WATER PERMEABILITY IN FIBER REINFORCED

PLASTIC (FRP)-WRAPPED CONCRETE

by

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ABSTRACT

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A finite element analysis is performed using ANSYS software to analyze the progress of water and its circulation in FRP-wrapped concrete. This paper presents the modeling of water diffusion in FRP. Finite element programs do not usually address the issue of permeability or diffusion. Therefore, diffusion of water in FRP is modeled by an analogy with thermal conduction. A theoretical background is presented in the paper. The recommended finite element modeling procedures are listed. Diffusion coefficient of FRP matrix Tyfo SCH 41S-1 obtained from an inspection report is used to analyze water permeability of FRP. Tyfo SCH 41S-1 is the most popular FRP used by Tx DOT in most of their bridge retrofit projects. Use of real material property with the proper boundary conditions has made this study more realistic. This paper explains how to model water diffusion using ANSYS software. Not only modeling, it also presents the results and conclusions.

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CHAPTER 1

INTRODUCTION

<u>1.1 Background</u>

Deterioration, damage, and defects in concrete structures are the main causes for concrete repair. Studies show, over 500 million cubic yards of concrete are replaced every year in the United States alone. These repairs are needed to improve and prolong service life of these structures. Structural health monitoring is a vital aspect of the maintenance of large civil infrastructures and extending service life, especially in areas of high seismic activity and corrosive environment. There are many ways of repairing existing concrete structures such as epoxy-coating and protective coatings. Fiber Reinforced Plastic (FRP) wrap is an effective product used for rehabilitation and strengthening of concrete structures. Figure 1.1 shows a structure being repaired with a composite wrapping system.

Figure1.1 FRP Wrapped Structure (Source: www.quakewrap.com)

FRP composite materials have been used in recent years as a method of providing added strength and ductility to existing reinforced concrete structures. The conventional FRP system is a fabric saturated with an epoxy resin, which is "wrapped" in layers on the concrete

surface. FRP wrapping has been the most widely used in applications where seismic actions pose a threat to the strength and deformation capacity of an existing structure.

FRP is a composite material widely used in structural strengthening for steel, wood, concrete, seaport and aerospace applications. Because of its cost-effectiveness and superior performance in strength, self-weight, corrosion resistance, blast resistance and earthquake protection, FRP is widely used in retrofitting projects. FRP-wrapped specimens exhibit prolonged life, decreased reinforcement mass loss, and reduced concrete chloride content. Studies on bond durability show that moisture plays an important role in the reliability of the bond between FRP and concrete. The interfacial adhesion between FRP and concrete is at risk of moisture attack. Therefore, further investigation of the progress and circulation of moisture in FRP-wrapped concrete structures is needed.

<div align="center">1.2 Research Objectives</div>

The main objective of this research is to perform a finite element analysis of FRP-wrapped concrete using ANSYS software to analyze progress of water ingress and its circulation. This thesis presents the modeling of water diffusion in FRP. Finite element programs do not usually address the issue of diffusion. Diffusion of water in FRP can be modeled by an analogy with thermal conduction. Finite element analyses were performed to study the moisture diffusion in the FRP-adhesive-concrete system. The objectives of computer modeling are to:

• Examine the water diffusion in FRP-wrapped concrete; and

• Establish a methodology for applying computer modeling to reinforced concrete beams and bridges strengthened with FRP.

CHAPTER 2

LITERATURE REVIEW

Significant research has been conducted on the modeling of the moisture diffusion in porous material, composite, and polymer. Little research has been conducted on the moisture transportation in multilayered structures containing FRP composites, polymer adhesive and concrete.

Weitsman, Y. (1977) investigated the water attack on epoxy and mild steel joints. The results indicated that the deprivation of joints could be defined as the attainment of a critical moisture status at the bond interface. Nguyen, T. (1998) directly measured the moisture status at the bond interface of an epoxy covered concrete specimen. The results indicated that a few water molecule layers were present in the epoxy and concrete interface after the specimens were exposed to water for certain duration. Ouyang, Z. and Wan, B. (2008), conducted an experimental study to investigate the relation between the bond interface region, relative humidity, and fracture energy of FRP and concrete bond joints. The results showed that interface region relative humidity was one of the primary factors that affected the bond fracture energy of FRP and concrete specimen in a moist environment. The results indicated highly uneven moisture distribution along adhesive thickness, especially for a relatively short period of exposure. This causes the adhesive layer to have highly even distribution of its mechanical properties. The moisture accumulated in the interface mainly came from the bond free area close to the FRP and the sides of the specimen. Higher environmental RH increased not only the IRRH at the given exposure time, but also the wetting speed.

2.1 Significance of FRP Retrofit

Shoemaker, C. L (2004) shows: there are 235,000 traditionally reinforced concrete bridges and 108,000 prestressed concrete bridges in the U.S.A. Out of them, 15% are

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structurally deficient because of corrosion and other deterioration related mechanisms. The main contributing factors are changes in their use, amplified load requirements and corrosion deterioration due to exposure to adverse environment. In order to safeguard these bridges, rehabilitation is considered vital to maintain their ability to carry traffic and to boost public safety. Repair methods include surface repair systems, removal and replacement, protective coatings, membranes, pile jacketing, strengthening systems, and crack repair.

FRP composites have been used only for a few years for strengthening structural members in reinforced concrete bridges. It has been found FRP composite strengthening as an efficient, reliable, and cost-effective means of rehabilitation. As an example, Horsetail Creek Bridge used in Columbia River Highway east of Portland, Oregon is classified as a structurally poor bridge (Kachlakev, D. 2001). This famous bridge built in 1914 is used on the Historic Columbia River Highway. Initially, it was not considered to be adequate to carry traffic loads. No shear stirrups were provided in any of the beams. In general, the structure was in very good condition except for a number of exposed and corroded reinforcing steel found throughout by an on-site inspection. The Oregon Department of Transportation (ODOT) decided to use FRP composites to reinforce the beams. Strengthening the beams with FRP composites was considered to be the best option due to the historic character of the bridge, insufficient funding, and time constraints.

<div align="center">2.2 Types of FRP Retrofit</div>

There are several methods used for retrofitting of concrete structures using FRP, as follows:

<div align="center">2.2.1 FRP Jacketing</div>

According to Miller E. A. (2006), FRP confinement can be provided using several composite materials including fiberglass, carbon fiber, and Kevlar bonded to the confined concrete surface using epoxy. FRP jackets do not affect the weight and cross-section of the retrofitted member. Since stress concentrations can build up in the FRP wrap around the

corners of square or rectangular cross-sections, FRP jackets are mainly applicable for circular columns. Two types of FRP retrofits, wraps and prefabricated composite jackets, are typically used. An FRP jacket requires preparation of the surface to be retrofitted. It takes less time to prepare surfaces for circular sections. Actual application of the material does not take a long time. This method provides ample protection from corrosion, but is susceptible to fire damage.

<div align="center">2.2.2 FRP Wraps</div>

FRP wraps have several advantages including high strength, light weight, resistance to corrosion, low cost and flexibility (Saadatmanesh et al. 1997). Figure 2.2.1 shows the portion of FRP wrapped concrete specimen. FRP wrapping is performed by first cleaning the surface of the member to be retrofitted. Epoxy or resin is then used to attach the FRP fabric to the surface of the member.

The preferred method is to soak the fabric in epoxy before application to allow for better adhesion to the member. The fabric is then curved out to make sure no air pockets exist and extra epoxy is squeezed out from the sides. A new layer of epoxy should be applied between each layer of fabric and a final layer of epoxy on the outermost surface of the fabric. The wrap should then be allowed to cure at ambient temperatures.
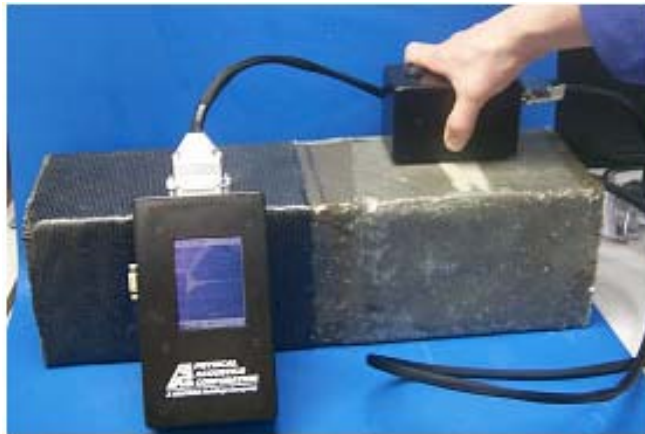
Figure 2.1 FRP Wrapped Concrete (Source: www.pacndt.com)

Saadatmanesh et al. (1997) applied FRP wraps to repair harshly damaged reinforced concrete columns. Seriously stressed regions such as near the column footing joint are repaired

with FRP wrap. It is obvious from the results presented in his research that FRP composite wraps effectively restore flexural strength and ductility in damaged columns.

Carbon FRP wrap were used to improve the performance of reinforced concrete cap beams and cap beam-column joints. The FRP wraps can significantly increase the shear capacity and ductility of cap beams and cap beam-column joints. Added layers of FRP resulted in increased flexural strength.

Verhulst et al, (2001) present the detailed procedure involved in FRP wrapping. There are three major steps in wrapping procedure. First step is to prepare all specimens according to the manufacture's instruction. In this step, one has to ensure adequate adhesion and secure encapsulation of the concrete. A surface has to be cleaned and free of all rough edges, which can be done by grinding the surface of the concrete. Second step is to mix all the epoxy matrix components and apply onto the cut fabric. Saturated fabric is applied on the concrete specimens making sure air bubbles were pushed out manually before applying a new layer. Figures 2.2 through 2.4 shows these steps.

Figure 2.2 Cut FRP Fabric (Source: Verhulst et al, 2001)

Figure 2.3 Application of Epoxy on FRP (Source: Verhulst et al, 2001)

Figure 2.4 Wrapped Columns (Source: www.sciencedirect.com)

Third step is post wrap treatment. In this step, defects are repaired by injecting a thick epoxy mix into the wrap. All edges of the FRP wrap have to be ground off to prevent it from absorbing moisture. After surface achieves a tacky feel, composite are painted. Figure 2.5 and 2.6 shows these steps.

Figure 2.5 Sealing Voids (Source: Verhulst et al, 2001)

Figure 2.6 Painting FRP Wrapped Column (Source: Verhulst et al, 2001)

<u>2.2.3 Prefabricated FRP Composite Plates</u>

FRP composite plates are, in general, shells which are prefabricated in a quality-controlled setting prior to field application. Fiber reinforcement is united with resin and allowed to cure in the preferred dimensions to create a shell. Shells are fabricated to form a multilayer roll or cut into an individual single-layer. Once cured, the shells are opened and clamped around the column to be retrofitted. Adhesive or epoxy is applied to connect the shells to the column surface. Extra adhesive is applied between each shell layer. Xiao and Ma (1997) have used prefabricated glass fiber shells to repair damaged full-size, "as built" columns. It was found that prefabricated jacket systems delay column failure by improving the hysteretic response and increasing the ductility of the retrofitted specimens. Xiao et al. (1999) continued this research by testing plates individually cured and plates cured together as a continuous system. They found improved shear and ductility and considerable difference between the two systems.

Prefabricated plates and FRP fabric increase the load carrying capacity of a bridge and its stiffness. There is no need for formwork and extra concrete if FRP retrofitting is used. Surface preparation is very important in FRP retrofit. FRP wraps are very sensitive to stress concentrations. The prepared surface needs to be clean but rough enough to provide a bond for the material. All retrofit methods discussed show increased member strength and confinement. If prefabricated plates are prepared, an additional cost is associated with the production of the plates.

<u>2.3 FRP Confinement</u>

As shown in website (www. quakewrap.com), FRP confined concrete behaves differently than concrete confined by steel transverse reinforcement. Resin type should not manipulate the confining effect of FRP. Shape of cross sections of columns can directly affect the confinement effectiveness of externally bonded FRP jackets. Benefit of strength is higher for circular than for square or rectangular sections. Poor confinement may be due to low FRP jacket stiffness (dependent on type of FRP and number of plies) or to sharp edges in cross-

sections. Carbon and glass fiber wraps are two of the most widely used fiber composites. Usually, fiber composites behave linearly elastic to failure. E-glass is one of the oldest and least expensive of all composites. Disadvantages of E-glass include lower modulus, lower fatigue resistance, and higher fiber self-abrasion characteristics as compared to other structural FRP.

