# FE Modeling and Experimental Verification of an FRP Strengthened Bridge

**Kasidit Chansawat**[1], **Damian I. Kachlakev**[2], **Thomas H. Miller**[1], and **Solomon C.S. Yim**[1]

1 Oregon State University
Department of Civil, Construction, and Environmental Engineering
202 Apperson Hall, Corvallis, OR 97331-2302

2 California Polytechnic State University
Civil and Environmental Engineering Department
San Luis Obispo, CA 93407

**ABSTRACT**

The Horsetail Creek Bridge in Oregon, built in 1914, was classified as structurally deficient due to an increase in load requirements and an outdated code-based design. To increase the load-carrying capacity of the bridge, fiber-reinforced polymer (FRP) sheets were laminated to the bridge where the structural capacity was insufficient. After the FRP retrofitting, the bridge capacity now exceeds the load requirements. During the FRP retrofit, fiber optic sensors were also installed on the concrete and attached to the surface of the FRP composite on the beams. These sensors were used to record response under actual truck loading to compare with behavior from an analytical model.

A three-dimensional non-linear finite element model is developed to examine the structural behavior of the Horsetail Creek Bridge strengthened with the FRP laminates. Truck loadings are applied to the FE bridge model at the same locations as those in the actual bridge test. Comparisons between FEA predictions and field data are made in terms of strains. The analysis shows that the FE bridge model does not crack under the applied service truck loads. The FE bridge model well predicts the trends in the strains versus the various truckload locations.

**NOMENCLATURE**

$\sigma$ = Compressive stress
$\sigma_{cu}$ = Compressive strength
$\sigma_t$ = Tensile strength
$\varepsilon$ = Strain
$\varepsilon'_0$ = Strain at compressive strength
$E_0$ = Initial modulus of elasticity

**1. INTRODUCTION**

Many bridges in Oregon are in need of strengthening due to increases in load requirements, corrosion problems, or outdated code-based designs. The Horsetail Creek Bridge (HCB) was considered as structurally deficient[1]. The bridge was found to have only 6% of the required shear capacity for the transverse beams and only 34% for the longitudinal beams (due to the absence of shear stirrups in both beams) and approximately 50% of the required flexural capacity for the transverse beams[1].

An effective solution to upgrade the bridge was the use of fiber-reinforced polymer (FRP) materials. FRP sheets were laminated to the bridge where the structural capacity was insufficient. Both transverse and longitudinal beams of the bridge were strengthened due to the deficiencies in shear and flexural capacities. In the case of the transverse beams, both shear (GFRP (Glass-FRP)) and flexural (CFRP (Carbon-FRP)) laminates were applied on the beams, while only GFRP laminates were needed for the longitudinal beams.

In this paper, three-dimensional finite element bridge models using ANSYS software are developed to replicate the HCB after FRP strengthening using the finite element method (FEM). Modeling methodology and the nonlinear analysis approach in ANSYS are presented. The results obtained from the FE bridge model are discussed and compared with the field test data in terms of strains on both transverse and longitudinal beams versus various truck load locations on the bridge deck.

**2. MODELING METHODOLOGY AND NONLINEAR ANALYSIS APPROACH**

Three materials are involved in the bridge structure in this study; i.e., concrete, steel, and FRP. The material properties defined for each component in the FE bridge model follow those used in the actual bridge. SOLID65, LINK8, and SOLID46 elements in ANSYS are used to model concrete, discrete reinforcing steel bars, and FRP laminates, respectively, in the bridge model. Nonlinear material properties are defined for the first two types of elements.

