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Verification of empirical models for FRP strengthened RC beams using ANSYS FE model

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ABSTRACT: There are many empirical models that exist that are used to predict the failure loads for a fiber reinforced polymer (FRP) strengthened reinforced concrete (RC) beam. Few finite element (FE) models exist that accurately predict the failure loads for FRP strengthened RC beams. Most of the FE models that exist do not model the layer of epoxy between the FRP and the concrete. A perfect bond is assumed. In this research, several FRP strengthened RC beams with different material properties for the constituents were modeled in ANSYS using finite elements. The epoxy layer between the FRP layers and the concrete was modeled and a non-perfect bond was assumed between the concrete and the FRP layers. Nonlinear analyses were run on the FRP strengthened RC beam models. The trends in the behavior of the FRP strengthened RC beam at failure of the ANSYS models were compared to the behavior of experimental FRP strengthened RC beams. The ANSYS failure load results were then compared to the predicted failure load values from several different empirical models. The ANSYS finite element model can be used to show which empirical models are most accurate to predict the failure loads for fiber reinforced polymer (FRP) strengthened reinforced concrete (RC) beams.

1 ANSYS MODEL

A reinforced concrete simply supported beam under 4-point bending load that had been strengthened with various layers of fiber reinforced polymer composites was analyzed using ANSYS finite element analysis software. A thorough investigation based on numerous ANSYS analyses was performed to determine the best method for modeling a FRP strenghthened RC beam and this can be seen in its entirety in Britton (2010). Based on the results of the investigation by Britton (2010), it was determined that the models of Kachlakev (2001), Jia (2003), and Wolanski (2004) could be used as the basis for the models used in this research; therefore, this research built upon these past models. Because of symmetry, only half of the beam was modeled. The FRP layers were applied to the tensile side of the beam using a thin epoxy layer, 1 mm thick. The FRP layers were modeled as 1.27 mm thick. The concrete was reinforced with two number 3 rebar. The overall beam geometry and ANSYS model used can be seen in Figures 1 and 2 respectively.

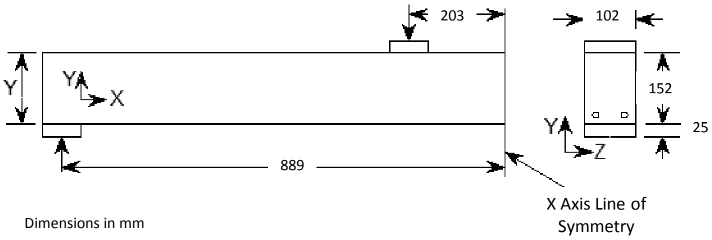

Figure 1. Beam geometry

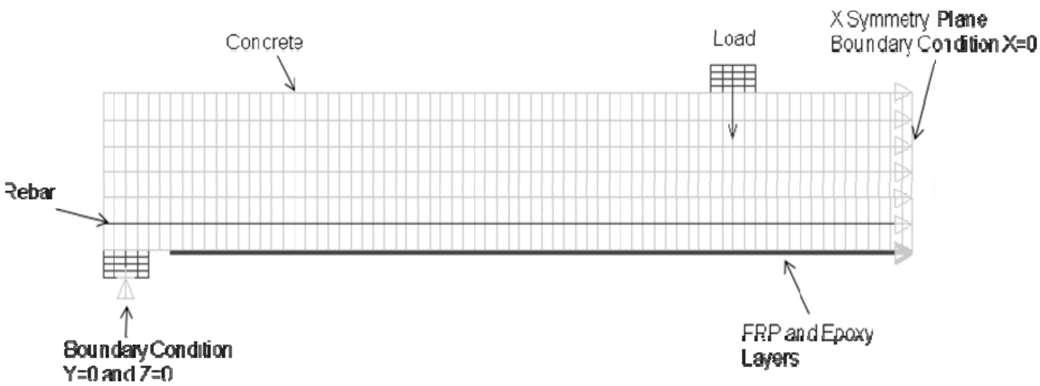

Figure 1. Example of overall beam geometry and ANSYS finite element model.