<div align="center">2.4 Theoretical Background</div>

The ANSYS 13.0 software was used herein to model water diffusion in FRP. In order to model water diffusion into FRP, an adaption of the heat flow equations had to be used. Fick's first and second laws for diffusion in one dimension is as follows (Mrotek, J. L 2001):

$$F = -D\frac{\partial C}{\partial x} \qquad (2.4.1)$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 x} \qquad (2.4.2)$$

Where,

F= heat flux; C = Concentration of diffusion; X = distance; D = Diffusion coefficient; T= time

The corresponding heat transfer equations are (Mrotek, J. L 2001):

$$F = -k\frac{\partial \theta}{\partial x} \qquad (2.4.3)$$

$$\frac{\partial \theta}{\partial t} = (\frac{k}{c\rho})\frac{\partial^2 \theta}{\partial^2 x} \qquad (2.4.4)$$

Where,
θ= Temperature; K = thermal conductivity; ρ= Density; C = the specific heat per unit mass

By comparing Eqs. 2.4.1, 2.4.2, 2.4.3, and 2.4.4, diffusion can be modeled by equating temperature to concentration and the diffusion coefficient to thermal diffusivity. If it is assumed that the moisture forms an ideal solution in the polymer then relative humidity can be equated to

the concentration in the polymer i.e. temperature in heat transfer, then without loss of generality we can take cp equal to 1, and D equivalent to k (Mrotek, J. L 2001).

If the water needs to be modeled with different solubility, it should be noted that diffusion is controlled by activity gradient. The relative humidity is only equal to the molar concentration when the activity coefficient is equal to one. Activity (a) is defined as in Eq. 2.4.5. (Mrotek, J. L 2001).

$$a = \frac{PH_2O}{P_{sat}} = RH = \gamma * x \qquad (2.4.5)$$

Where γ^*= Activity coefficient (constant); x = Mole fraction of water polymer; PH_2O= Partial pressure of water; P_{sat}= Saturated vapor pressure. The activity can be related to the concentration of moisture, C, by Eq. 2.4.6 (Mrotek, J. L 2001).

$$a = \gamma_{eff} C \qquad (2.4.6)$$

$$\gamma_{eff} = \gamma * f \qquad (2.4.7)$$

Where, γ_{eff}= effective activity coefficient; f = conversion factor between concentration in the polymer and vapor pressure in the surrounding air. The activity is equal to the relative humidity (Mrotek, J. L 2001).Therefore, the relationship between the relative humidity and concentration of moisture can be concluded in Eq. 2.4.8.

$$RH = \gamma_{eff} C \qquad (2.4.8)$$

By comparing equations 2.4.1, 2.4.2, and 2.4.6 we can conclude:

$$D' = D / \gamma_{eff} \qquad (2.4.9)$$

The solubility of water in the polymer, C_∞, is the concentration of moisture in equilibrium with 100% humidity in the surrounding air. From 2.4.8,

$$C_\infty = \frac{1}{\gamma_{eff}} \qquad (2.4.10)$$

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Thus, different solubility can be accounted for by varying γ*eff*. A polymer with high solubility will have a low γ*eff*. An equivalency between the diffusion and heat transfer parameter is needed to model different solubility in ANSYS. Table 2.4.1 shows the equivalency of Diffusion and Heat Transfer.

Table 2.1 Diffusion and Heat Transfer Parameter Equivalency Table (Mrotek, J. L 2001)

Diffusion	Heat Transfer
RH	T
D/γ_{eff}	K
D	$k/c*\rho$
	ρ = 1(for convenience)
	$c = \dfrac{1}{\rho \gamma eff}$

According to Ouyang, Z. and Wan, B. (2008), moisture potential can be included via Kelvin-Laplace equation in the form of relative humidity as shown in Eq. 2.4.11:

$$\varphi = \frac{RT}{W_u} InRH$$

(2.4.11)

Where φ =moisture potential; T= temperature in Kevin; Wu= molecular weight of the water; R= gas constant and H=relative humidity.

Polymer and composites are nonporous material for which the moisture diffusion is controlled by the water activity gradient for a given temperature. The relative humidity can be considered equivalent to the water activity gradient for the nonporous materials. Ouyang, Z. and Wan, B. (2008) further states, Eqs. 2.4.12, 2.4.13, and 2.4.14 can be derived in terms of relative humidity for concrete, epoxy, and FRP:

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$$\frac{\partial H}{\partial t} = \nabla\{D^c(H)x\nabla H\} \quad \text{For concrete} \qquad (2.4.12)$$

$$\frac{\partial H}{\partial t} = \nabla\{D^e(H)x\nabla H\} \quad \text{For epoxy} \qquad (2.4.13)$$

$$\frac{\partial H}{\partial t} = \nabla\{D^f(H)x\nabla H\} \quad \text{For FRP plate} \qquad (2.4.14)$$

Where $D^c(H), D^e(H), D^f(H) =$ moisture diffusivity of concrete, epoxy and FRP

respectively.

Ouyang, Z. and Wan, B. (2008) showed that diffusivity of concrete is nearly constant for relative humidity greater than 90% and smaller than 70%. However, the diffusivity drastically decreases in between 70-90% relative humidity. A simplified model of diffusivity for concrete is shown in Figure 2.7. In this multi-linear model, the diffusivity is a constant, which equals D_0 when the relative humidity is smaller than H_{1D}. When the relative humidity is greater than H_{1D} but smaller than H_{2D}, the diffusivity is proportional to the relative humidity with slope of K_{D1}. When the relative humidity is greater than H_{2D} but smaller than H_{3D}, the diffusivity is proportional to the relative humidity with slope of K_{D2}. When the relative humidity is greater than H_{3D} and up to 100% RH, the diffusivity keeps constant again as D_∞.
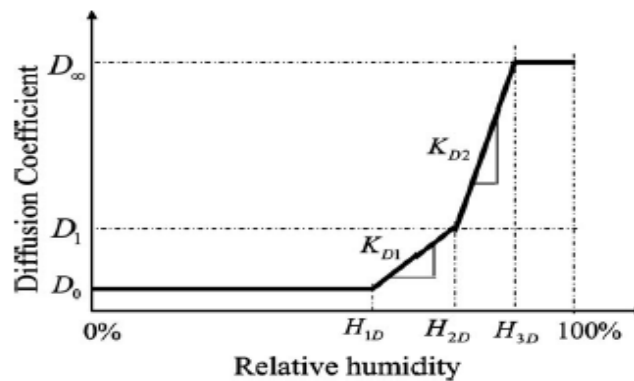
Figure 2.7 Diffusivity Model of Concrete (Ouyang, Z. and Wan, B. 2008)
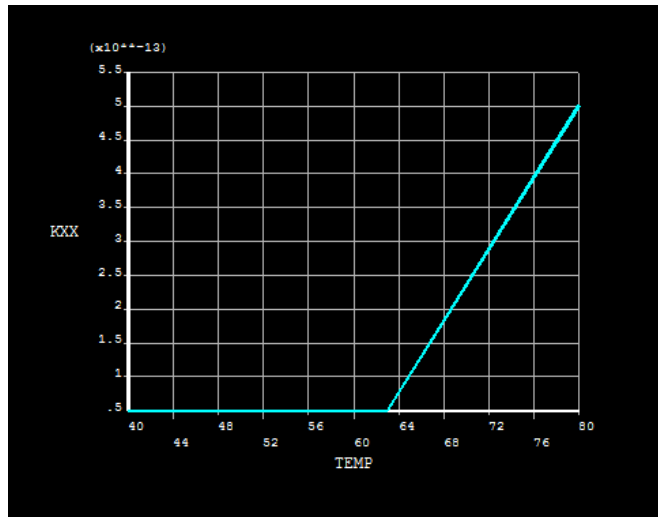
Figure 2.8 Conductivity vs. Temperature Graph of Concrete

As explained in section 2.4, diffusivity represents conductivity and relative humidity represents temperature while modeling in ANSYS. To prove this point, a graph of conductivity vs temperature of a concrete was plotted in ANSYS as shown in Figure 2.8. Comparing Figure 2.7 and 2.8, a similar pattern of graph can be noticed.
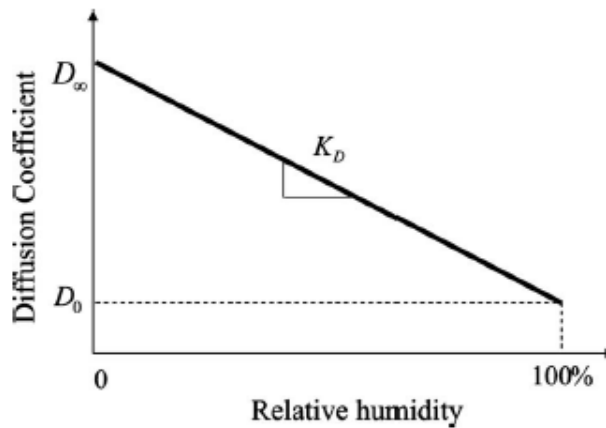
Figure 2.9 Diffusivity Model of Epoxy (Ouyang, Z. and Wan, B. 2008)

Ouyang, Z. and Wan, B. (2008) further states, the diffusivity of epoxy normally decreases with the increase of relative humidity of epoxy from available test data. This trend is opposite to that of concrete. A linear diffusivity model of epoxy is shown in Figure 2.9. Similarly, conductivity vs. temperature of epoxy adhesive is plotted in ANSYS as shown in Figure 2.10. Comparing Figure 2.9 and 2.10 also demonstrate the similar graph pattern.
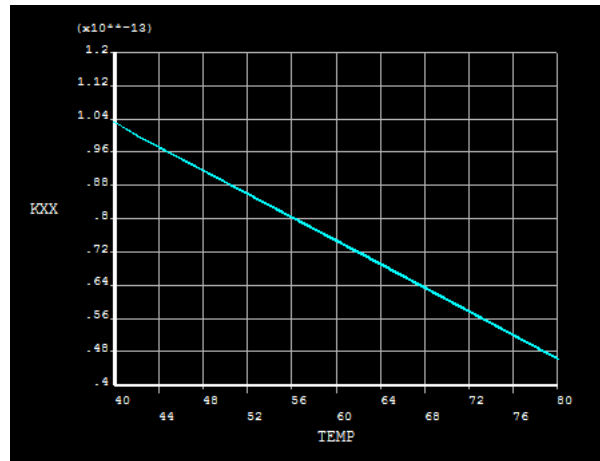
Figure 2.10 Conductivity vs. Temperature Graph of Epoxy

The environmental RH can be transferred to moisture content in the form of weight percentage in concrete by the help of isotherm curve of concrete as shown in Figure 2.11.
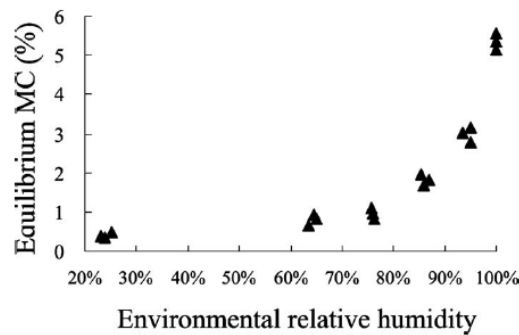
Figure 2.11 Moisture Isotherm Curve of Concrete (Ouyang, Z. and Wan, B. 2008)

CHAPTER 3

INTRODUCTION TO FINITE ELEMENT ANALYSIS

Finite element analysis consists of modeling a part by breaking it down into small discrete pieces, which are called elements. The quantity of interest is assumed to vary simply across each element to form a piece wise approximation to the behavior across the whole specimen.

