Finite Element Analysis of CFRP wrapped Bonded and Unbonded Post Tensioned Beams

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Abstract - *Four Finite Element (FEM) models has been developed using Ansys 15 for Bonded and Unbonded Post tensioned prestressed concrete beams retrofitted with frp designed based on American guidelines ACI and AASHTO. In this research comparison of two guidelines AASHTO and ACI by formulating excel sheets for generalized solution and validation of results by finite element modeling in ANSYS software is done. This work gives the comparison of total stresses, flexure capacity increase, deflection reduction, crack control, displacement curves and the check for shear on the same model from both the methods ACI and AASHTO for bonded and unbonded PT beams. Although a great amount of work has been done on retrofitting of concrete and prestressed concrete bridge girders but comparison of these two design procedures for prestressed beams with bonded and unbonded strands for residential is really beneficial to design professionals. The results showed that FRP strength was effectively utilized in the section selected herein, which could be addressed through economy for the amount of FRP and prestressing steel used, thereby increasing the section ductility. The ACI and AASHTO approach produced comparable results to the FEM and can be effectively and conveniently used in design.*

Key Words: *Bonded tendons, Unbonded tendons, Fiber Reinforced Polymer, CFRP, Flexure, Post-tensioned, Strengthening beams, ACI 440-2R, AASHTO LRFD, ANSYS.*

1.INTRODUCTION

Pre-stressed concrete structures has been growing increasingly in construction industries its applications varies from bridges, commercial, high rise residential to where beams exhibit complicating features and heavy loads. PSC beams should be designed with proper codal provisions without which it leads to undesirable structural behavior like pre-stress loss in strands and less strength hierarchy and other causative aspects are deterioration of prestressed concrete and steel caused by environmental factors, natural hazards such as earthquakes and cyclones, increase in loads due to change in usage leads to loss of strength, deflection, cracking, spalling etc. Since Post tensioned prestressed concrete beams cannot be reconstructed or replaced completely, repair and retrofitting is more suitable.

Retrofitting refers to structural interventions aimed at strengthening of existing structures to resist higher design loads due to deterioration; construction deficiency or increase ductility has been accomplished using conventional material FRP and construction techniques for prestressed concrete structure. Fiber-reinforced polymers (FRP) are recent innovations in structural engineering and increasingly adopted in India, as compared to other construction materials, it has advantages such as high stiffness-to-weight and strength-to-weight ratios, corrosion resistance, and

Constructability. Civil engineering applications of FRP sheets include strengthening a sound structural member to resist increased loads, and correction of design or construction errors. In India a large construction of commercial buildings is using post tensioned beams and retrofitting using frp wrapping is economic then reconstruction of the whole structure. Carbon fiber reinforced polymer (CFRP) is advantageous over other fibers due to high elastic modulus, high strength.

ACI Committee 440 provides guidance for the selection, design, and installation of FRP wrapping systems for externally strengthening prestressed concrete structures, based on experimental research, analytical work, and field applications. The ACI report outlines design procedure for flexure. ACI 318 was used for shear check. ACI 440 also mentions areas that require additional research, including design of unbonded PT beams frp strengthened and theoretical modeling of FRP strengthened structures. Besides experimental and field tests, finite element modeling of FRP strengthened structural members is an alternate and economic avenue to determine their behavior.

The objective of this research was comparative study of two design guidelines for a model PT retrofitted beam and validate the results using the finite element software ANSYS 15, for flexural and shear strengthening with FRP. To compare the results obtained by using ACI 440.2r, ACI 318, ACI 423.3r, AASHTO LRFD, AASHTO guide specifications for design of bonded, is popular and is widely used in India. All the designs have been formulated in excel sheets for both flexural strengthening and shear check. Excel sheets formulation serves a tool for design engineer to design for any sections in short time. This study provides important information on the FEM procedure for FRP strengthened prestressed concrete T beams. The results obtained are very helpful to designers and researchers in understanding practical and cost-effective design procedure for flexure and shear strengthening of Bonded and Unbonded post tensioned prestressed concrete T beams with CFRP wrapping.