Several models were built in ANSYS with a single layer of epoxy and various layers of FRP. Two different groups of models were built, Group 1 and Group 2. Each group consisted of six models. Within the groups, only the number of FRP layers varied from model to model. The layers of FRP ranged from one layer to six. The material properties for the constituents varied from Group 1 to Group 2. All models in Group 1 were represented by G1 and a number that represents the number of FRP layers. For example, G1-2 would mean Group 1 model with 2 layers of FRP. From the experiments of Deng (2002) and Zhao (2005), the type of failure of the FRP strengthened, reinforced concrete beam partially depended on the type of epoxy used: organic or inorganic. This research used organic epoxy, modeled in ANSYS with linear elastic properties, to bond the FRP layers to the tensile side of the reinforced concrete beam. The concrete was described in ANSYS by using the embedded ANSYS concrete model, multilinear elastic properties, and linear elastic properties. The cracking of the concrete was the controlling factor for failure for the ANYSY model. The rebar was modeled with the linear isotropic model in conjunction with a bilinear isotropic model. The X axis direction represented the direction of the fibers in the FRP. The FRP was modeled in ANSYS as an orthotropic material that was also transversely isotropic. The models were loaded incrementally and for all analyses, the model was considered converged when it failed at 0.45 kg load increments. A comparison of the material properties used for Group 1 and Group 2 can be seen in Table 1.

Table 1. Material Properties

Component	Material Property	Group 1	Group 2
Concrete	Modulus of Elasticity (GPa)	30.3	33.5
	Poisson's Ratio	.3	.3
	Tensile Strength (MPa)	4.0	2.3
Rebar	Modulus of Elasticity (GPa)	200.0	200.0
	Poisson's Ratio	.3	.3
	Yield Stress (MPa)	413.7	427.0
	Tangential Modulus (MPa)	20	20
Epoxy	Modulus of Elasticity (GPa)	3.3	3.2
	Poisson's Ratio	.4	.4
FRP	Modulus of Elasticity in X (GPa)	62.1	228.2
	Modulus of Elasticity in Y (GPa)	4.8	27.4
	Modulus of Elasticity in Z (GPa)	4.8	27.4
	Major Poisson's Ratio XY Plane	.22	.22
	Major Poisson's Ratio YZ Plane	.30	.3
	Major Poisson's Ratio XZ Plane	.22	.22
	Shear Modulus XY Plane (GPa)	3.3	17.5
	Shear Modulus YZ Plane (GPa)	1.9	10.5
	Shear Modulus XZ Plane (GPa)	3.3	17.5

2 ANSYS RESULTS

ANSYS nonlinear, static analyses were run on all models in Group 1 and Group 2. Each model was loaded in small increments until failure. After failure, the ANSYS results were compared to the experimental failure trends documented by Deng (2002) and Zhao (2005). After comparing the ANSYS results to the experimental results, the ANSYS failure loads will be compared to the failure loads calculated by using the empirical models of ACI 440 (2008), Zhao (2005), Teng et al. (2002) and Shehata et al. (2001) and the empirical models will be verified.

It must be noted, before the results are discussed, that ANSYS assumed a "perfect world." For example, no air bubbles existed in the bond layer between the FRP and the concrete or between FRP layers. There were no inconsistencies in epoxy layer thickness or inconsistencies of any kind in the system. All fibers in the FRP layers were the same thickness. Voids in fibers or epoxy were not present.

The ANSYS strains at the failure load of each model in Group 1 and Group 2 were studied and compared to the ACI 440 (2008) hand calculated strains for FRP rupture and debonding strain. Before the ANSYS strain results were reviewed and compared to the rupture and debond strain calculated with ACI 440 (2008) equations, it was important to know the failure trends that have been observed in experiments. From the experiments of Deng (2002) and Zhao (2005), the type of failure of the FRP strengthened, reinforced concrete beam partially depended on the type of epoxy used: organic or inorganic. According to Deng's (2002) experiments, FRP layers bonded to the tension side of reinforced concrete beams with organic epoxy always have delamination failures. When an inorganic epoxy was used, Zhao (2005) reported the failure mode was due to FRP rupture for two, three, and four layers of FRP; however, when five and six layers of FRP were used, the failure mode switched to debonding. The experiments of Deng (2002) showed that for inorganic epoxy, failure was always due to fiber rupture. For five layers of FRP, delamination was also reported in addition to the fiber rupture. Deng (2002) explained the mode of failure difference occurred because the organic epoxy was more flexible than the inorganic epoxy. The flexibility allowed more deflection and caused more cracks which resulted in higher strains. In order to compare the failure of the ANSYS model to what was shown to occur in experiments, the strains at failure of the ANSYS Group 1 and Group 2 models needed to be investigated.