FRP composites consist of two constituents. The constituents are combined at the macroscopic level. One constituent is the reinforcement, which is embedded in the second constituent, a continuous polymer called the matrix. The reinforcing material is in the form of fibers such as carbon and glass, which are typically stiffer and stronger than the matrix. The FRP composites are anisotropic materials; which means that their properties are not the same in all directions.
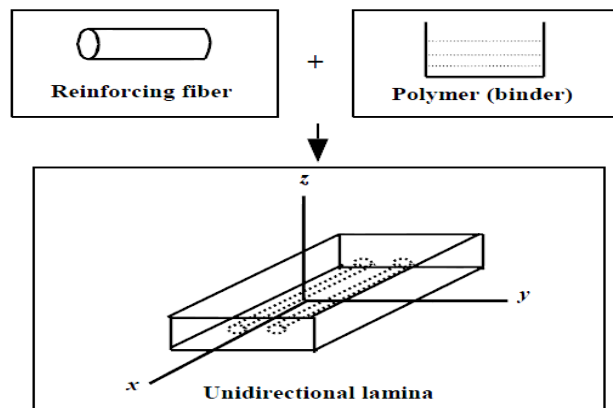
Figure 3.1 Diagram of FRP Composites (Kachlakev, D. 2001)

As shown in Figure 3.1, the unidirectional laminas have three mutually orthogonal planes of material properties. The xyz coordinate axes are referred to as the principal material coordinates where the x direction is the same as the fiber direction, and the y and z directions are perpendicular to the x direction. The orthotropic material is also transversely isotropic, where the properties of the FRP composites are nearly the same in any direction perpendicular to the fibers. Thus, the properties in the y direction are the same as those in the z direction (Kachlakev, D. 2001).

<u>3.1 Types of Element Used</u>

ANSYS PLANE77 is a higher order version of the 2-D, 4-node thermal element (PLANE55). The element has one degree of freedom, temperature, at each node. The 8 node elements have compatible temperature shapes and are well suited to model curved boundaries like FRP wrapping.

The 8-node thermal element is applicable to a 2-D, steady-state or transient thermal analysis.

Figure 3.2 PLANE77 Geometry (ANSYS 1998)

The geometry, node locations, and the coordinates system for this element are shown in Figure 3.2. The element is defined by eight nodes and orthotropic material properties. A triangular shaped element may be formed by defining the same node number for nodes K, L, and O.

Orthotropic material directions correspond to the element coordinate directions. Specific heat and density are ignored for steady-state solutions. Convection or heat flux (but not both) and radiati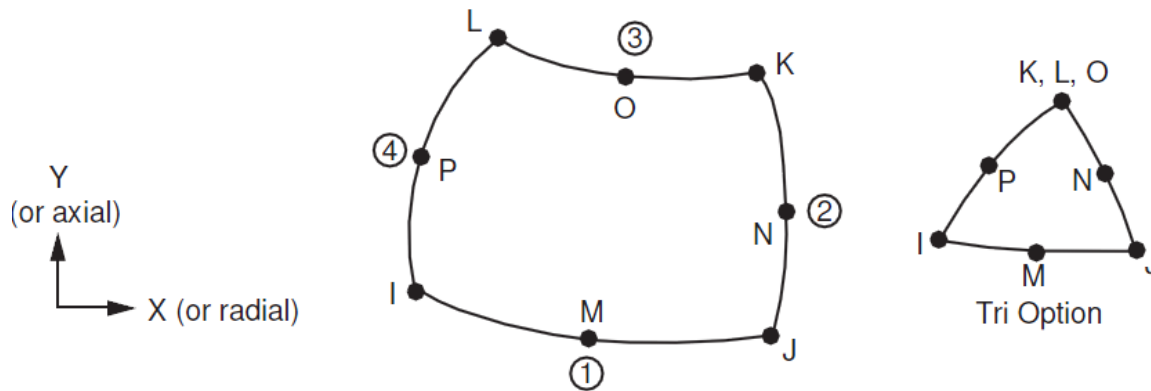on may be input as surface loads at the element faces. Heat generation rates may be input as element body loads at the nodes.

3.2 PLANE77 Assumptions and Restrictions (ANSYS 1998)

- The area of the element must be positive.

- The 2-D element must lie in a X-Y plane and the Y-axis must be the axis of symmetry for axisymmetric analysis.

- An axisymmetric structure should be modeled in the +X quadrants. A face with a removed midside node implies that the temperature varies linearly, rather than parabolically, along the face.

- The specific heat and enthalpy are evaluated at each integration point to allow for abrupt changes within a coarse grid.

- Thermal transients having a fine integration time step and a severe thermal gradient at the surface will require a fine mesh at the surface.

3.3 Finite Element Discretization

Finite element analysis first requires meshing of the model. In other words, the model is divided into a number of small elements, and after loading, temperature contours are plotted. A vital step in finite element modeling is the selection of the mesh density. A convergence of results is obtained when a sufficient number of elements is used in a model. This is achieved when an increase in the mesh density has an insignificant effect on the results. In this finite element modeling, smart mesh tool was used to mesh the model.

3.4 Nonlinear Solution

In nonlinear analysis, the total load applied to a finite element model is divided into a series of load increments called load steps. At the completion of each incremental solution, the

stiffness matrix of the model is adjusted to reflect nonlinear changes in structural stiffness before proceeding to the next load increment. The program carries out a linear solution, using the out-of-balance loads, and checks for convergence. If convergence criteria are not satisfied, the out-of-balance load vector is re-evaluated, the stiffness matrix is updated, and a new solution is attained. This iterative procedure continues until the problem converges.

3.5 Load Stepping

For the nonlinear analysis, automatic time stepping in the ANSYS program predicts and controls load step sizes. Based on the preceding solution history and the physics of the models, if the convergence behavior is smooth, automatic time stepping will increase the load increment up to a selected maximum load step size. If the convergence behavior is abrupt, automatic time stepping will bisect the load increment until it is equal to a selected minimum load step size. The maximum and minimum load step sizes are required for the automatic time stepping.

CHAPTER 4

ANALYTICAL MODEL OF FRP WRAPPED BEAMS

4.1 Fundamentals of FRP Wrapped Beam Analysis

The analysis of the beam was considered as a two- dimensional problem. Two different cross-sections of FRP-wrapped beams were investigated. The environmental RH is different in the morning, during the day, and at the evening. The average environmental RH of Houston and the Corpus Christi of Texas is about 90% in the morning. The average daily environmental RH of Dallas, Texas area is 6 4%. Therefore the beam exposed to 100% environmental RH and 6 4% environmental RH was analyzed.

4.2 FRP Wrapped Simply Supported Beam

A simply supported beam wrapped with FRP normally has a small bond free area next to the supp ort. The b ond free a rea is pre sent in b eams because of difficulty in con struction created by the supports.
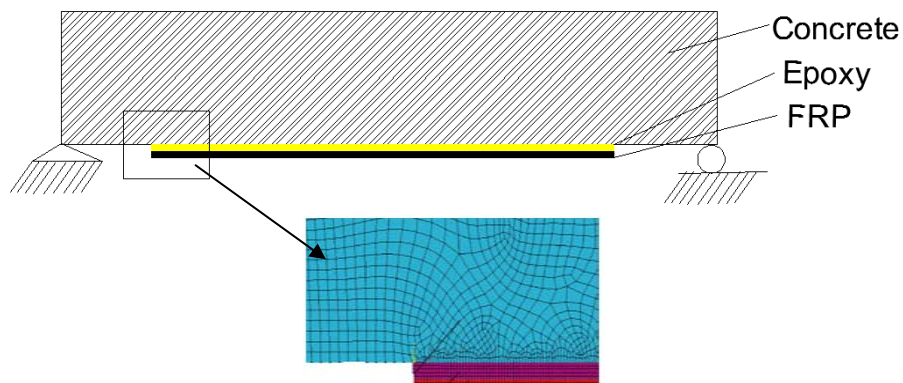

Figure 4.1 Bond Free Areas near Support in FRP Wrapped Simply Supported Beam

This bond free area as shown in Figure 4.1 is vulnerable to moisture attack because concrete is porous material and moisture can easily get into it. A small area as shown in Figure 4.1 was analyzed herein to see the moisture movement. Analysis was focused on the water permeability of the FRP matrix. The dimensions of the model used were concrete 38mm x 38mm, FRP thickness of 2mm, and epoxy adhesive thickness of 1.2mm. This model is analyzed with 64% and 100% environmental RH to see the different water movement pattern. Having the same diffusion coefficient valid, it is also analyzed for 10 years of exposure time frame.
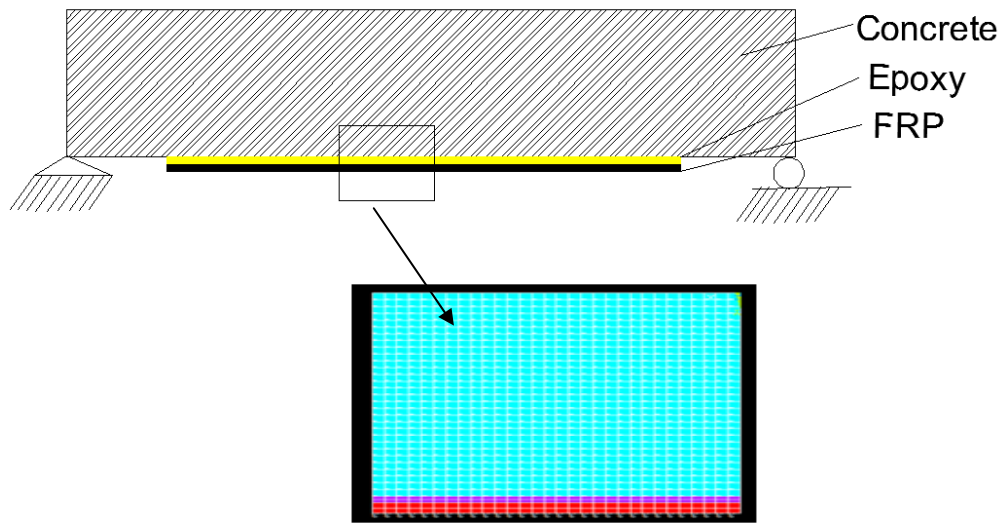
Figure 4.2 Bonded Areas at the Middle Section of FRP-Wrapped Simply Supported Beam

The area of the middle section of the beam as shown in Figure 4.2 was also analyzed to see the moisture movement. The moisture movement in the middle section of the beam was compared with the section near the support. A comparison graph and contour map are presented in the sixth chapter.

4.3 FRP-Wrapped TXDOT Type IV Beam Cross Section

A TxDOT Type IV beam wrapped with FRP was modeled in ANSYS to see the water movement through the FRP. The purpose of this modeling was to find any different pattern of

water movement. The Type IV beam was wrap ped from bottom to middle hei ght as shown in Figure 4.3 was analyzed in parts.
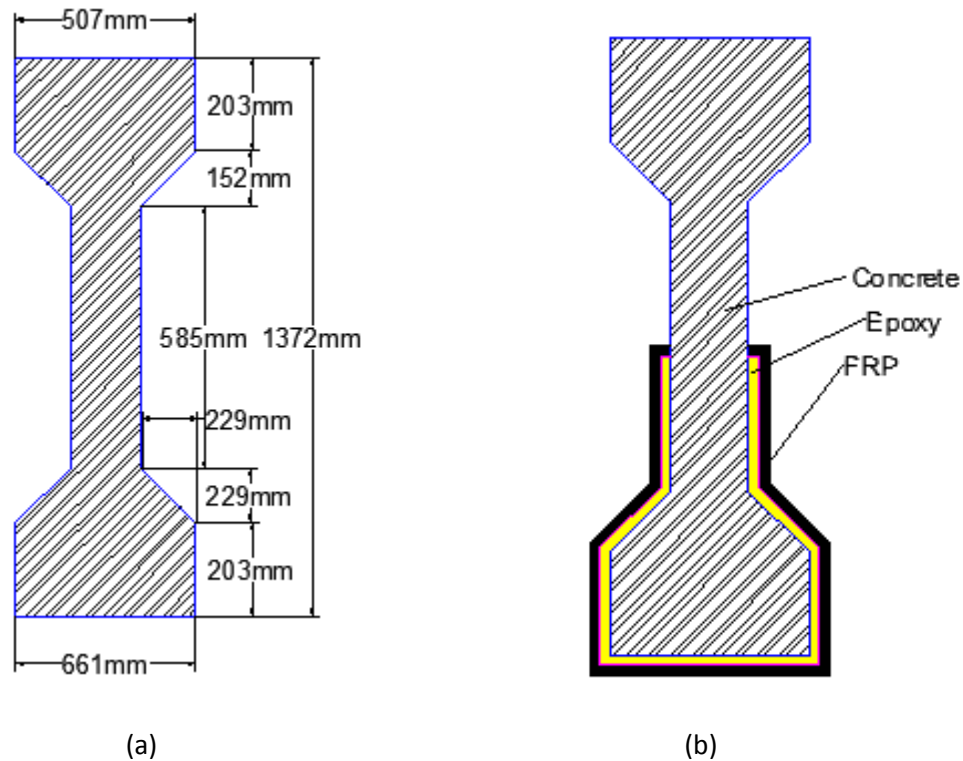
Figure 4.3 TxDOT Type IV Beam Cross Section (a) with dimension (b) with half retrofit

Since the FRP thickness of 2mm an d epoxy thickne ss of 1.2 mm are to o small as compared with the dimension (661mm x 1372mm) of the beam, a zoomed-in model not in scale was used for analy sis. A top part of the beam section where FRP terminates and a base part were modeled separately. By modeling separately, we can clearly notice the different patterns of water movement. This will be discussed in the fifth and sixth chapters.