2. LITERATURE REVIEW

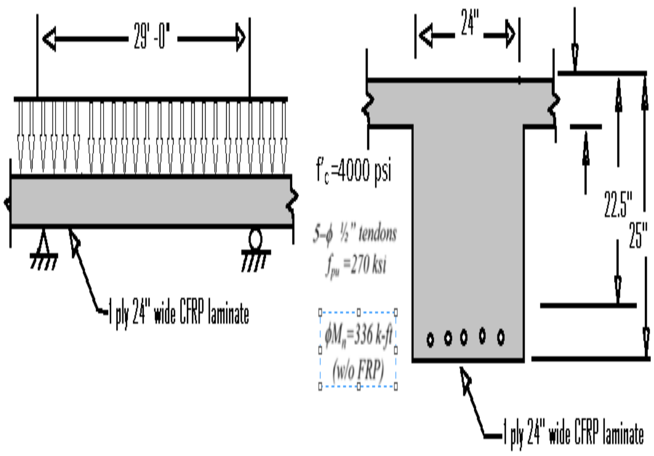
NurYazdani, FarziaHaque, and IstiaqueHasan Oct (2016), tells about structurally deficient AASHTO type prestressed concrete bridge girder with FRP wrapping was analyzed using the ANSYS FEM software and the ACI analytical approach. Both flexural and shear FRP applications, including vertical and inclined shear strengthening, were examined. Results showed that FRP wrapping can significantly benefit prestressed concrete bridge girders in terms of flexure, shear capacity increase, deflection reduction, and crack control. The FRP strength was under utilized in the sections elected herein, which could be addressed through decrease of the amount of FRP and prestressing steel used, thereby increasing the section ductility. The ACI approach produced comparable results to the FEM and can be effectively and conveniently used in design.

Bharath G R Sep (2015), carried out work for Strengthening of post-tensioned beams by externally bonded and anchored Natural Sisal fiber reinforced polymer composites In this Experimental work the flexural behavior, ductility characteristics and ultimate load carrying capacity of post-tensioned beams strengthened by NSFRPs were evaluated under two point loading. To achieve this 4 PT beams of size 200mmx200mmx2000mm were casted as per IS1343-1980 in that 3 beams are strengthened by NSFRP wrapping in flexure zone and anchored. The ultimate load carrying capacity of the anchored beams was found to be increased by 27.27% compared to control beams. From the test results and observations found that role of the anchorages is to transform a brittle type of failure into a more ductile failure.

Jayalin.D, August (2015), analyses Finite Element (FEM) model developed using Ansys 15 for beams with openings strengthened by Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) Concrete sheets for both inside and around the opening. The model consists of a beam of length 1800mm, width 150mm and depth 250mm is considered. The top longitudinal reinforcement consists of four bars of 12mm diameter and the bottom longitudinal reinforcement consists of two bars of 8mm diameter with spacing 150 mm. The size of the opening was 200x100mm was provided. As a result, the percentage of increase in load carrying capacity for CFRP sheets is 50%, where as in GFRP sheets percentage of increase in load carrying capacity is 37%.

3. RESEARCH METHODOLOGY

The beam specimen used herein is taken from ACI 440.2r and solved for Bonded and Unbonded post tensioned prestressed concrete with external Frp wrapping at the bottom , five 12.7 mm diameter bonded prestressing strands with low relaxation are placed. The beam requires an increase in load carrying capacity by 28.28 %. In this research, four T beam of length 8840mm, flange width 2210mm, flange depth 102mm, web width 610mm, web depth 533mm is designed. The longitudinal reinforcement consists of five prestressed bars of 12.7mm diameter with spacing 101.66 mm. The strands are bonded in two cases and unbonded in other two, a uniformly distributed load is acting at the top of flange. The value of factored load acting is 110.2N/mm.



ELEVATION **SECTION**

Fig 1: Post tensioned Prestressed concrete T beam with FRP wrapping at base.