The rupture strain and debond strain of the FRP layers was needed in order to investigate how the ANSYS models predicted failure of the FRP strengthened RC beam. Because ACI 440 (2008) empirical model equations are the most commonly used, these equations were used to determine the predicted design debond strains and rupture strains of the FRP strengthened RC beams that were analyzed in ANSYS. The equations and examples of the calculations using the ACI 440 equations can be found in Britton (2010). A comparison of the calculated rupture and debond strain and the ANSYS strain at failure for each ANSYS model in both groups can be seen in Figure 3 for Group 1 and Figure 4 for Group 2. A comparison between just the ANSYS failure strains for Group 1 and Group 2 can be seen in Figure 5.

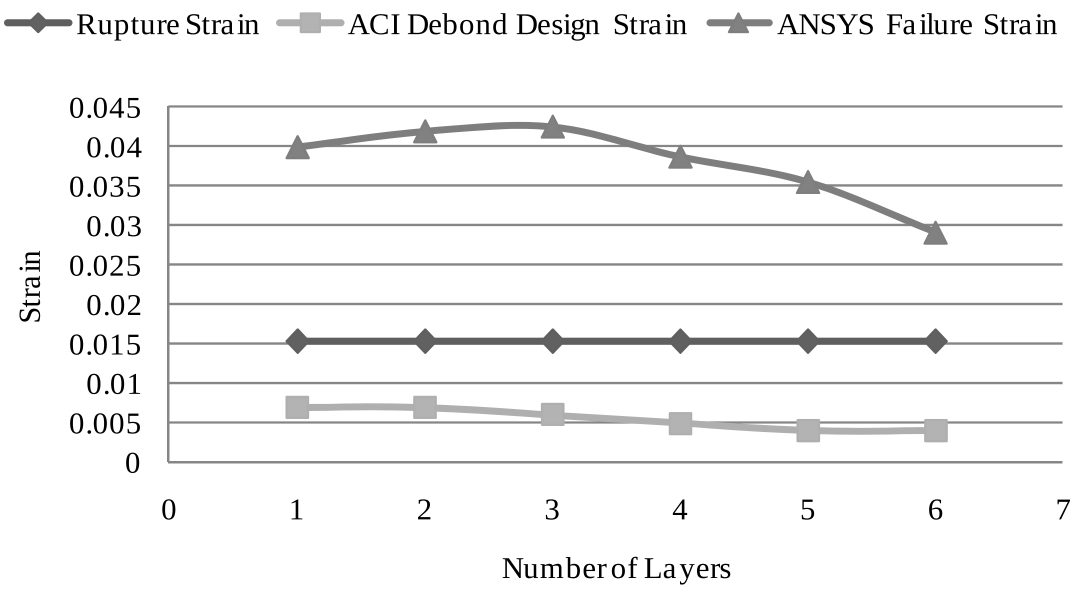

Figure 3. Strain Comparisons for Group 1.