For all thre e types of models, the diffusio n coefficient of FRP wa s obtained from a published inspection report (Xian, G. 2 008). The diffusion coefficient and relative humidity of epoxy and concrete were taken from a previous research paper by Ouyang, Z. and Wa n, B. (2008). The following table shows the values used in this finite element analysis:

Table 4.1 Diffusion Coefficient with Relative Humidity

Element	Diffusion Coefficient	Relative Humidity	Days
Concrete	0.05×10^{-12} m^2/s	40%	7
	0.05×10^{-12} m^2/s	45%	14
	0.133×10^{-12} m^2/s	68%	28
	0.5×10^{-12} m^2/s	80%	56
Epoxy	10.32×10^{-14} m^2/s	40%	7
	10.00×10^{-14} m^2/s	45%	14
	6.34×10^{-14} m^2/s	68%	28
	4.64×10^{-14} m^2/s	80%	56
TYFO SCH 41S-1	3.0×10^{-15} m^2/s*	-	-

*Obtained from an inspection report

As discussed in the theoretical background chapter, the diffusion coefficient of concrete is constant until 70°C temperature is reached and it rises from 70°C to 90°C. Beyond 90°C, it stays constant again. The epoxy diffusion coefficient decreases along with time. The FRP diffusion coefficient does not depend on temperature, so it has only one value.

CHAPTER 5

FRP- WRAPPED BEAM ANALYSIS AND RESULTS

This chapter presents analysis of FRP wrapped beams using the finite element method. Analytical models used in ANSYS were described in the chapter four. Analysis was focused on water permeability of FRP.

5.1 Finite Element Model

In real life, structural responses to loads are time-dependent. Steady state calculations supply temperature for a unit which is fully warmed up and has reached equilibrium temperatures. For steady state response a static analysis is required which neglects the dynamic effect. Transient state is the response before statics in which dynamic effect cannot be ignored. The problem analyzed here is transient in nature.

Transient thermal analysis is the most common of all thermal analyses. Almost all heat transfer processes are transient in nature. This kind of analysis is used to determine temperature and other thermal quantities in a body due to different thermal loads. Thermal loads applied to a structure are time dependent. For practical problems, transient thermal analysis can be a difficult task especially when dealing with complicated shapes and long periods.

Table 5.1 Assumptions

Moisture flux in longitudinal direction =0	Under isothermal condition there is no heat flux affecting the moisture transport
Initial uniform pore RH of concrete = 30%	To treat the concrete as matured specimen
Initial RH of FRP and epoxy = 0%	Epoxy and FRP initially dry
Surrounding environmental RH (1) = 100%	Morning environmental RH of Houston area is above 90% and to speed up the moisture uptake
Surrounding environmental RH (2) = 64%	Average yearly environmental RH of Dallas is 64%
Density =1	Already taken care when finding diffusion
Specific heat per unit mass = 1	coefficient (Ouyang, Z. and Wan, B. 2008)

Element PLANE77 with two dimensional thermal conduction capability was used for meshing the FRP geometry model. The model was meshed with smart mesh tool. Concrete was meshed with the finer size of 1 and the epoxy and FRP layers were meshed with a coarser mesh size of 6.

Based on this assumption, the moisture diffusion in the FRP bonded concrete reduced to a two dimensional problem. It was also assumed that the diffusivity is independent of the direction in the materials. Although diffusivity is dependent on the fiber direction of FRP, both directions in the 2D model are perpendicular to the FRP fiber's direction. Therefore, in the 2D model, only the diffusivity of FRP perpendicular to the fiber direction was needed.

As discussed before, the analogy between thermal and diffusion analysis for input and output variables was used. Temperature represented relative humidity and thermal conductivity represented the diffusion coefficient. Different diffusion coefficients of concrete, epoxy and FRP are tabulated in the fourth chapter.

<u>5.2 Finite Element Results</u>

5.2.1 FRP-Wrapped Simply Supported Beam

Figure 5.1 and Figure 5.2 presented below show the differences between the bonded areas near the middle of the beam and the bond free areas near the supports of the beam. Moisture movement is higher in the bond free area than in the bonded area.

5.2.1.1 Bond Free Area near Support

Figure 5.1 presents the material RH contour in a bond free area in the beam near the supports. The largest material RH is in the edge part of the FRP and Concrete. It decreases closer to the middle of the model, which is expected. The difference in the pattern of material RH show that moisture moves inside with the time. A finer mesh generated finer contours. More material RH variation in epoxy can be noticed in Figure 5.1 (b). This could have resulted from mechanical properties of the epoxy. Mechanical property means here diffusion coefficient, which decreases with increased time.
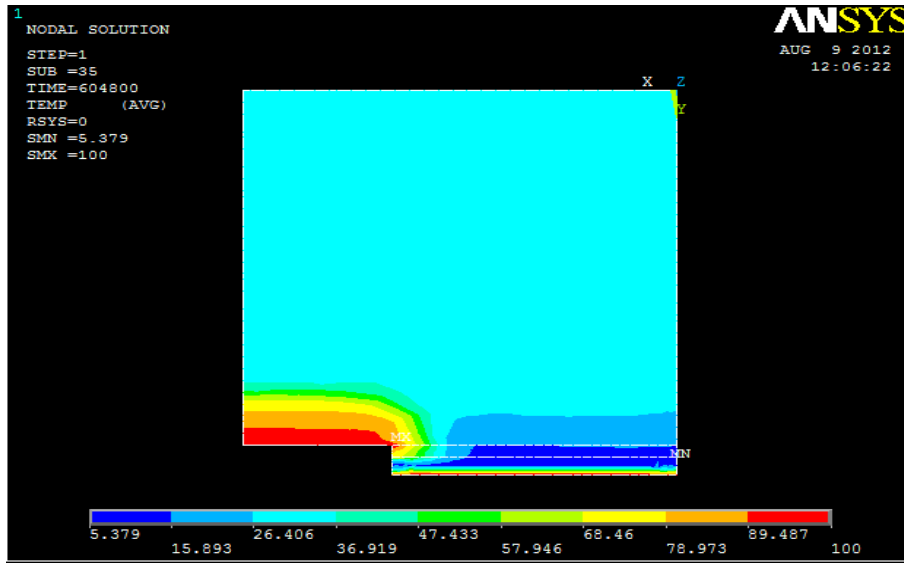
(a)
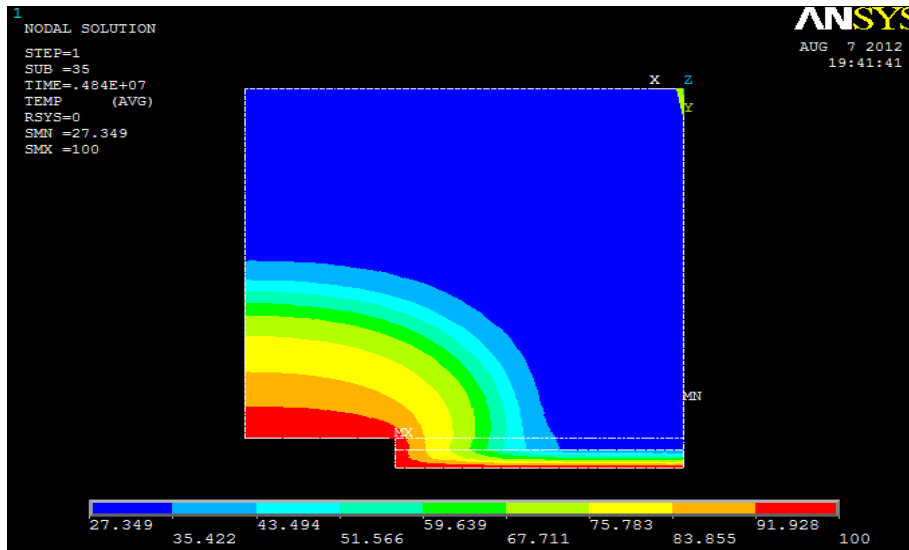
(b)

Figure 5.1 Bond Free Areas near Support of Beam: Material RH Contour at (a) 7 days (b) 56 days
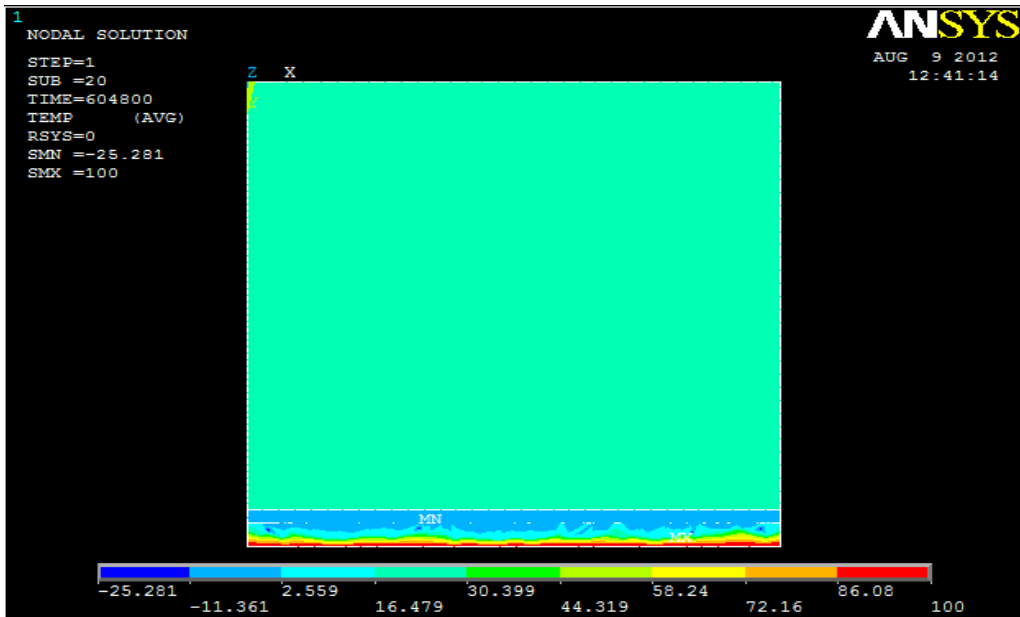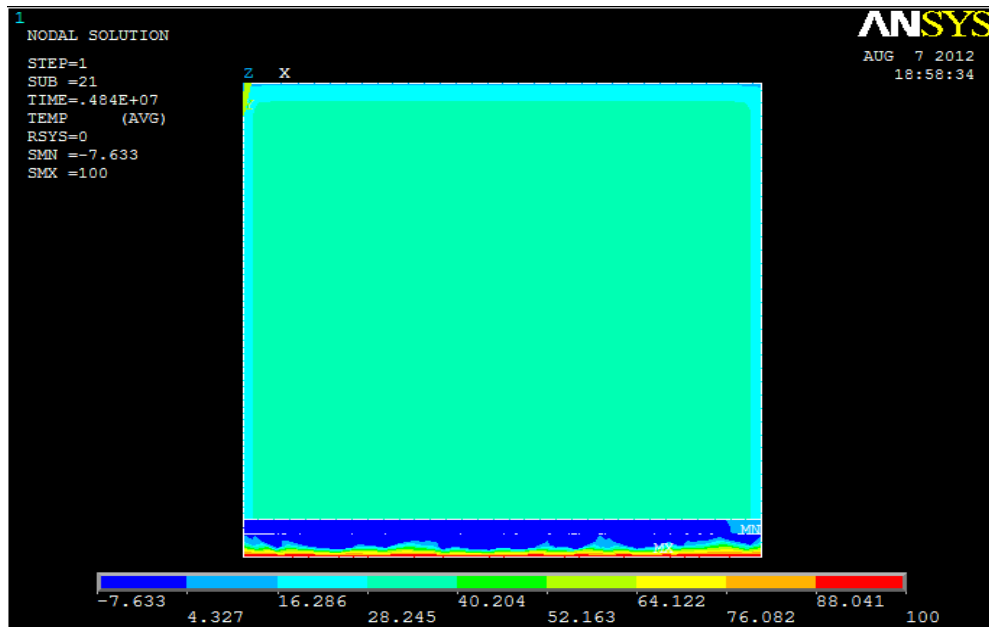
(a)

(b)

Figure 5.2 Bonded Areas at Middle of Beam: Material RH Contour at (a) 7 days (b) 56 days

5.2.1.2 Bonded Area near Middle

Figure 5.2 presents the material RH contours in the bonded area at the middle of the simply

supported beam. The largest material RH is still in the edge part of the FRP and Concrete.

