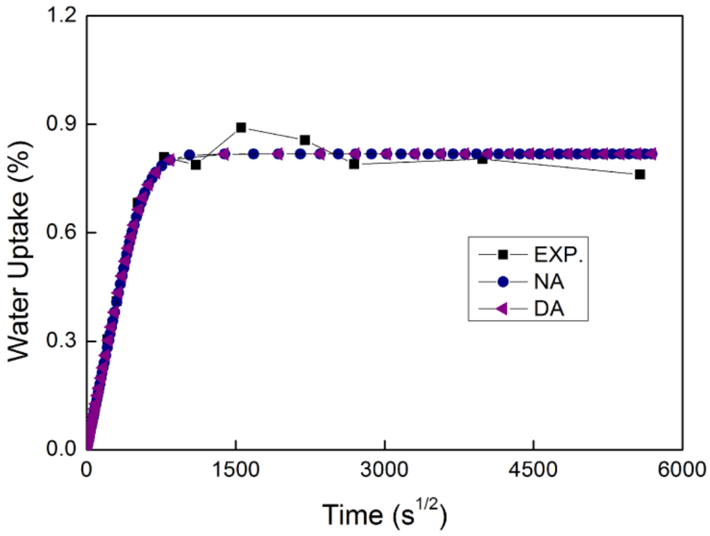


Figure 2 Comparison of the water uptake – square root of exposure time curves from experimental test and simulation based on NA and DA.

The moisture uptake of the epoxy adhesive as square root of the exposure time is shown in Fig.2. The weight gains of the adhesive samples increase proportionally to the square root of immersion time before reaching the saturation level, after one year and it follows the Fickian law of moisture uptake (Karbhari and Xian 2009).

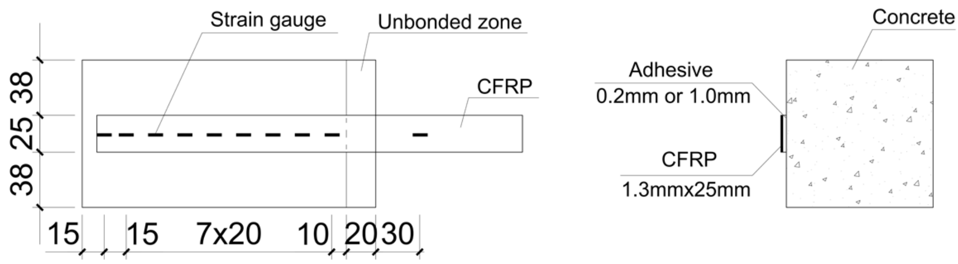
$$M_t = M_\infty \left\{1 - \exp\left[-7.3\left(\frac{Dt}{h^2}\right)^{0.75}\right]\right\} \quad (13)$$

where M_t is the moisture uptake at time t, M_∞ is the quasi-equilibrium moisture uptake, D is the diffusion coefficient, h is the thickness of the sample (2 mm for the samples in the experiment). D and M_∞ were determined using curve fitting with Eq.13, and 0.217 x 10^{-6}, 0.818% were determined for D and M_∞, respectively.

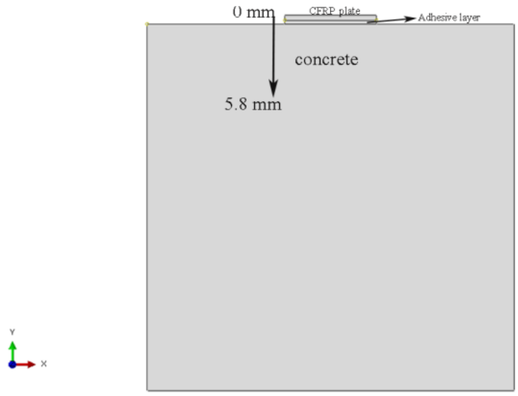
The results obtained from analogy schemes of the NA and DA are shown in Fig.2. It is obviously observed that both NA and DA produce the same moisture diffusion process. Fig.2 shows that the test of water uptake-time curve are accurately predicted by FEM model. It indicates that the NA and DA can handle the single-material system. The discrepancy after 167 days between FEM results and experimental results obtained owing to the swelling, plasticization, and irreversible damage (Karbhari and Xian 2009). It results in the damage of epoxy. The damage of epoxy was not considered in present FEM model.