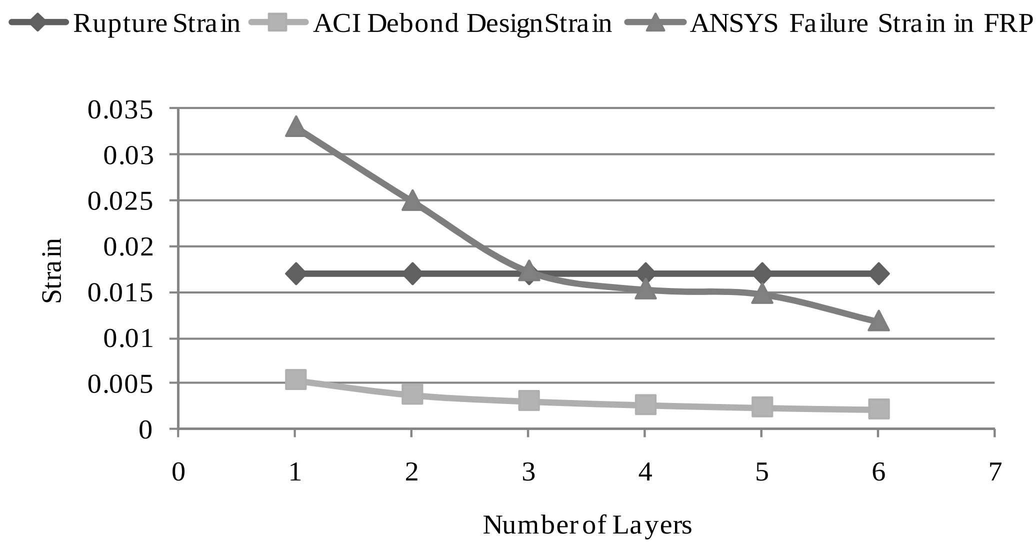

Figure 4. Strain Comparisons for Group 2.

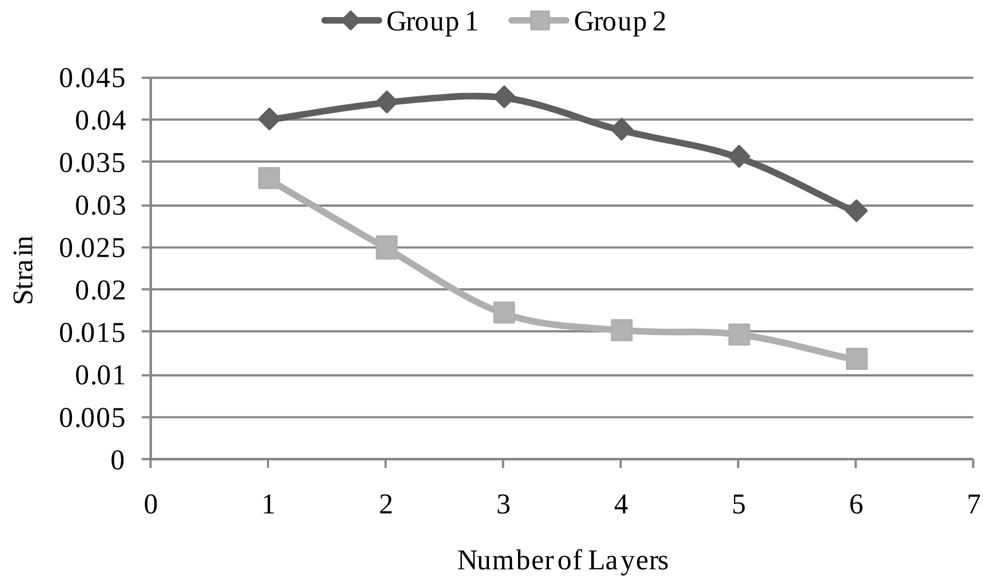

Figure 5. ANSYS Strain Comparisons between Group 1 and Group 2.

The FRP layers used in Group 1 had a much lower modulus of elasticity than the FRP layers used in Group 2. The FRP modulus of Group 2 was approximately five times greater than the FRP modulus of Group 1. By observation of the strain plots in Figure 3, 4, and 5, it can be concluded that the stiffness of the FRP greatly affected the strain level at failure in the FRP. It can be seen in Figure 3, all strains were greater than the rupture strain of the FRP. It was easy to see from Figure 4, Group 2 exhibited both debond failure and fiber rupture failure. For layers one, two, and three (G2-1, G2-2, and G2-3), the max strain at failure registered by ANSYS in the FRP was greater than the rupture strain of the fiber; therefore, fiber rupture failure. For layers four, five, and six (G2-4, G2-5, and G2-6), the max strain recorded at failure by ANSYS in the FRP layers was less than the rupture strain and greater than the ACI 440 (2008) calculated design debond strain; therefore, debonding occurred.

The trends for predicted failure of the ANSYS results compared very well to the experimental failure trends documented by Deng (2002) and Zhao (2005). Deng (2002) reported delamination failure always occurred. This was shown to be the case with the ANSYS results. Every model had strains greater than the calculated debond strain; therefore, some level of debonding occurred in each model. Although, an inorganic epoxy was used, Zhao (2005) reported the failure mode switched between fiber rupture and delamination depending on the number of FRP layers used. This was very similar to the results for Group 2 in the ANSYS results. For 1-3 layers there was delamination and fiber rupture and for 4-6 layers there was only delamination failures.