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There is a large difference in relative humidity of concrete, epoxy, and FRP. This increase in material RH is what we would expect the solution to be. A comparative graph is presented in the sixth chapter.

5.2.2 FRP Wrapped TXDOT Type IV Beam

Figure 5.3 presents symmetric half of the beam cross section. The highlighted part of Figure 5.4 (a) was analyzed. The beam is divided into two separate parts for the purpose of modeling. Figure 5.4 (a) shows the material RH at 7 days and Figure 5.4 (b) shows the material RH at 56 days. The figure clearly shows larger moisture movement in the FRP terminating area than in the non- terminating area. This is a reasonable difference in material RH. The figure below shows that material RH is increasing linearly along with increased time.
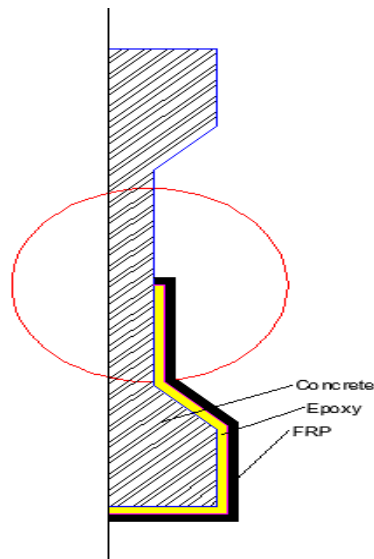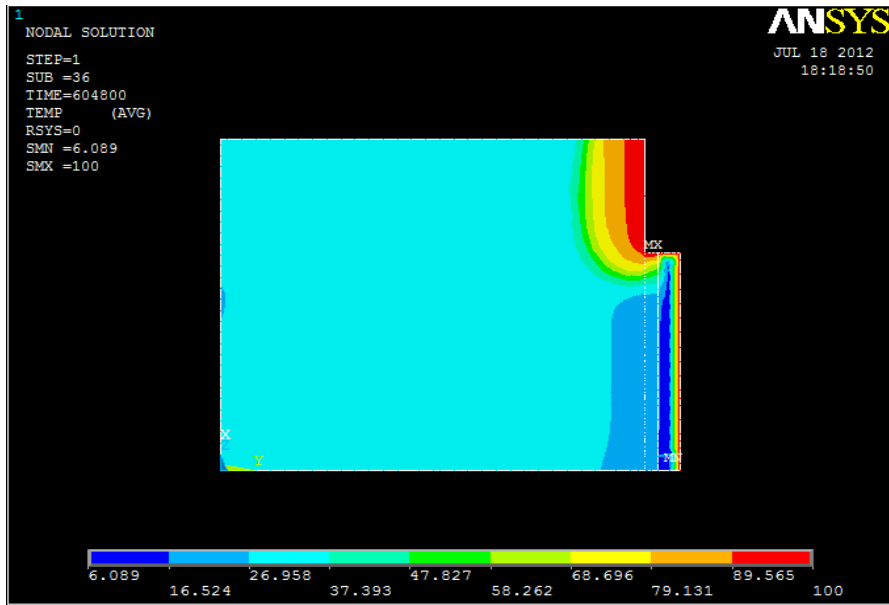

Figure 5.3 Symmetric Half of the TxDOT Type IV Beam Cross Section

(a)
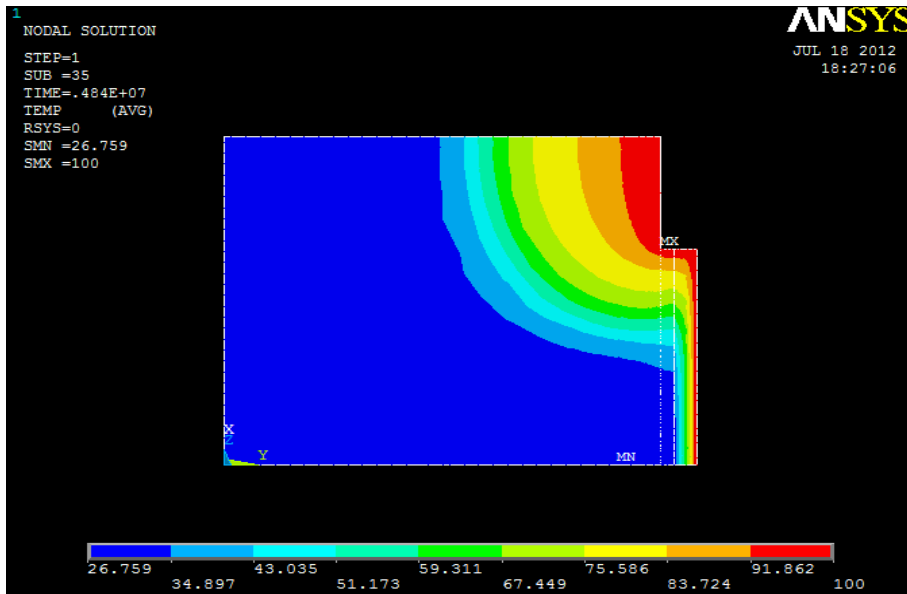
(b)

Figure 5.4 TxDOT Type IV Beam Top Section: Material RH Contour at (a) 7 Days (b) 56 Days
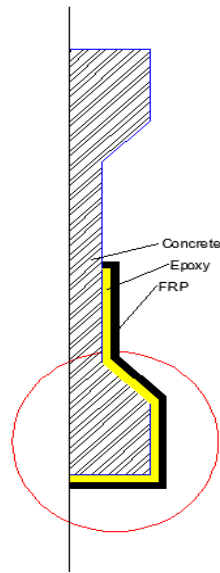
(a)
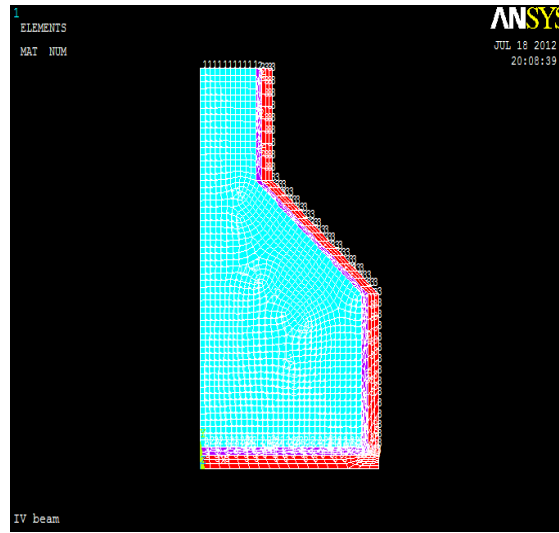
(b)
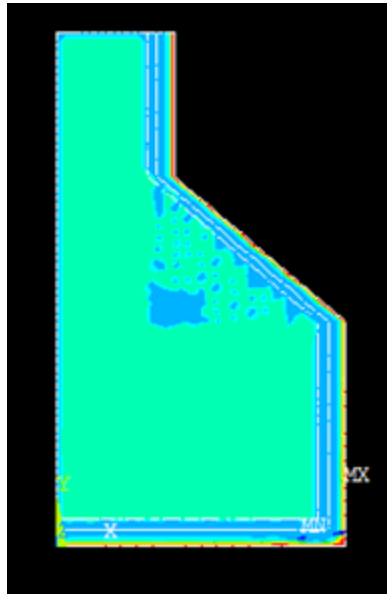
(c)

Figure 5.5 TxDOT Type IV Beam Section: (a) Bottom Half of the Cross Section; (b) Modeling in ANSYS (c) Material RH Contour at 56 days

(a)   (b)
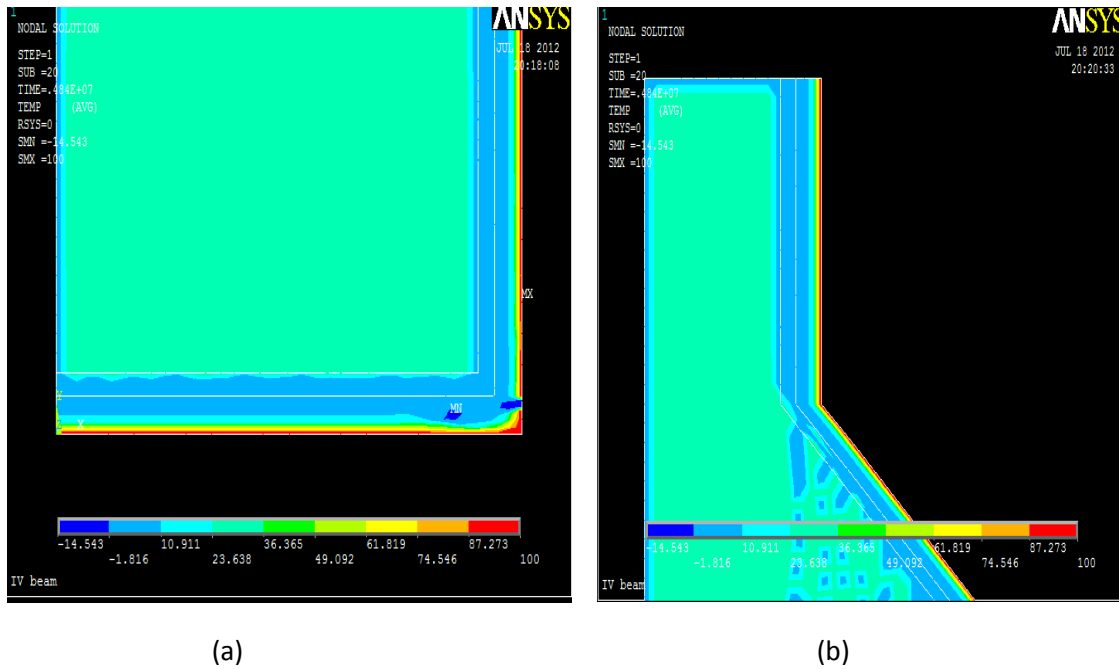
Figure 5.6 Zoomed-in Part of Beam (a) Lower Section (b) Top Section

Figure 5.5 (a) shows the bottom highlighted part of the Type IV beam. Figure 5.5 (b)

shows the meshed geometry of the beam in ANSYS. It was meshed with the size control

method. The difficult part was to model the angled or curved section. It was also hard to select

the nodes around this area while applying initial relative humidity. Different areas were modeled

first and then separate areas were added to create a concrete block, FRP layer, and the epoxy

layer. Figure 5.5 (c) shows the material RH contour at 56 days. The dimension (661mm x

1372mm) of the beam was large compared with the 1.2mm thickness of epoxy layer and 2mm

thickness of the FRP layer. To clearly monitor the moisture movement, a zoomed-in figure of

the bottom and top sections are shown in Figure 5.6 (a) and (b). The figures clearly show less

moisture movement in the area. This is an expectable result because moisture movement is

less in non FRP terminating area.

CHAPTER 6

PARAMETRIC STUDY OF FRP-WRAPPED BEAM

This chapter discusses the difference between the bond free area and the bonded area of a FRP- wrapped simply supported beam and the TxDOT Type IV beam. A discussion of the moisture movement along with time is presented in a time dependent graph.