**2.1 Concrete:** The SOLID65, 3-D reinforced concrete solid element is used to represent concrete in the models. This element is capable of cracking in tension and crushing in compression. Cracking is treated as a “smeared band” of cracks, rather than discrete cracks in ANSYS[2] and occurs as soon as stresses in the concrete exceed the tensile strength of the material. The crushing capability of the SOLID65 element is deactivated in this study to avoid premature failure in the FE simulation. This element can model concrete with or without reinforcing bars. If the rebar capability is used, the bars will be smeared throughout the element. Nevertheless, in this study a discrete bar element is used instead of the smeared reinforcing approach. The most important aspect of the SOLID65 element is the treatment of nonlinear material properties. The response of concrete under loading is characterized by a distinctly nonlinear behavior. The typical behavior expressed in the stress-strain relationship for concrete subjected to uniaxial loadin

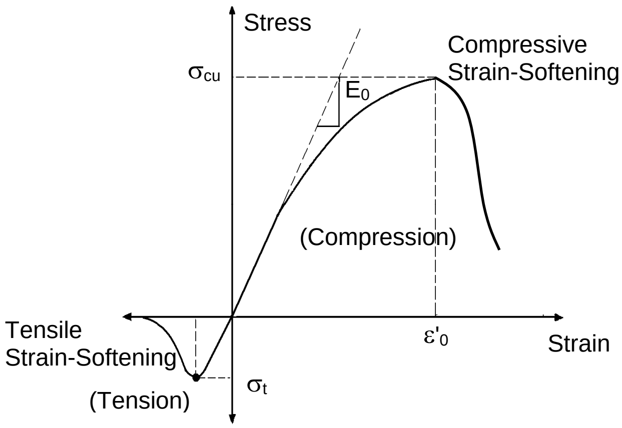


Fig. 1 Typical concrete behavior under uniaxial loading[3]

Uniaxial tensile and compressive strengths ($\sigma_{cu}$ and $\sigma_t$) and the uniaxial nonlinear stress-strain relationship for concrete are defined for the SOLID65 element. The first two parameters are required to define the failure surface for the concrete due to a multiaxial stress state[4]. The uniaxial tensile strength, $\sigma_t$, can be calculated, based on[5]:

$$\sigma_t = 0.623\sqrt{\sigma_{cu}} \text{ (MPa)} \quad [1]$$

For the ascending portions of the curve in compression, the stress-strain relationship is defined as follows:

$$\sigma = \frac{E_0 \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon'_0}\right)^2} \quad [2]$$

$$\varepsilon'_0 = 2\frac{\sigma_{cu}}{E_0} \quad [3]$$

$$E_0 = 4730\sqrt{\sigma_{cu}} \text{ (MPa)} \quad [4]$$

A perfectly plastic relationship is used instead of the compressive strain-softening curve in this study. Under uniaxial tension, the material is assumed to be linearly elastic with a modulus of elasticity of $E_0$ up to the tensile strength.

**2.2 Reinforcing Steel Bars:** The LINK8, 3-D spar element, is used to represent the reinforcing steel bar. Its behavior is characterized by a uniaxial tension-compression element that can also include nonlinear material properties. An elastic-perfectly plastic relationship is assumed in this study.

**2.3 FRP Laminates:** The SOLID46, 3-D layered structural solid element, is used to represent the FRP materials. This element allows up to 250 different material layers. Layer thickness, layer material direction angles, and orthotropic material properties also need to be defined. No slippage is assumed between the element layers (perfect interlaminate bond). FRP laminates have stress-strain relationships that are roughly linear up to failure. In the nonlinear analysis of the full-scale transverse beams([6], [7]), no FRP elements show stresses higher than their ultimate strengths. Consequently, in this study it is assumed that the stress-strain relationships for the FRP laminates are linearly elastic.

**2.4 Modeling Modifications:** To make the FE models more efficient and to reduce the model complexity, run-time, and memory requirements, modifications were made to the HCB model as follows:

- ***Equivalent Thickness of FRP Laminates:*** The HCB is retrofitted with several different combinations of both CFRP and GFRP laminates. The non-uniformity in thickness leads to a potential modeling difficulty. With the special layer modeling capability in the SOLID46 (FRP) element, a portion of the structure consisting of different materials and fiber orientations can be represented using just one type of SOLID46 element. Moreover, the thickness of the FRP laminates, which varies along the actual bridge, can be kept constant using equivalent thickness modeling. For example, if the actual laminate thickness is reduced by half in the model, the moduli of elasticity (E) and shear moduli (G) in all directions are doubled.
- ***"Lumping" of Reinforcing Steel Bar Areas:*** In addition to the several different combinations of the FRP laminates, the HCB also includes a number of steel reinforcement details. To limit the number of elements effectively, reinforcing steel bars in both transverse and longitudinal beams are lumped in locations associated with the FE mesh for the model.