After the ANSYS failure trends were verified with experimantal failure trends, the overall behavior of the failure loads of the ANSYS beam with the addition of FRP layers was compared to experimental results. The failure loads were also compared to empirical model calculated failure loads. There are many empirical models that have been developed to describe the flexural behavior of a FRP strengthened, RC beam. Several models have been developed that can be used to find the ultimate failure load of the system. A few of these models include the empirical models of ACI 440 (2008), Zhao (2005), Teng et al., (2002), and Shehata et al., (2001). The failure loads were calculated using each of these empirical models by entering the equations into MATHCAD. The equations for each empirical model used and an example of each calculation can be seen in Britton (2010). The ANSYS failure load results and the empirical model failure load results can be seen in Table 2.

Table 2. Failure Load Comparisons

		Failure Load (kg)				
Group	ANSYS Model	ANSYS	ACI 440 (2008)	Zhao (2005)	Teng et al. (2002)	Shehata et al. (2001)
1	G1-1	1,626	2,344	1,736	1,632	1,812
	G1-2	2,002	2,542	1,987	1,902	2,520
	G1-3	2,394	2,707	2,168	2,069	3,160
	G1-4	2,574	2,839	2,314	2,180	3,733
	G1-5	2,781	2,963	2,437	2,270	4,238
	G1-6	2,791	3,065	2,545	2,344	4,677
2	G2-1	2,948	3,125	2,373	2,419	2,971
	G2-2	3,660	3,577	2,825	2,752	4,495
	G3-3	3,666	3,882	3,141	2,949	5,652
	G4-4	4,093	4,106	3,387	3,080	6,436
	G5-5	4,565	4,280	3,587	3,175	6,854
	G6-6	4,630	4,419	3,753	3,246	6,904

From Table 2, it can be seen that as the number of layers of FRP increased, in both Groups 1 and 2, the failure load increased. This was also shown in experiments by Zhao (2005). According to Zhao’s experiments, as the number of layers increased from five to six layers, there was no significant effect on the ultimate load. This was also apparent with the ANSYS results shown in Table 2. The difference in the ultimate loads caluclated for five layer and six layer models was less than 10 kg for Group 1 and 65 kg for Group 2. The experimental trends given by Zhao (2005) when compared to ANSYS results are in close agreement. Based on the above comparisons, not only do the ANSYS models modes of failure follow closely to the experimental trends, the effects the addition of FRP layers has on the overall failure load also followed the same patterns as seen in the experimental results.

From Table 2, it can be seen that there are good correlations between the ANSYS predicted failure loads and the empirical model predicted failure loads except for the Shehata et al. (2001) model predictions. The equations of ACI 440 (2008) predicted the failure loads very well compared to the ANSYS results for Group 2. Zhao (2005) and Teng et al. (2002) predicted the failure loads very well compared to the ANSYS results for Group 1. There was a good correlation with the ACI 440 (2008) predictions except for G1-1 and G2-2. According to ACI 440 (2008), future development is needed on the effect the strength of concrete has on the FRP strengthened system. The effect the concrete strength had on models G1-1 and G1-2 could be a reason for the discrepancy between the ACI predicted failure loads and the ANSYS failure loads. Zhao (2005) stated that another shortcoming of the ACI 440 (2008) was the equations were purely empirical and not theoretical based. Besides G1-1 and G2-2, the ANSYS failure loads were very similar to the ACI 440 (2008) predicted failure loads. Based on the comparisons shown and the similarities to experiment, ANSYS can be used to verify empirical models. From this research, it can be concluded that the empirical models of ACI 440 (2008), Zhao (2005), and Teng et al. (2002) are good and can be used to predict failure loads. The Shehata et al. (2001) model appeared to not be as accurate as the other models when compared to ANSYS models.

It should also be noted that the empirical models did not take into account the epoxy thickness. The epoxy thickness was modeled in this research. It was shown by Britton (2010) that the thickness of the epoxy had an effect on the failure load of the beam. New analyses were run on the G1-3 model with varied epoxy thickness. The epoxy thickness varied from 0.508 mm, 0.762 mm, 1.016 mm, and 1.27 mm for the new G1-3 models called ET1, ET2, ET3, and ET4 respectively. The failure loads from each model were compared to the previous empirical models stated and percent errors were calculated. The failure loads for the empirical models were listed previously in Table 2 for G1-3. The results can be seen in Table 3.