TABLE 1
PROPERTIES OF CONCRETE

Young's Modulus Ec	24700 N/mm^2
Poisson's ratio	0.15
Density	2400 kg/m^3

TABLE 2
PROPERTIES OF PRETSRESSING STEEL

Diameter of pretsressing strands dp	12.7 mm
Area Ap	495 mm^2
Grade of prestressing steel fpu	1860 N/mm^2
Young's modulus Ep	1.96 $\times 10^5$ N/mm^2
Yield strength fpy	1586 N/mm^2
Poisson's ratio μ	0.3
Density	7850 Kg/m^3

TABLE 3
FRP SYSTEM PROPERTIES

Thickness tf	1.02mm
Ultimate tensile strength ffu	621 N/mm^2
Rupture strain ε_{fu}	0.015 mm/mm
Modulus of elasticity Ef	37000 N/mm^2
Poisons ratio	0.22
density	1500 m^3

3.1 Flexural design of CFRP wrapped prestressed T section for bonded prestressing steel:

ACI 440.2r 10.2.10-The nominal flexural strength of the section with frp wrapping can be computed using

$$\emptyset M_n = \emptyset[M_{np} + \Psi_f M_{nf}]$$

=573 KN-m

where

$$M_{np} = A_p f_{ps}\left(d_p - \frac{\beta_1 c}{2}\right)$$

$$M_{nf} = A_s f_{fe}\left(d_f - \frac{\beta_1 c}{2}\right)$$

$$\Psi_f = 0.85$$

$$\phi = \begin{cases} 0.90 \text{ for } \varepsilon_{ps} \geq 0.013 \\ 0.65 + \dfrac{0.25(\varepsilon_{ps} - 0.010)}{0.013 - 0.010} \text{ for } 0.010 < \varepsilon_{ps} < 0.013 \\ 0.65 \text{ for } \varepsilon_{ps} \leq 0.010 \end{cases}$$

M_{np} =	$A_pf_{ps}(d_p - \beta_1c/2)$			ACI 440.2R-2008, Equation 10-13		
=	42703288.4	Nmm				
Use =>	42703288.4	Nmm		*Existing steel contribution included*		
M_{nfrp} =	$A_ff_{fe}(d_f - \beta_1c/2)$			ACI 440.2R-2008, Equation 10-13		
=	13478821.4	Nmm				
ϕM_n =	$\phi(M_{ns} + \psi\phi M_{nfrp})$			where ϕ =	0.9	(Eqn 10-5)
=	48744258.0	Nmm		& ψ =	0.85	
ϕM_{nfrp} =	584931095	Nmm =	48744258.0 Nmm			
		>=	397.0 Nmm			
		DCR =	0.000	OK		

=> Use 1 layers x 610 in wide of CFRP Fabric

on the underside of the concrete beam

EXCEL SHEET 1: ACI BONDED BEAM

The maximum strain that can be achieved in FRP reinforcement will be governed by strain limitations due to either concrete crushing, FRP rupture, FRP debonding, or pretsressing steel rupture.The effective design strain for FRP reinforcement at the ultimate limit state for failure controlled by concrete crushing is calculated as

$$\varepsilon_{fe} = 0.003\left(\frac{d_f - c}{c}\right) - \varepsilon_{bi} \leq \varepsilon_{fd}$$

AASHTO specification 5.7.3.1(6th Edition)- For rectangular T section subjected to flexure about one axis, for which f_{pe} is not less than $0.5f_{pu}$, the average stress in prestressing steel, f_{ps}, may be taken as

$$f_{ps} = f_{pu}\left(1 - k\frac{c}{d_p}\right)$$

Where

TABLE 4 : VALUE OF K

Type of Tendon	fpy/fpu	Value of k
Low relaxation strand	0.90	0.28
Stress-relieved strand and Type 1 high-strength bar	0.85	0.38
Type 2 high-strength bar	0.80	0.48

$$c = \frac{A_{ps} f_{pu} + A_s f_s - A'_s f'_s - 0.85 f'_c (b - b_w) h_f}{0.85 f'_c \beta_1 b_w + K A_{ps} \frac{f_{pu}}{d_p}}$$