Figure 6.1 Time Dependent Graph for 100% Environmental RH at Bond-free Area (15mm horizontal from FRP edge)
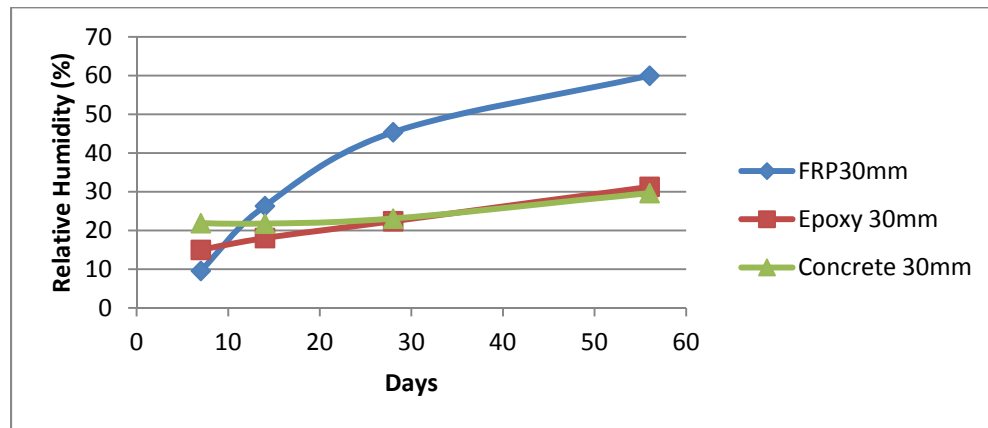
Figure 6.2 Time Dependent Graph for 100% Environmental RH at Bond-free Area (30mm horizontal from FRP edge)

Figure 6.1 and 6.2 shows the graph of moisture movement in FRP (Tyfo SCH41S-1), epoxy, and concrete up to 56 days when specimen is exposed to 100% e nvironmental RH. Figure 6.1 and Figure 6.2 is plotted for the area 15mm and 30mm horizontal from FRP edge of the bond-free area of simply supported beam. As per Figure 6.1, the material RH of concrete at the end of 56 days is 76.6%. From moisture isotherm curve of concrete as shown in Figure 2.5, 76.6% RH is equal to 1.2% of equilibrium moisture content in concrete. Values at 15mm have a higher material relative humidity value compared to the val ues at 30 mm. It dem onstrates material RH decreases towards the middle section of the beam.
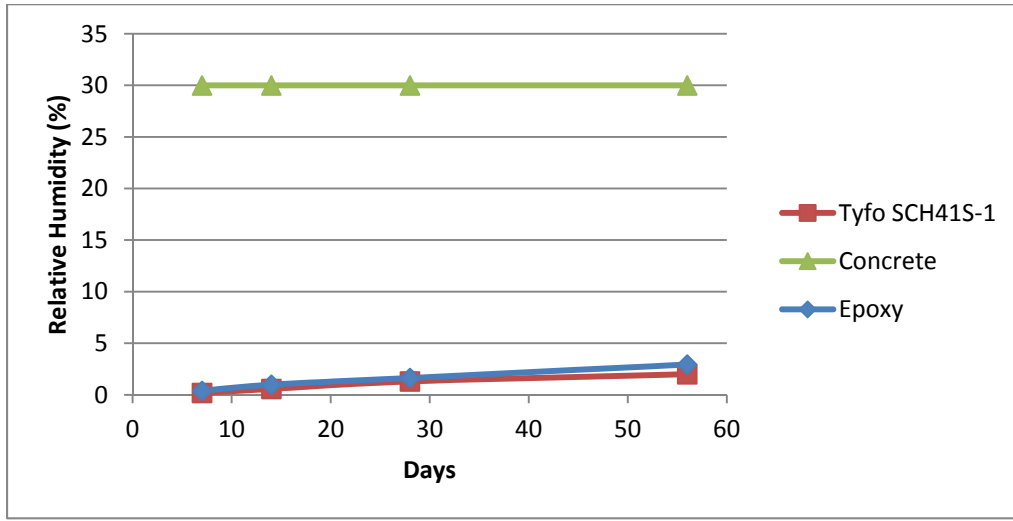
Figure 6.3 Time Dependent Graph for 100% Environmental RH at Middle Section of the Beam

Figure 6.3 show the graph of moisture movement up to 56 days at a middle section of a FRP-wrapped beam. This graph is plotted for the area in contact with the epoxy, which is the inner surface of the 2mm FRP. At the i nner surface, the relative humidity is 1.9% from finite element analysis at 56 days. This shows that water movement is less in this region of the beam when compared to the bond free area near the support. Figure 6.3 also plot the relative humidity of concrete at 38mm in transverse direction from the edge of beam. The relative humidity stays the same as the initial condition. As described before, concrete is modeled with 30% RH initial

condition in order to ma ke it matured concrete specimen. The RH of concrete at 38 mm in transverse direction from the edg e of the beam i s still 30% after 56 days which means there is no risk of moisture attack for concrete.

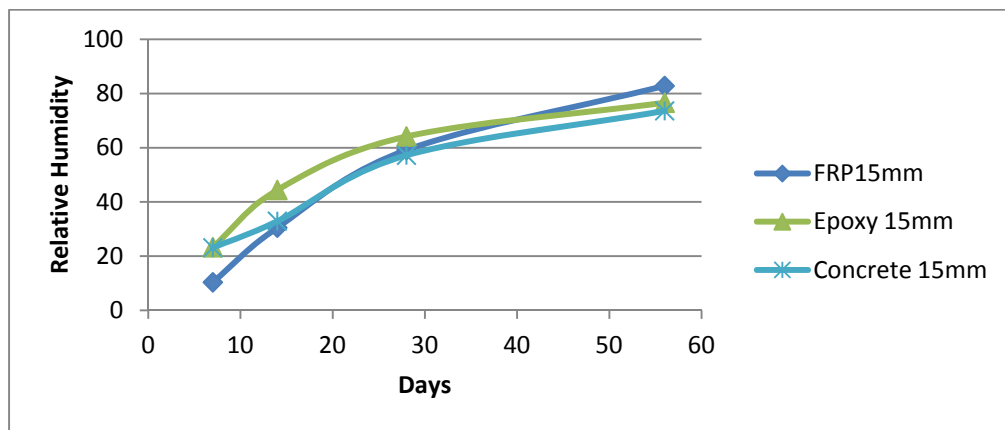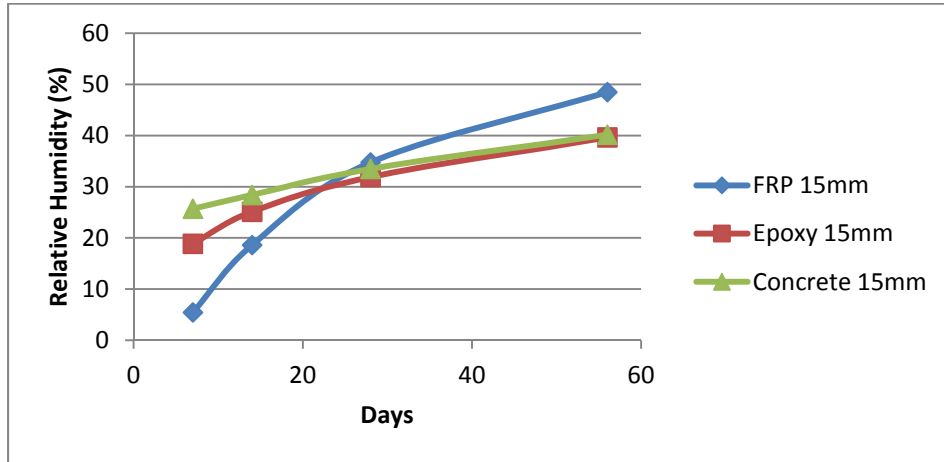Figure 6.4 Time Dependent Graph for 64% Environmental RH at Bond-free Area
(15mm from FRP edge)
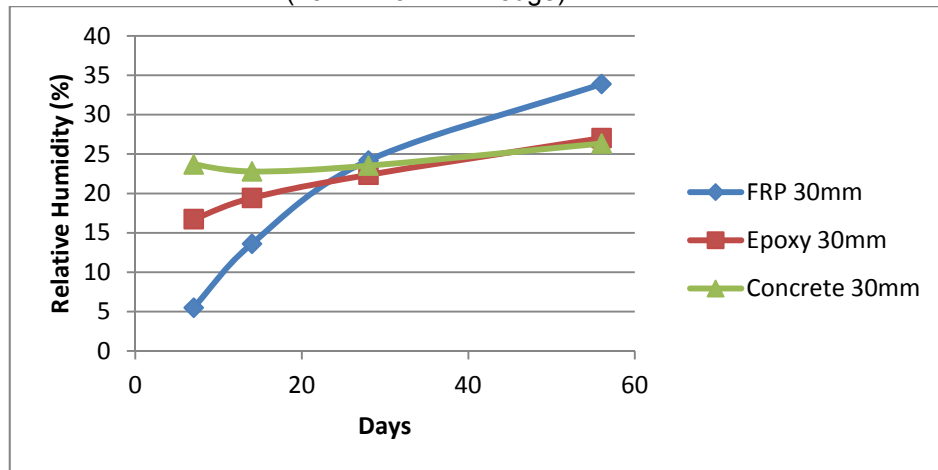
Figure 6.5 Time Dependent Graph for 64% Environmental RH at Bond-free Area
(30mm from FRP edge)

This sample is also analy zed with 64% environmental RH. Co ncrete RH is 40.17% at the same location wh en the sa mple is exposed in 64% enviro nmental RH. From isothe rm curve, 40.17% RH is equal to 0.5% equilibrium moisture content in concrete. Comparing the material RH from Figures 6.1 and 6.2 with Figures 6.4 and 6.5; higher the en vironmental RH

higher the m aterial RH. A compa rison of beam with and without FRP and e poxy layer was performed and plotted in time dependent graph shown in Figure 6.6.
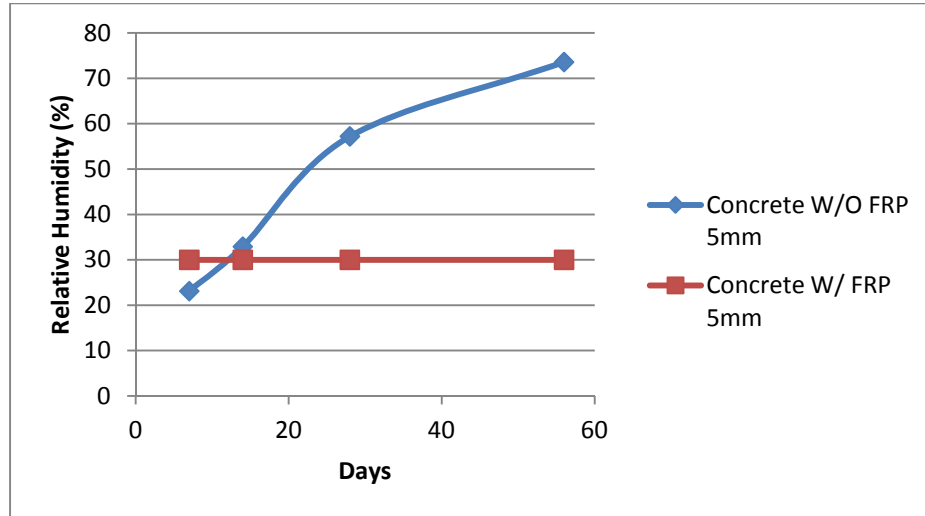
Figure 6.6 Time Dependent Graph for 64% Environmental RH with and without FRP and Epoxy Layer

The material RH is still 30% as initial set material RH in the bea m with FRP and Epoxy. This clearly shows that the beam with FRP and epoxy layer has very little or no moi sture movement. The material RH of concrete is 73% i n the beam without epoxy and F RP. From isotherm curve, 73% RH is equal to 1.1% equilibri um moisture content in concrete. This graph demonstrates that the FRP and epoxy pays a role of moisture barrier in the concrete. The same specimen is run for 10 yea rs with 64% environmental RH assuming the diffusion coefficient at 56 days valid for the time frame. A time dependent graph of concrete is plotted in Figure 6.7. This graph is plotted for concrete at 38mm horizontal distance and at 5mm, 12 mm, 25mm and 38mm vertical distance from the edg e of the beam. This graph shows that the materi al RH decreases with increased vertical distance from the edge of the beam.