Table 3. Failure Load Percent Error Calculations

ANSYS Model	ANSYS Failure Load (kg)	ACI 440 (2008) % Error	Zhao (2005) % Error	Teng et al. (2002) % error	Shehata et al. (2001) % error
ET-1	1,916	29	12	7	39
ET-2	2,088	23	4	1	34
ET-3	2,394	12	10	16	24
ET-4	2,106	22	3	2	33

From the percent error calculations shown in Table 3, it appeared that failure loads calculated with the models of Zhao (2005) and Teng et al. (2002) were best approximated by the failure loads calculated by ANSYS. The ACI 440 (2008) model and the Shehata et al. (2001) model predicted higher failure loads; whereas, the ANSYS model and the other empirical models were more conservative in the ultimate failure load. The ANSYS ultimate failure loads for ET-2 and

ET-4 were very similar to the results calculated by Zhao (2005) and Teng et al. (2002). The percent errors ranged from 1-7% for these models. For ET2, the percent errors for Zhao (2005) and Teng et al. (2002) are 4% and 1%, respectively. For ET4 the percent errors for Zhao (2005) and Teng et al. (2002) are 3% and 2%, respectively. ET3 also compared well to Zhao (2005) and ACI 440 (2008). The percent error for Zhao (2005) and ACI 440 (2008) was 10% and 12%, respectively.

Depending on the thickness of epoxy used, an empirical model can be chosen that will best approximate the ultimate failure load. For 0.03 inches and 0.05 inches of epoxy, the best empirical models to predict the failure load based on ANSYS results were the models of Zhao (2005) and Teng et al. (2002). When the epoxy layer was increased to 0.04 inches, the model of Zhao (2005) and the ACI 440 (2008) predicted the failure load very well when compared to the ANSYS calculated failure load.

3 CONCLUSIONS

ANSYS can be used to predict failure modes for organically bonded FRP reinforced concrete beams. By observing the failure strains in the FRP, it can be determined if the beam failed due to fiber rupture, debonding or a combination of the two. The ANSYS results followed the same trends as the experimental work of Deng (2002) and Zhao (2005). When empirical models were compared to ANSYS results, results can vary with varying the epoxy thickness.

ANSYS can be used to predict the failure load of FRP reinforced concrete beams and to validate empirical models. Results from ANSYS were very similar to ACI 440 (2008) predicted failure loads as well as the failure loads predicted by the empirical models of Zhao (2005) and Teng et al. (2002).

4 REFERENCES

American Concrete Institute (ACI). 2008. *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, *ACI 440.2R-08*, MI, USA.

Britton, H. 2010. "Prediction of bond failure of FRP layers and concrete interface using a finite element method." PhD dissertation: University of Alabama in Huntsville, Huntsville, Alabama.

Deng, Y. 2002. "Static and Fatigue Behaviors of RC Beams Strengthened with Carbon Fiber Sheets Bonded by Organic and Inorganic Matrices." PhD Dissertation: University of Alabama in Huntsville, Huntsville, Alabama.

Jia, M. (2003). "Finite element modeling of reinforced concrete beams strengthened with FRP composite sheets." MS thesis: University of Alabama in Huntsville, Huntsville, Alabama.

Kachlakev, D., Miller, T., Yim, S., Chansawat, K., and Potisuk, T. (2001). *Finite Element Modeling of Reinforced Concrete Structures Strengthened with FRP Laminates,* Oregon Department of Transportation, Salem, Oregon.

Shehata, I. A. E. M., Cerqueira, E. C., Pinto, C. T. M., and Shehata, L. C. D. 2001. "Strengthening of R.C. beams in flexure and shear using CFRP laminate." *Proc., Fifth International Conference on the Fiber Reinforced Plastics for Reinforced Concrete Structures,* Cambridge, England, 97-106.

Teng, J.G., Chen, J.F., Smith, S.T., and Lam, L. 2002. *FRP-Strengthened RC Structures,* Chichester, West Sussex, UK: John Wiley and Sons, 331-101.

Wolanski, A.J. (2004). "Flexural behavior of reinforced and pre-stressed concrete beams using finite element analysis." MS thesis: Marquette University, Milwaukee, Wisconsin.

Zhao, L. 2005. "Characterizations of RC beams strengthened with carbon fiber sheets." PhD dissertation: University of Alabama in Huntsville, Huntsville, Alabama.