Flexural resistance of prestressed concrete T beam is

$$M_r = \emptyset\left[A_s f_s (d_s - k_2 c) + A'_s f'_s (k_2 c - d'_s)\right] + \emptyset_{frp} T_{frp} (\square - k_2 c)$$

Where, $T_{frp} = b_{frp} N_b$

$$K_2 = 1 - \frac{2\left[\left(\frac{\varepsilon_c}{\varepsilon_o}\right) - \arctan\left(\frac{\varepsilon_c}{\varepsilon_o}\right)\right]}{\beta_2 \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2}$$

$$\beta_2 = \frac{Ln\left[1 + \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right]}{\left(\frac{\varepsilon_c}{\varepsilon_o}\right)}$$

Calculation of Moment								
Apsfps	960146.479							
dp-(a/2)	543.246361							
b-bw	733.2		β2	0.29399				
(a/2)-(hf/2)	-23.246361		arctan(εc/εo)	0.2985				
0.85*f'c*(b-bw)hf((a/2)-(hf/2))	-40785483		εc	0.0004				
φfrp	0.85		εo	0.00131				
Tfrp=bfrp*Nb	260079.6		bfrp	610*1.02	mm^2	Nb		418 N/mm^2
h-k2c	612.836976		k2	0.33939				
ϕfrpTfrp(h-k2c)	135478436		φ	0.95				
Mn	616289034							
ϕMn	585.474582	Mpa	**safe**					
	1 layer x 610 mm wide frp used							

EXCEL SHEET 2: AASHTO BONDED BEAM

3.2 Flexural design of CFRP wrapped prestressed T section for Unbonded prestressing steel:

ACI proposed revision, Subsection 10.3.2- In sections having unbonded prestressed reinforcement, the unbonded steel slips relative to the surrounding concrete resulting in the calculation of steel strain or stress becoming a function of overall member deformation rather than just section curvature. The effect of concrete precompression strain on the tendon stress at nominal flexural capacity is assumed to be minor and may be neglected in unbonded members.

The strain level in the unbonded prestressed steel at the corresponding critical section can be found from Eq. (10-27 28) (Harajli 2012, El Meski and Harajli 2014):

$$\varepsilon_{ps} = \varepsilon_{pe} + N_p\, \varepsilon_c \left(\frac{d_p - C}{L_a}\right)$$

$$\phi = \begin{cases} 0.90 \text{ for } \varepsilon_{ct} \geq 0.005 \\ 0.65 + \frac{0.25(\varepsilon_{ct} - 0.002)}{0.005 - 0.002} \text{ for } 0.002 < \varepsilon_{ct} < 0.005 \\ 0.65 \text{ for } \varepsilon_{ct} \leq 0.002 \end{cases}$$

$$\varepsilon_{ct} = \varepsilon_c \left(\frac{d_p - c}{c}\right)$$

Estimate the moment capacity by considering the contribution of prestressing steel , frp flexural strength				
(β1*c)/2	dp-β1c/2	df-(β1c/2)		
17.40514756	553.5949	618.61485		
Mn	7.22E+08	Nm	ϕ=	0.9
φMn	650.244	KNm	safe	
one layer of frp with dimension 1.02 mm×610mm is used .				

EXCEL SHEET 3: ACI UNBONDED BEAM

AASHTO specification 5.7.3.2 (6th Edition)- For unbonded rectangular T section subjected to flexural stresses, for which f_{pe} is not less than $0.5f_{pu}$, the average stress in prestressing steel, f_{ps}, may be taken as

$$f_{ps} = f_{pe} + 900\left(\frac{d_p - c}{l_e}\right) \leq f_{py}$$

Where $l_e = \frac{2l_1}{2 + N_s}$

$$c = \frac{A_{ps} f_{ps} + A_s f_s - A'_s f'_s - 0.85 f'_c (b - b_w) h_f}{0.85 f'_c \beta_1 b_w}$$

c	-82.92269112 mm					
fps	TRUE	1237.382 N/mm^2				
φfrp	0.85	φ	0.95			
Tfrp	520159.2	β2	0.293986			
h-k2c	612.836976	εc	0.000402			
φfrpTfrp(h-k2c)	270956872.5	ε0	0.001308			
Mn	635329818.2	k2	0.339389			
φMn	603.5633273 Mpa	bfrp	622.2 mm^2	Nb	418 N/mm^2	
	safe					
	3 layers of frp are usedx 610 mm wide strip at bottom					