**2.5 Analysis Assumptions:**

- The bonds between each element/material type are assumed perfect.
- The shear transfer coefficients in ANSYS for closed and open cracks in the SOLID65 concrete element are assumed to be 1.0 and 0.2, respectively.
- Cracking controls the failure of the structure.
- The concrete material is assumed to be isotropic prior to cracking and orthotropic after cracking([2], [8], [9]). The steel is assumed to be isotropic. The FRP material is assumed to be specially orthotropic-transversely isotropic.

**2.6 Nonlinear Analysis in ANSYS:** The status transition of the concrete from an uncracked to a cracked state, and the nonlinear material properties of concrete in compression and for the steel as it yields cause the nonlinear behavior of the structure under loading. Newton-Raphson equilibrium iteration is used to solve nonlinear problems in ANSYS.

**3. HCB LOAD TEST AND FE MODELING**

**3.1 Bridge Description:** The HCB (18.3 m (60 ft.) long and 7.3 m (24 ft.) wide) is supported on spread footing foundations and has three 6.1 m (20 ft) spans. Fiber optic sensors have been attached on both the concrete and FRP laminates on the bottom and on the sides of one transverse beam and one longitudinal beam of the HCB.

**3.2 Loading Conditions and Field Data:** Two different truck loadings are applied along the centerline of the bridge deck; i.e., empty-truck and full-truck loads. Strain data from fiber optic sensors attached on both beams (shaded areas in Fig. 2) are collected for seven locations of the truck for both load levels. Field test data for the bridge were provided by the Oregon Department of Transportation (ODOT)[10]. Only field test data collected after FRP strengthening are available. The positions of the truck, shown as the distance of the front axle of the truck from the right end of the bridge, including the axle weights, are indicated in Fig. 2. Note that the truck is shown only at positions 1 and 7 in Fig. 2.

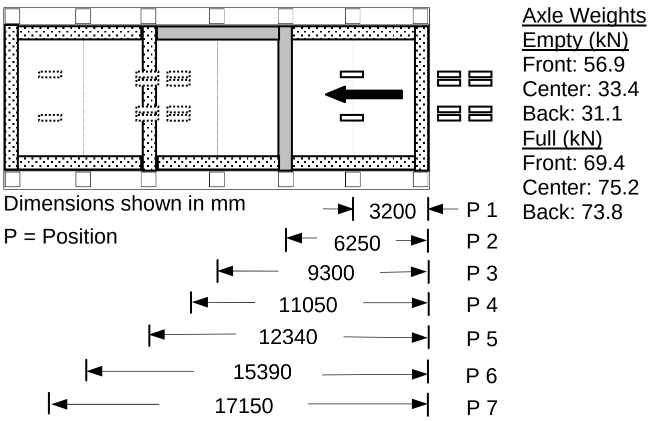


Fig. 2 Locations of truck and monitored beams

**3.3 FE Bridge Modeling:** Taking advantage of symmetry, only a longitudinal half of the bridge is modeled. Typical steel reinforcement details in the transverse and longitudinal beams are shown in Fig. 3. The steel details in the deck and columns are not shown. Fig. 4 shows the FE bridge model with FRP laminates on the beams.