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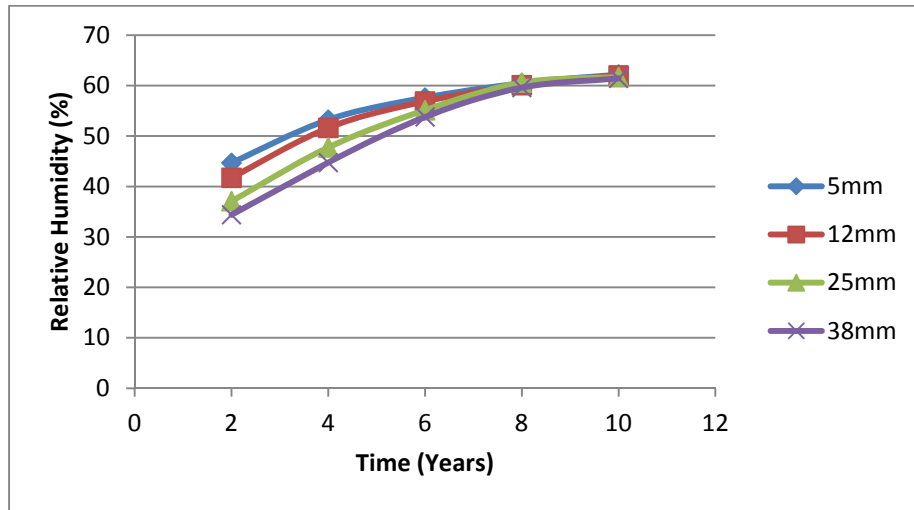
Figure 6.7 Time Dependent Graph for 10 Years with 64% Environmental RH
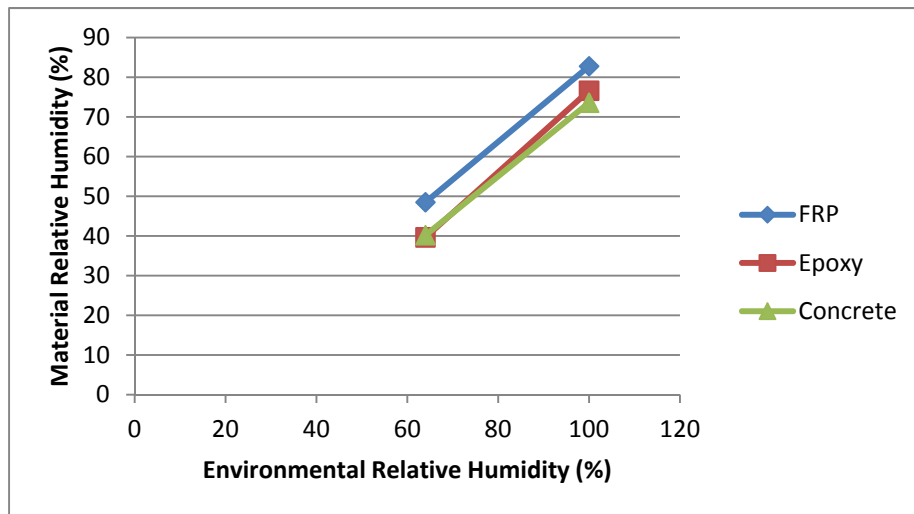
Figure 6.8 Materials RH vs. Environmental RH

A graph is plotted to show the relationship of material RH with environmental RH in Figure 6.8. This graph demonstrates that material relative humidity of FRP, epoxy, and concrete increases with increased environmental relative humidity. Since there is difference in environmental relative humidity throughout the day, material relative humidity will also vary throughout the day.

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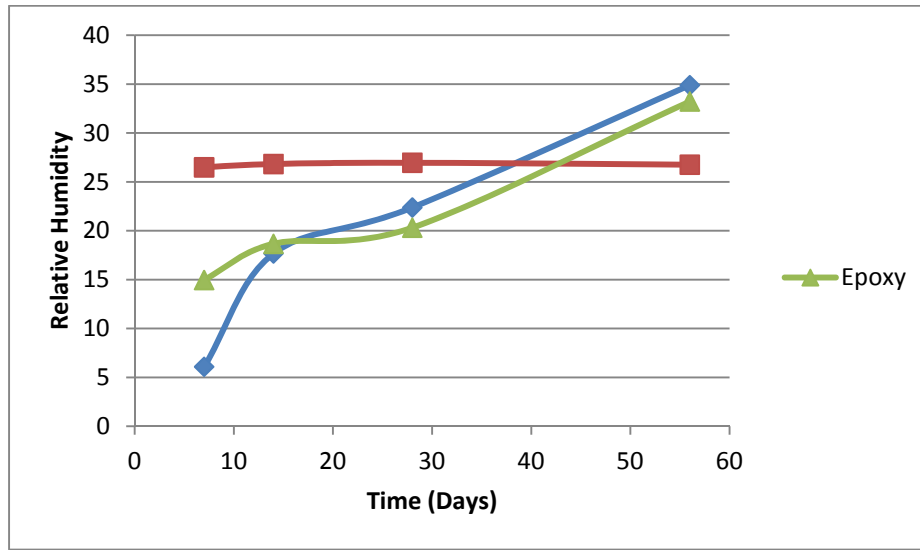
Figure 6.9 Time Dependent Graph of Top Section of FRP-wrapped TXDOT Type IV Beam

Figure 6.9 show the graph of moisture movement in F RP at 56 days in an FRP-wrapped TXDOT Type IV beam. This graph is plotted for the area in contact with epoxy, which is the inne r surface of th e FRP. Since ther e is a bond free area pre sent in the model, the relative humidity value is expected to be higher. At the in ner surface, the relative humidity is 35% at 56 days, whereas the relative humidity of concrete at 38mm from the edge of the beam is 30%. This shows no water movement in concrete at 38mm from beam's edge.

Figure 6.10 shows the graph of m oisture movement in FRP at 56 days in the bottom section of an FRP-wrapped TXDOT Type IV beam. This graph is plotted for the area in contact with the epoxy, which is the inner surface of the FRP. Since there is no bond free area present in the model, the relative humidity value is ex pected to be lo wer. At the inn er surface, the relative humidity is 14% at 56 days, whereas the relative humidity of concrete at 38mm from the edge of the beam is 30%. This shows no water movement in concrete at 38mm from the beam's edge.
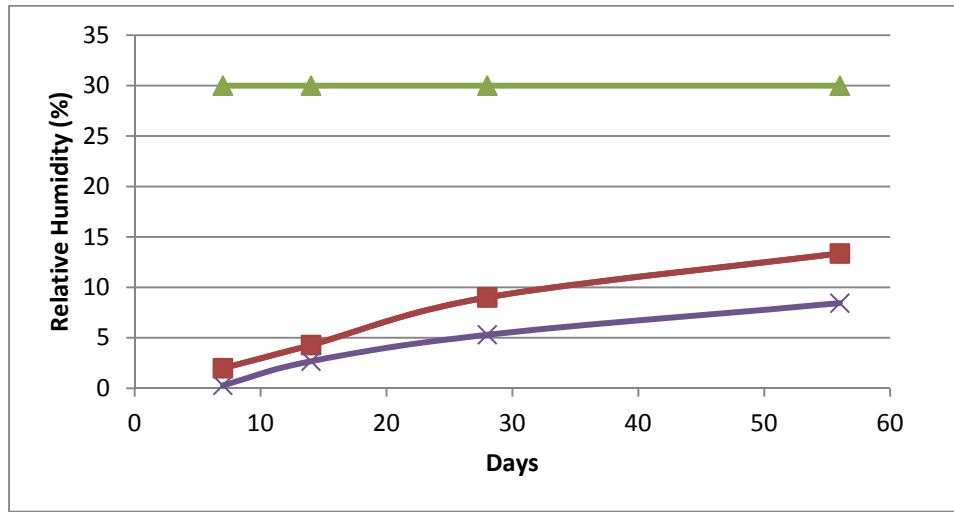
Figure 6.10 Time Dependent Graph of Bottom Section of FRP-Wrapped TXDOT- Type IV Beam

Comparison between Figure 6.9 and 6.10 demonstrates that the relative humidity of FRP is much higher in the top section of a Type IV beam than the bottom sections of the beam. There was not much difference in the relative humidity in concrete in both models.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

A finite element analysis was performed using the ANSYS software to analyze the progress of water and its circulation in FRP-wrapped concrete. Finite element programs do not usually address the issue of diffusion or permeability. Therefore, the diffusion of water in FRP was modeled by analogy with thermal conduction. Two different sections of simply supported FRP-wrapped beam sections were analyzed: (1) The section next to the support, normally the bond free area, (2) The section at the middle of the beam section, the bonded area. Water movement in concrete at 38mm from the edge of the beam was also analyzed in both sections. The specimen was run with different environmental relative humidity exposure. A TXDOT Type IV beam was analyzed to examine if there was any different water movement in the bottom and top sections of the beam.

Based on the finite element analysis results, the following conclusion can be drawn:

a. Moisture between epoxy and concrete mainly came from concrete in the bond free area near the support of a simply supported beam and the FRP terminating section of TXDOT Type IV beam.

b. Irregular moisture distribution was found in the epoxy thickness. This could have resulted from the mechanical properties of the epoxy. Mechanical property here means conductivity of epoxy. As described in section 2.4, conductivity decreases with increased temperature.

c. Regardless of the shape and size of the cross section of a beam, water movement in FRP is higher in the bond free area than in the bonded area of a beam.

d. Relative humidity increases in the FRP layer linearly along with time.

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e. The relative humidity at the end of 56 days in the FRP layer was 1.9% in the bonded area near the middle of the simply supported beam, which is much lower compared to 35% relative humidity of the bond free area near the support of simply supported beam.

f. Water movement in the top section of the Type IV beam is higher as compared to the bottom sections of the beam.

g. There was little or no water movement in concrete at 38mm horizontal and 38mm vertical direction from the edge of the beam in all four models of FRP wrapped concrete structures as described in sixth chapter.

h. Moisture moves from FRP terminating area and travels longitudinally towards middle of the beam along with time.

i. Moisture content of concrete beam without FRP and Epoxy layer was higher compared to the concrete with FRP and Epoxy layer.

j. Higher the environmental relative humidity higher the material relative humidity.

k. From the model run for 10 years with environmental RH 64%, the material moisture content of concrete at 38mm horizontal and 38mm vertical from FRP edge was found to be 61.45% which is equivalent to 1.2% moisture content in the concrete. This moisture may accelerate the corrosion process and damage the structure.

7.1 Recommended FE Modeling Procedure

1. Symmetry should be used in modeling to reduce computation time and computer disk space requirement. Only longitudinal half of the column was modeled in this research paper.

2. Realistic material property values can be used for model accuracy. This can be done by defining proper boundary condition. A real FRP Tyfo SCH-41S-S was used in this paper.

3. Minimum and maximum sizes of each load step should be properly defined to assist in convergence of the solutions and reduction in computer computational time.

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7.2 Recommended on Future Research

1. This thesis has used only one type of FRP matrix for analysis. Other type of FRP by different manufactures can be investigated.

2. Realistic material property values of different epoxy adhesives in combination with FRP materials could give different results in terms of water movement. This area can be focused in future.

3. The thesis presented herein is modeled in two dimensional models. A three dimensional ANSYS model can be simulated for studying water movement in FRP wrapped concrete structures.

4. Based in the analysis presented in this thesis, a cracked beam retrofitted with FRP can be modeled to see the moisture movement.