EXCEL SHEET 4: AASHTO UNBONDED BEAM

3.3 Shear check of CFRP wrapped prestressed T section for bonded and Unbondede prestressing steel

ACI 440.2r section 11.3- The design shear strength should be calculated by multiplying nominal shear strength by strength reduction factor φ, as specified by ACI 318.05-

$$\varphi V_n \geq V_u$$

and

$$\varphi V_n = \varphi\left(V_c + V_s + \Psi_f V_f\right)$$

where

$$V_f = \frac{A_f f_{fe}(sin\alpha + cos\alpha) d_{fv}}{s_f}$$

AASHTO FRP strengthening section 4.3.1- The factored shear strength is defined by

$$V_r = \emptyset\left(\left(V_c + V_s + V_p\right) + \emptyset_{frp}\, V_{frp}\right)$$

where

$$V_{frp} = \frac{A_{frp} f_{fe} d_f\left(\sin\alpha_f + \cos\alpha_f\right)}{s_f}$$

4. MODEL SIMULATION

ANSYS Parametric Design Language (APDL) 15 was used to model four different T beams frp wrapped for bonded and unbonded post tensioned beams. Both the bonded and unbonded groups with one and two layers of CFRP were modeled. Ansys is used to validate the results obtained from design calculations using ACI and AASHTO. Ansys analyses the beam using non linear finite element analysis. The Elements used for analysis of beams were Solid 65, link180 and shell 41. Solid 65 is used for the three- dimensional modeling of concrete. The element is defined by 8 nodes. Link180 elements are used for prestressed reinforcement and Shell 41 for both the CFRP wrapping and epoxy.

TABLE 5
MATERIAL AND ELEMENT TYPE

Material type	Elements	No. of nodes
concrete	Solid 65	8
Prestressed steel	Link 180	2
CFRP	Shell 41	8

An optimum mesh size of $50\times 50 \times 100$ mm was used herein. The FRP layer is assumed to be perfectly bonded to the concrete surface, and the epoxy layer between the FRP and the concrete was ignored. The element solid 65 is used for simulating concrete cracking in tension and crushing in compression. It has eight nodes and three degrees of freedom at each node such as translations in the nodal x, y, and z directions. The element is also capable of simulating plastic deformation and creep. Link 180 element is used for uniaxial tension-compression. It is a two node element with three degrees of freedom at each node such as translations in the nodal$x$, y, and z directions. It is capable of rotation, large deflections, and large strain. Shell 41 element has four nodes and three degrees of freedom at each node such as translations in the nodal x, y, and z directions. It is a 3D element having membrane stiffness but no bending stiffness and has variable thickness, stress stiffening, and large deflection options.

Four sets of FEM real constants are used. Set 1 has solid 65 element with properties as smeared reinforcement material numbers, volume ratio, and orientation angle as zero. Set 2 was Link 180 element to represent longitudinal prestressing steel. Set 3 is used for Shell 41 elements to model epoxy adhesive. Set 4 is used for the FRP modeling with Shell 41 elements. Other parameters, such as element x-axis rotation, elastic foundation stiffness, and added mass, were also kept zero as it was not applicable to this model.