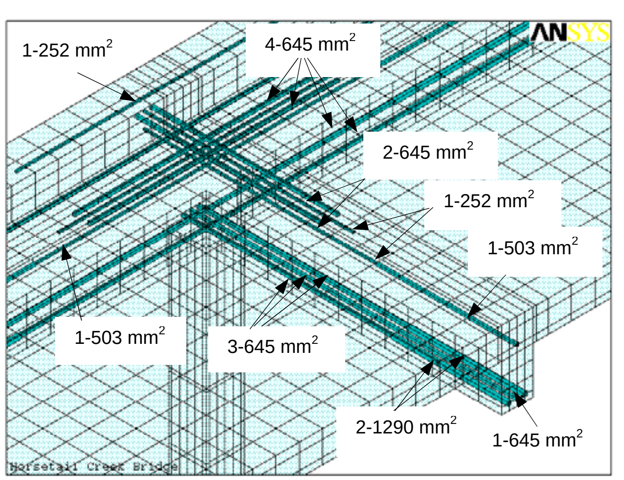


Fig. 3 Typical steel reinforcement in the transverse and longitudinal beams

Note that 1-503 mm$^2$ represents one steel bar with an area of 503 mm$^2$, while 2-1290 mm$^2$ represents two steel bars with an area of 1290 mm$^2$ for each bar, and so on.

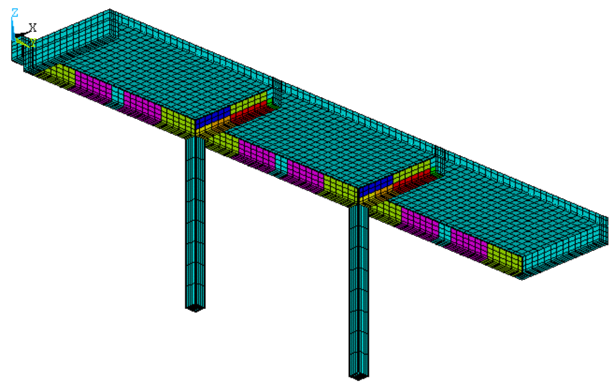

Fig. 4 FE bridge model with FRP laminates

## 4. RESULTS

The strains from ANSYS predictions and the field data for both truck loadings applied on the HCB after retrofitting are plotted versus the distances of the single front axle of the truck from the end of the bridge, as “influence lines” (Fig. 5). In this paper, the strains in two locations are examined. The first (Strain A) is at the center bottom fiber of the concrete for the transverse beam at midspan, while the second (Strain B) is at one inch-off center for the bottom fiber of the concrete for the longitudinal beam at 1625 mm to the left of the midspan.

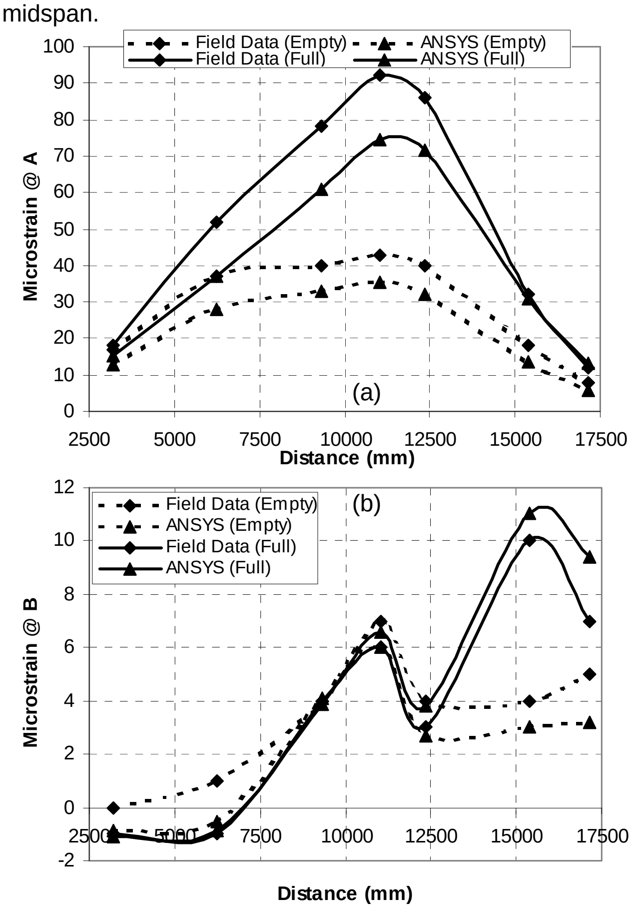


Fig. 5 Comparisons between ANSYS predictions and field data for strains vs. distance of the front truck axle from the end of the bridge

After examining the ANSYS results for all of the truck positions, it was found that the bridge does not crack even for a full-truck load. Therefore, the truck loading study is essentially a linear analysis

As seen in Figs. 5 (a) and (b), ANSYS very well predicts the trends in the strains versus the various truck locations. It is observed from Fig. 5 (a) that the maximum strains for Strain A for both load levels are obtained if the single axle of the truck is at 11.05 m (Position 4) from the end of the bridge deck. At this location the main load from the tandem axle is directly above the transverse beam to which the fiber optic sensor is attached.