DIFFUSION MODELING IN CFRP-TO-CONCRETE SYSTEM

In practice, the adhesive is located at the interface between CFRP plate and the concrete substrate and it is not feasible to directly measure the water ingress. It was assumed that there is no moisture flux along the longitudinal direction of the specimens. Figure 3a schematically represents the single-lap shear testing specimen and a two-dimensional model was shown in Figure 3b. Table 2 shows the constitute materials property in the simulation.



(a)



(b)

Figure 3 Schematic sketch of the single-lap shear testing setup (a), and 2 D model in ABAQUS (all units in millimeters) (b).

Table 2 Material properties of CFRP-concrete system.

		Direct analogy(DA)	Normalized analogy(NA)
	Field variable	Moisture concentration (C)	Normalized concentration (ϕ)
CFRP plate	Density	1	1
	Conductivity	4.36 x 10^{-7}	3 x 10^{-8}
	Specific heat	1	0.007
Adhesive	Density	1	1
	Conductivity	4.4 x 10^{-5}	1.2 x 10^{-6}
	Specific heat	1	0.027
Concrete	Density	1	1
	Conductivity	3 x 10^{-3}	2.1 x 10^{-4}
	Specific heat	1	0.071

Figure 4 shows the simulation results based on the two analogy schemes. The average moisture content in the CFRP-to-concrete system at different location (from 0 mm to 5.8 mm) in terms of the nodal heat corresponding to various immersion times was determined. As shown in Figure 4a, the moisture content in the concrete is more than that of the adhesive and CFRP plate. The water mainly comes from the adjoining laminate, e.g., the moisture molecular migrating from the concrete to the adhesive. The phenomenon is observed from the simulation results based on both NA and DA from 2 weeks to 8 weeks in Figure 4. It can be understood that more moisture molecular comes from the materials with higher equilibrium moisture content of materials to the materials with lower equilibrium moisture content. The continuous moisture distribution for the direct analogy is observed at CFRP/adhesive (1.4 mm) and adhesive/concrete (2.4 mm) interfaces. The moisture content at CFRP/adhesive interface (1.4 mm) subjected to 2 weeks immersion is more than the equilibrium moisture content of the adhesive (as shown in Figure 4b,c&d), whereas it violates the constrains of the analogy schemes. The same case is found at 2.4 mm.

The normalized analogy produces the discontinuity of moisture distribution both at CFRP/adhesive and adhesive/concrete interface (see in Figure 4). This discrepancy at the interface is mainly attributed to the different constitute equilibrium moisture content. The swelling stress is determined by Eq.14 (Systèmes 2010).

$$\sigma = \alpha \Delta c \qquad (14)$$

where α is coefficient of moisture expansion, Δc is moisture content.

In comparison of the normalized analogy, it indicates that the DA causes the substantial errors in calculating. The interfacial stress and constitute materials of swelling stress can be induced by water.