5. RESULTS AND DISCUSSION

Following are the results obtained by design calculatons using ACI and AASHTO guidelines ,ploted under graphical format as shown below:

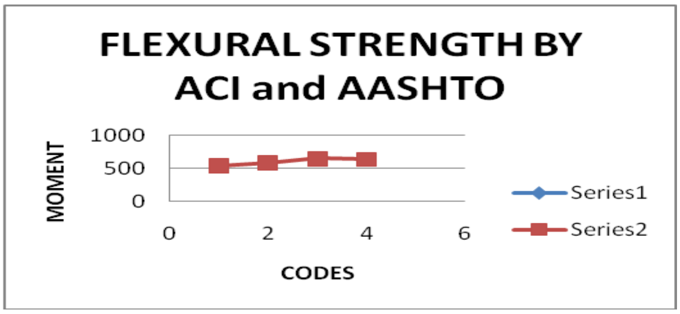


Fig 3: The above graph is the plot for codes Vs moment of resistance which is the comparison of ACI 440.2r and AASHTO on the parameter of flexural strength for the four specimens.

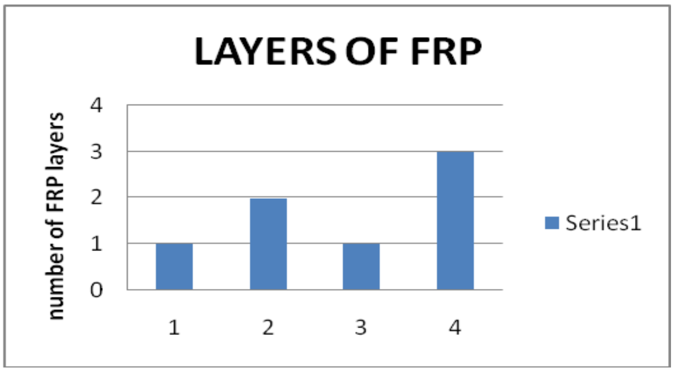


Fig 4: The above plot is the number of layers obtained for the four specimes Vs codes used for the design calculation

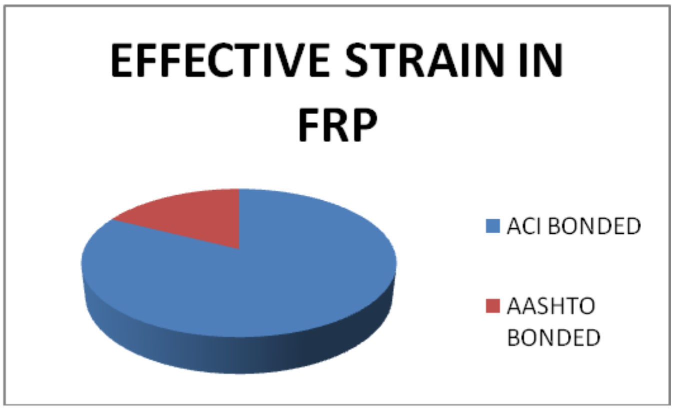
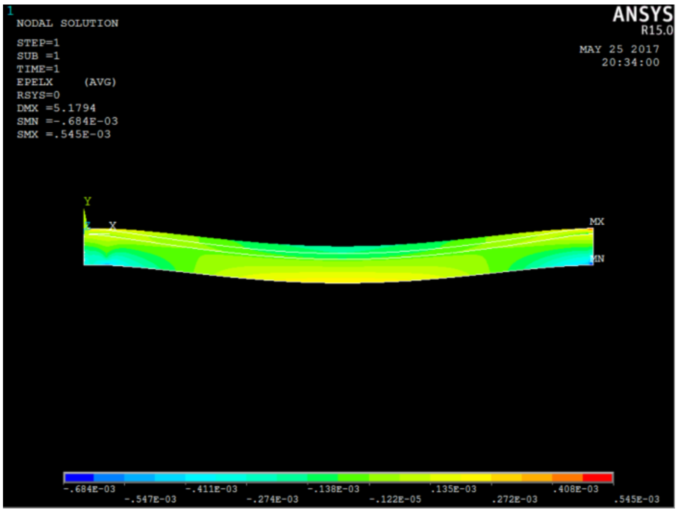