For Strain B (Fig. 5 (b)), the maximum strain is produced for the empty-truck load case when the truck is at 11.05 m (Position 4) from the end as the load from the single axle is closest to the sensor. However, the maximum is reached under full load with the truck at 15.39 m (Position 6) from the end because the load from the tandem axle dominates.

## 5. CONCLUSIONS AND RECOMMENDATIONS

**5.1 Conclusions:** The comparisons between ANSYS predictions and the experimental data show that the proposed FE model is a good representation for the HCB in terms of the number of elements, structural details, and in providing reasonably accurate results. The HCB does not crack under the applied truck loads, and the bridge structure still behaves essentially linearly. The trends in the strain results for the various locations of the truck obtained from ANSYS model are very similar to those from the field test data. In general, the maximum strain at a particular sensor is developed when the load from either the single or tandem axle is closest to the sensor.

**5.2 Recommendations:** Modeling a reinforced concrete structure in a nonlinear analysis (after cracking) in ANSYS is generally challenging. Reinforced concrete FE models either with or without FRP strengthening are susceptible to numerical instability. Loads must be applied incrementally, and tolerances for both force and displacement criteria must be closely monitored. Mesh size and value of the shear transfer coefficient also affect solution convergence. The current analysis of the HCB, however, is still essentially linear due to the fact that the bridge does not crack under the applied truck loads. Consequently, these convergence difficulties are avoided. Nonlinear behavior and failure of the bridge will be examined in the next phase of the project.


## ACKNOWLEDGMENTS

This project was financially supported by the Oregon Department of Transportation (ODOT), Salem, OR.


## REFERENCES


[1] CH2M-HILL Consulting Engineers in conjunction with TAMS Consultants, *Evaluation and Resolution of Under Capacity State Bridges: Bridge #04543, Horsetail Creek Bridge*, CH2M-HILL, Inc., Corvallis, OR, 1997.

[2] ANSYS User's Manual; Revision 5.5, Swanson Analysis System, Inc., Houston, PA, 1998.

[3] Bangash, M.Y.H., Concrete and Concrete Structures: Numerical Modeling and Applications, Elsevier Science Publishers, LTD., Essex, England, 1989.

[4] William, K. J., and Warnke, E. P., *Constitutive Model for the Triaxial Behavior of Concrete*, *Proceedings, International Association for Bridge and Structural Engineering*, Vol. 19, ISMES, Bergamo, Italy, 174, 1975.

[5] ACI Committee 318, *Building Code Requirements for Standard Concrete (ACI 318-99) and Commentary (ACI 318R-99)*, ACI, Farmington Hills, MI, 1999.

[6] Kachlakev, D.I., Miller, T.H., Yim, S.C.S., Chansawat, K., and, Potisuk, T., *Linear and Nonlinear Finite Element Modeling of Reinforced Concrete Bridge Beams Strengthened with FRP Laminates*, ODOT Final Report (draft), Salem, OR, 2001.

[7] Potisuk, T., *Finite Element Modeling of Reinforced Concrete Beams Externally Strengthened by FRP Composites*, *MS Thesis*, Oregon State University, Corvallis, OR, 2000.

[8] Isenberg, J., *Finite Element Analysis of Reinforced Concrete Structures II*. ASCE, New York, NY, 1993.

[9] Kant, T., *Finite Elements in Computational Mechanics*. 1, Pergamon Press, Inc., Elmsford, NY, 1985.

[10] ODOT Field Test Data, *Private Correspondence*, Salem, OR, November, 2000.