APPENDIX A

FINITE ELEMENT COMMANDS USED IN MODELING

Modeling Simply Supported Beam near Support

- Main Menu/preprocessor/Material properties/material Library/Select/Units

- Main Menu/Preprocessor/Thermal/h-Method

- Main Menu/Preprocessor/Element Type/add/edit/delete/solid/PLANE77

- Main Menu/Preprocessor-/Material Properties/Material

  Models/Thermal/Conductivity/Isotropic/KXX

    o Set 4 different conductivity with 4 different Temperature as presented in Table

      2.4.1

    o Name this model as concrete

- Material/New Model/Thermal/Conductivity/Isotropic-KXX

    o Set 4 different conductivity with 4 different Temperature as presented in Table

      2.4.1

    o Name this model as epoxy and repeat same for FRP

- Main Menu/Preprocessor-/Material Properties/Material Models/ Density

    o Set density for concrete, epoxy, and FRP for all 4 different Temperatures

- Main Menu/Preprocessor-/Material Properties/Material Models/ Specific Heat

    o Set specific heat for concrete, epoxy, and FRP for all 4 different Temperatures

- Main Menu/Preprocessor/Modeling/Create/Key Points/ (0,0) (38, 38) (25, 38) (25, 39.2)

  (25, 41.2) (0, 39.2) (0, 41.2) (0, 38)

- ANSYS Utility Menu/Plot Controls/Numbering

- MainMenu/Preprocessor/Modeling/Create/Lines/Through Key points

- MainMenu/Preprocessor/Modeling/Create/Areas/ Through Lines

- Main Menu/Preprocessor/Operate Meshing/Mesh Attributes/Picked Areas/Matrial #1 or

  matrial#2 or material #3

- Main Menu/Preprocessor/Meshing/Size Controls/ Manual Size/Gobal/Size/0.5

- Main Menu/Preprocessor/Modeling/Operate/Boolean/Glue/Area/Pick All/Ok

  - Main Menu/Preprocessor/Meshing/Mesh/Areas/Free/Pick All/Ok

  - Utility Menu/Plot Controls/ Numbering/Material Numbers/Ok

  - Main Menu/Solution/Define Loads/Apply/Thermal/Convections on Lines-film coefficient-bulk temperature

    - Set Film coefficient to 0 for all the Left lines

  - Solution/ Anslysis Type/ New Analysis/ Transient/Full

  - Solution/ Anslysis Type/ Sol'n Control/

    - Set time and automatic time steeping on /set the number of sunsteps to 20, max number of sub-steps to 100, and minimum number of sub-steps to 20

    - Set frequency to Write every substeps

    - Set line search on

    - Set max number of iteration to 100

  - Main Menu/Solution/define Loads/ Apply/Initial condition/ Define/

  - Pick concrete area and set to 30

  - Pick FRP and Epoxy area and set to 0

  - Main Menu/Solution/define Loads/ Apply/Thermal/ Temperature/On Lines

    - Set all lines to 100

    - Do not set temperature on left lines because this is center of the model

  - Utility Menu/Plot Controls/Symbols/Show Press and Count as Arrows/Ok

  - Main Menu/Solution/Solve/Current LS/Ok

  - General Post proc/Plot Results/Contour Plots/Nodal Solution/ DOF solution

  - Utility menu/PlotCtrls/Animate/Over Time

Modeling Simply Supported Beam near Middle

- Main Menu/preprocessor/Material properties/material Library/Select/Units

- Main Menu/Preprocessor/Thermal/h-Method

- Main Menu/Preprocessor/Element Type/add/edit/delete/solid/PLANE77

- Main Menu/Preprocessor-/Material Properties/Material
  Models/Thermal/Conductivity/Isotropic/KXX

  o Set 4 different conductivity with 4 different Temperature as presented in Table
  2.4.1

  o Name this model as concrete

- Material/New Model/Thermal/Conductivity/Isotropic-KXX

  o Set 4 different conductivity with 4 different Temperature as presented in Table
  2.4.1

  o Name this model as epoxy and repeat same for FRP

- Main Menu/Preprocessor-/Material Properties/Material Models/ Density

  o Set density for concrete, epoxy, and FRP for all 4 different Temperatures

- Main Menu/Preprocessor-/Material Properties/Material Models/ Specific Heat

  o Set specific heat for concrete, epoxy, and FRP for all 4 different Temperatures

- Main Menu/Preprocessor/Modeling/Create/Areas/Rectangles/By Dimensions/ (0,0) (38,
  38)

- MainMenu/Preprocessor/Modeling/Create/Areas/Rectangles/By Dimensions/ (0,38) (38,
  39.2)

- MainMenu/Preprocessor/Modeling/Create/Areas/Rectangles/By Dimensions/ (0,39.2)
  (38, 41.2)

- Main Menu/Preprocessor/Operate Meshing/Mesh Attributes/Picked Areas/Matrial #1 or
  matrial#2

- Main Menu/Preprocessor/Meshing/Size Controls/ Manual Size/Gobal/Size/0.5

- Main Menu/Preprocessor/Modeling/Operate/Boolean/Glue/Area/Pick All/Ok

- Main Menu/Preprocessor/Meshing/Mesh/Areas/Free/Pick All/Ok

- Utility Menu/Plot Controls/ Numbering/Material Numbers/Ok

- Main Menu/Solution/Define Loads/Apply/Thermal/Convections on Lines-film coefficient-bulk temperature

  - Set Film coefficient to 0 for all the Left lines

- Solution/ Anslysis Type/ New Analysis/ Transient/Full

- Solution/ Anslysis Type/ Sol'n Control/

  - Set time and automatic time steeping on /set the number of sunsteps to 20, max number of sub-steps to 100, and minimum number of sub-steps to 20

  - Set frequency to Write every substeps

  - Set line search on

  - Set max number of iteration to 100

- Main Menu/Solution/define Loads/ Apply/Initial condition/ Define/

- Pick concrete area and set to 30

- Pick FRP and Epoxy area and set to 0

- Main Menu/Solution/define Loads/ Apply/Thermal/ Temperature/On Lines

  - Set all lines to 100

- Do not set temperature on left lines because this is center of the model

- Utility Menu/Plot Controls/Symbols/Show Press and Count as Arrows/Ok

- Main Menu/Solution/Solve/Current LS/Ok

- General Post proc/Plot Results/Contour Plots/Nodal Solution/ DOF solution

- Utility menu/PlotCtrls/Animate/Over Time

Modeling TXDOT Type IV Beam

- Main Menu/preprocessor/Material properties/material Library/Select/Units

- Main Menu/Preprocessor/Thermal/h-Method

- Main Menu/Preprocessor/Element Type/add/edit/delete/solid/PLANE77

- Main Menu/Preprocessor-/Material Properties/Material Models/Thermal/Conductivity/Isotropic/KXX
  - Set 4 different conductivity with 4 different Temperature as presented in Table 2.4.1
  - Name this model as concrete
- Material/New Model/Thermal/Conductivity/Isotropic-KXX
  - Set 4 different conductivity with 4 different Temperature as presented in Table 2.4.1
  - Name this model as epoxy and repeat same for FRP
- Main Menu/Preprocessor-/Material Properties/Material Models/ Density
  - Set density for concrete, epoxy, and FRP for all 4 different Temperatures
- Main Menu/Preprocessor-/Material Properties/Material Models/ Specific Heat
  - Set specific heat for concrete, epoxy, and FRP for all 4 different Temperatures
- Main Menu/Preprocessor/Modeling/Create/Key Points/ (0,0) (33.7, 2) (0, 2) (31.7, 3.2) (0, 3.2) (30.5, 26.2) (0, 26.2) (10.5, 43.2) (0, 43.2) (10.5, 60), (30.5, 3.2) (31.7, 26.2) (31.7, 1.2) (33.7, 26.2)
- ANSYS Utility Menu/Plot Controls/Numbering
- MainMenu/Preprocessor/Modeling/Create/Lines/Through Key points
- MainMenu/Preprocessor/Modeling/Create/Areas/ Through Lines
- Main Menu/Preprocessor/Operate Meshing/Mesh Attributes/Picked Areas/Matrial #1 or matrial#2 or material #3
- Main Menu/Preprocessor/Meshing/Size Controls/ Manual Size/Gobal/Size/0.5
- Main Menu/Preprocessor/Modeling/Operate/Boolean/Add/Area
  - Add rectangular areas that make FRP, Epoxy, and Concrete area
- Main Menu/Preprocessor/Modeling/Operate/Boolean/Glue/Area
  - Glue All layers and concrete

- Main Menu/Preprocessor/Meshing/Mesh/Areas/Free/Pick concrete/Ok

- Main Menu/Preprocessor/Meshing/Size Controls/ Manual Size/Gobal/Size/0.01

- Main Menu/Preprocessor/Meshing/Mesh/Areas/Free/Pick Epoxy and FRP/Ok

- Utility Menu/Plot Controls/ Numbering/Material Numbers/Ok

- Main Menu/Solution/Define Loads/Apply/Thermal/Convections on Lines-film coefficient-bulk temperature

  o Set Film coefficient to 0 for all the Left lines

- Solution/ Anslysis Type/ New Analysis/ Transient/Full

- Solution/ Anslysis Type/ Sol'n Control/

  o Set time and automatic time steeping on /set the number of sunsteps to 20, max number of sub-steps to 100, and minimum number of sub-steps to 20

  o Set frequency to Write every substeps

  o Set line search on

  o Set max number of iteration to 100

- Main Menu/Solution/define Loads/ Apply/Initial condition/ Define/

- Pick concrete area and set to 30

- Pick FRP and Epoxy area and set to 0

- Main Menu/Solution/define Loads/ Apply/Thermal/ Temperature/On Lines

  o Set all lines to 100

  o Do not set temperature on left lines because this is center of the model

- Utility Menu/Plot Controls/Symbols/Show Press and Count as Arrows/Ok

- Main Menu/Solution/Solve/Current LS/Ok

- General Post proc/Plot Results/Contour Plots/Nodal Solution/ DOF solution

- Utility menu/PlotCtrls/Animate/Over Time

APPENDIX B

MECHANICAL PROPERTIES OF Tyfo SCH-41S-1 COMPOSITE

Mechanical Properties Of Tyfo SCH-41S-1 (Source: Delta Structural)

TYPICAL DRY FIBER PROPERTIES	
Tensile Strength	550,000 psi (3.79 GPa)
Tensile Modulus	33.4×10^6 psi (230 GPa)
Ultimate Elongation	1.7%
Density	0.063 lbs./in.³ (1.74 g/cm³)
Weight per sq. yd.	19 oz. (644 g/m²)

COMPOSITE GROSS LAMINATE PROPERTIES			
PROPERTY	ASTM METHOD	TYPICAL TEST VALUE	DESIGN VALUE*
Ultimate tensile strength in primary fiber direction, psi	D-3039	127,000 psi (876 MPa) (5.1 kip/in. width)	107,950 psi (745 MPa) (4.3 kip/in. width)
Elongation at break	D-3039	1.2%	1.0%
Tensile Modulus, psi	D-3039	10.5×10^6 psi (72.4 GPa)	8.9×10^6 psi (61.5 GPa)
Ultimate tensile strength 90 degrees to primary fiber, psi	D-3039	2,882 psi (19.9 MPa)	2,000 psi (13.8 MPa)
Laminate Thickness		0.04 in. (1.0mm)	0.04 in. (1.0mm)

* Gross laminate design properties based on ACI 440 suggested guidelines will vary slightly. Contact Fyfe Co. LLC engineers to confirm project specification values and design methodology.

EPOXY MATERIAL PROPERTIES		
Curing Schedule 72 hours post cure at 140° F (60° C).		
PROPERTY	ASTM METHOD	TYPICAL TEST VALUE*
T_g	ASTM D-4065	180° F (82° C)
Tensile Strength[1], psi	ASTM D-638 Type 1	10,500 psi (72.4 MPa)
Tensile Modulus, psi	ASTM D-638 Type 1	461,000 psi (3.18 GPa)
Elongation Percent	ASTM D-638 Type 1	5.0%
Flexural Strength, psi	ASTM D-790	17,900 psi (123.4 MPa)
Flexural Modulus, psi	ASTM D-790	452,000 psi (3.12 GPa)

[1] Testing temperature: 70° F (21° C)   Crosshead speed: 0.5 in. (13mm)/min.   Grips Instron 2716-0055 - 30 kips
* Specification values can be provided upon request.

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BIOGRAPHICAL INFORMATION

Jyoti Ojha graduated in December of the 2009 with an undergraduate degree on Civil Engineering from The University of Texas at Arlington. After the graduation, she joined FWT and worked as a Structure Design Engineer for one year. From February of 2010 to the date, she is currently working in American Tower as a Design Engineer. After working for one year, she realized she need graduate degree to perform well in the industry. As a result, she joined The University of Texas at Arlington to obtain a Master of Science in Civil Engineering degree. She is interested in doing continue research in structural engineering.