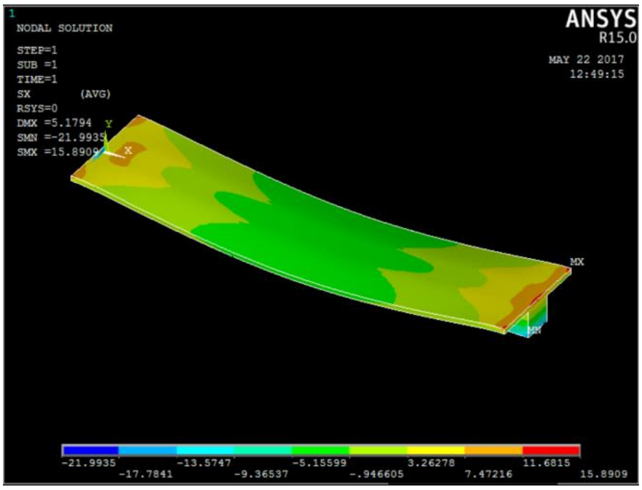
Fig 5: the pie chart diagram shows the effective strain in FRP Vs codes.

PARAMETERS	Moment of resistance	Depth of Neutral axis	Number of CFRP layer	The effective strain in FRP
ACI BONDED	538 KNm	47 mm.	One	0.0113 mm/mm.
AASHTO BONDED	585.4 KNm	65 mm.	Two	0.0024 mm/mm.
ACI UNBONDED	650.244 KNm	49.78 mm.	One	
AASHTO UNBONDED	641.45 KNm	82.9 mm	Three	

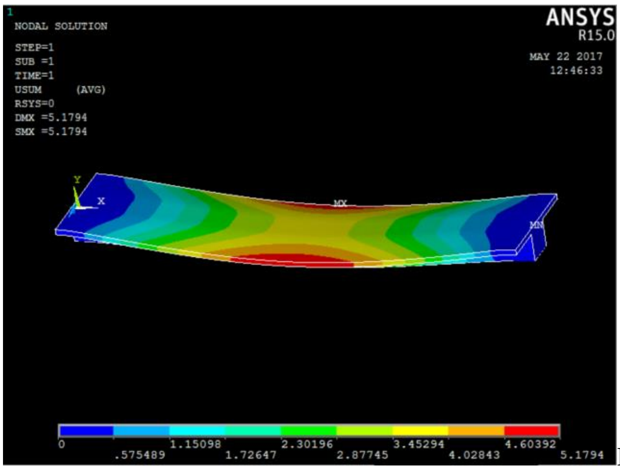
Following are the results obtained by finite element analysis based on certain parameters as follows:



ELASTIC STRAIN IN X DIRECTION BY ACI BONDED



BENDING STRESS ACI BONDED



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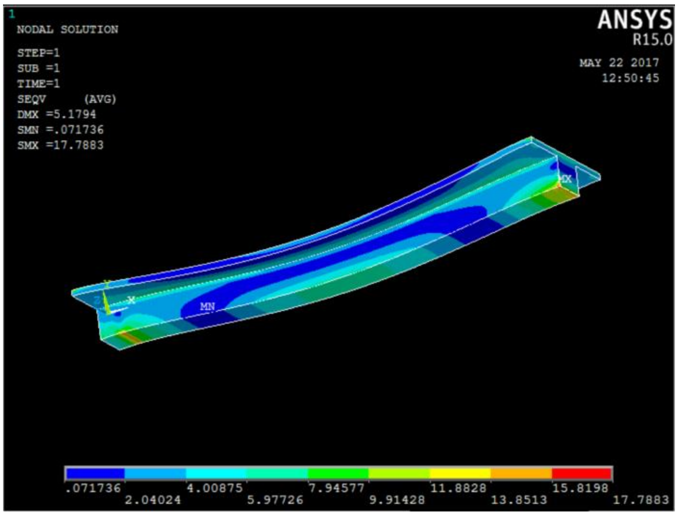
DISPLACEMENT PLOT OF ACI BONDED



TOTAL STRESS ACI BONDED

1. On validation with Ansys 15, the displacement of the t beam is before wrapping was 16.65mm and 5.17 mm after CFRP wrapping.
2. Bending stress at the mid span after CFRP wrapping is 6.402 N/mm^2 and by ANSYS 15 it is 5.156 N/mm^2.