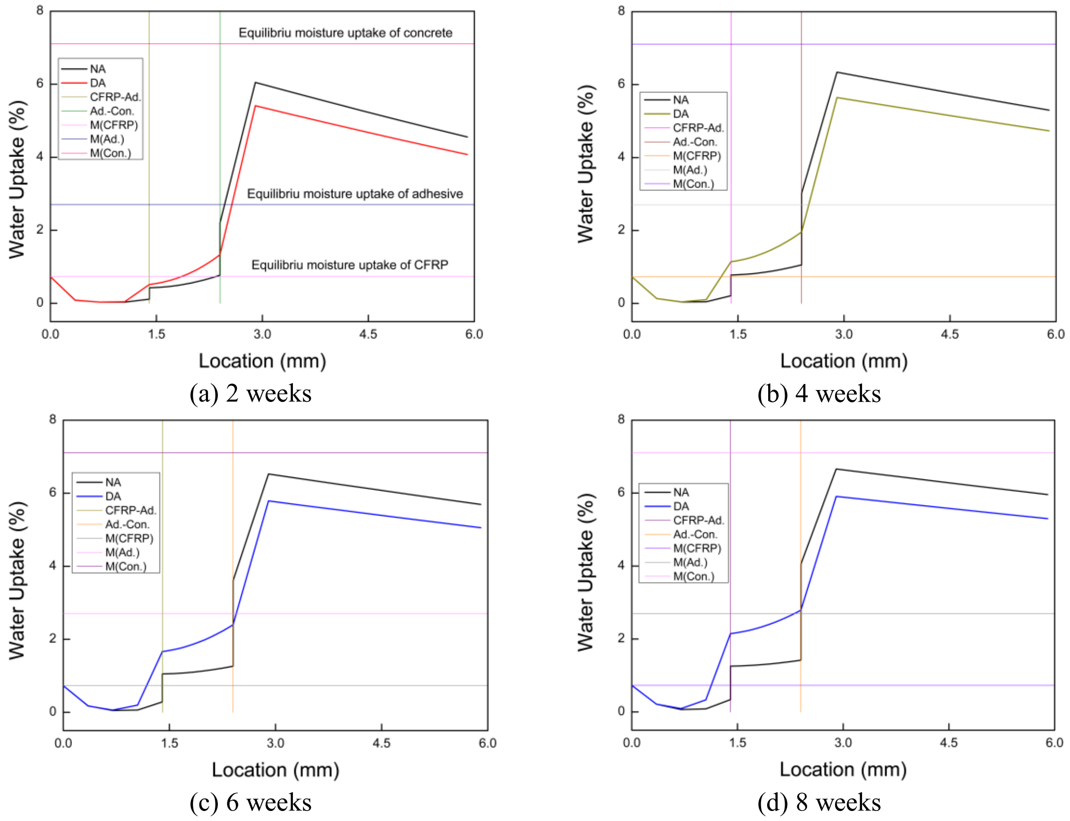


Figure 4 Moisture diffusion in the CFRP-to-concrete system.

CONCLUSION

The paper reviewed the thermal-moisture diffusion analogy schemes and investigated the diffusion and distribution of moisture in a homogeneous material system (i.e., epoxy adhesive) and CFRP-to-concrete system by FEM. Based on the simulated results, the following conclusions can be drawn.

1) The direct analogy is only valid for the homogeneous material. It cannot simulate the moisture distribution at the interface for the multi-component material system.

2) The normalized analogy can obtain the correct moisture distribution at the interface for the multi-component material system. It is an effective method to investigate the swelling stress induced by the water ingress for CFRP-to-concrete system.

ACKNOWLEDGEMENTS

This work was financially supported by the National Key Basic Research Program of China (973 Program) with Grant No. 2012CB026200, and by NSFC with Grant No. 51178147 & 51478145.

REFERENCE

Au, C. and O. Büyüköztürk (2006). "Peel and shear fracture characterization of debonding in FRP plated concrete affected by moisture." *Journal of Composites for Construction* 10(1), 35-47.

Grace, N. F. and M. Grace (2005). Effect of repeated loading and long term humidity exposure on flexural response of CFRP strengthened concrete beams. *Proceedings of the International Symposium on Bonded behavior of FRP in Structures (BBFS 2005), Chen and Teng (eds)*.

Karbhari, V. M. and G. Xian (2009). "Hygrothermal effects on high V f pultruded unidirectional carbon/epoxy composites: Moisture uptake." *Composites Part B: Engineering* 40(1), 41-49.

Lau, D. and O. Büyüköztürk (2010). "Fracture characterization of concrete/epoxy interface affected by moisture." *Mechanics of Materials* 42(12), 1031-1042.

Nguyen, T., et al. (1998). Water at the polymer/substrate interface and its role in the durability of polymer/glass fiber composites. *Proc., Durability of Fibre Reinforced Polymer (FRP) Composites for Construction (CDCC'98), 1st Int. Conf.*

Ouyang, Z. and B. Wan (2008). "Modeling of moisture diffusion in FRP strengthened concrete specimens." *Journal of Composites for Construction* 12(4), 425-434.

Shrestha, J., et al. (2014). "Durability of FRP concrete bonds and its constituent properties under the influence of moisture conditions." *Journal of Materials in Civil Engineering*.
Systèmes, D. (2010). "Abaqus 6.10 online documentation." *Abaqus User Subroutines Reference Manual*.
Yoon, S., et al. (2007). "On moisture diffusion modeling using thermal-moisture analogy." *Journal of Electronic Packaging* 129(4), 421-426.