6.CONCLUSIONS

1. Flexural strength of the specimen 1 and 2 are compared, moment of resistance offered by the beam to the new anticipated loads is more by AASHTO design guidelines.
2. The number of frp layers required to resist the increased loads of the structure and encore sufficient strength considering all failure criteria's, was designed for both of specimen 1 and 2. AASHTO gives more no. Of layers for frp wrapping, hence ACI is more conservative method of design.
3. Since for the calculation of depth of neutral axis, the method is an iterative analysis and check for equilibrium. ACI 440.2r is more tedious then AASHTO.
4. Flexural strength of unbonded specimen 3 and 4 was obtained to resist new anticipated loads; design calculations resulted in higher strength for ACI 440.2r.
5. In case of unbonded beams, Three no. of FRP layers are obtained by AASHTO whereas ACI gives only one. Thus, ACI is more economical method of design.
6. The shear strengthening of the beams at the supports can be done in many ways, here the frp wrapped in flexure is extended to the supports and check for shear is done. All the four beams are safe in flexure and shear capacity.
7. The value of effective strain in the frp after application of anticipated new loads considering all the failure criteria's such as frp rupture , debonding and delamination, AASHTO provides lower strain in FRP comparatively.
8. The displacement in the beam without CFRP was 12mm, whereas on wrapping of CFRP displacement is reduced to 6 mm.
9. Total calculated stress and stress obtained by finite element analysis is under limits and section is safe in flexure and shear.
10. Ansys gives higher values of accuracy then manual calculations and can be used for the analysis of bonded and unbonded post tensioned beams with FRP wrapping.

NOTATIONS

Ac= cross sectional area of concrete in compression member,

Af= cross sectional area of effectively confined concrete section,

CE= environmental reduction factor

ε_{bi} = Initial strain in the beam soffit, mm/mm.

M_{np}= moment of resistance for pretsressing steel.

Ap= area of pretsressing steel,

Fc= compressive strength of concrete, Mpa

Vc = the nominal shear strength provided by the concrete in accordance with AASHTO LRFD

V_s = the nominal shear strength provided by the transverse steel reinforcement.

V_p = componenet of the effective prestressing force in the direction of applied shear as specified in AASHTO Article 5.8.3.3

V_{frp} = the nominal shear strength provided by the externally bonded FRP system in accordance with Article with Article 4.

ε_{pe}= strain in prestressing steel, mm/mm.

φ =Resistance factor defined in AASHTO LRFD Article 5.5.4.2;

ε_c= strain in concrete (mm/mm)

Ns = number of support hinges crossed by the tendon between anchorages or discretely bonded points

REFERENCES

[1] ACI 440.2r ‘Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures’ 2008.

[2] ACI 318, Building code requirement of structural concrete,1995.

[3] American Association of State Highway and Transportation Officials (AASHTO LRFD) 6th Edition, 2012.

[4] AASHTO “Guide specifications for Design of bonded frp system for repair and strengthening of concrete bridge elements” , first edition 2012.

[5] Muruganandam Mohanamurthy and Nur Yazdani, ‘Flexural Strength Prediction in FRP Strengthened Concrete Bridge Girders’2015.

[6] NurYazdani, Farzia Haque, and Istiaque Hasan, ‘Flexural and Shear Behavior of FRP Strengthened AASHTO Type Concrete Bridge Girders’, july 2016.

[7] El Meski, F. and Harajli, M.“Flexural Capacity of Fiber-Reinforced Polymer Strengthened Unbonded Post-22 tensioned Members.” 2015

[8] Harajli, M. “Tendon Stress at Ultimate in Continuous Unbonded Post-tensioned Members: Proposed Modification to ACI Eq. (18-4) and (18-5).” 2012.