

Finite Element Analysis of Fiber Reinforced Polymer (FRP) Bridge Deck Structures

Mr.Suryawanshi S.R.¹, Prof.Dr.K.B.Ladhane², Prof.V.R.Rathi³

1ME (Structural Engineering) Student, Dept.of Civil Engineering, PREC, Loni, India

2 Professor, Dept. of Civil Engineering, PREC, Loni, India

3 Associate professor, Dept. of Civil Engineering, PREC, Loni, India

ABSTRACT: Many RCC bridge decks are showing the sign of distress due to corrosion of the reinforcements much before its design life span. Use of fiber reinforced polymer (FRP) bridge deck structures is increasingly rapidly all over the world due to its many advantages over the conventional materials. The FRP bridge deck is lighter, durable, easy to work with, maintenance free and expected to have low life cycle cost. For a relatively practical configuration as in FRP rectangular and skew bridge deck the extensive use of the finite element software package ABAQUS have been observed to be justified as such the problems of FRP bridge deck subjected to uniform pressure is analyzed by developing a finite element model of FRP bridge deck by using ABAQUS first and results obtained are compared with the work done by previous researchers. In all the cases the results obtained by the present FE model compared very well. As such the finite element model based on ABAQUS is used to generate many new results for FRP bridge deck subjected to under Indian loading conditions (IRC).

KEY WORDS: fiber reinforced polymer, Finite element analysis, FRP bridge deck.

I. INTRODUCTION

Use of advanced fiber reinforced polymer/plastic (FRP) composites in strengthening reinforced concrete structures and other structures is already well known and used for maintain and upgrading essential infrastructures in all parts of the world. Other than maintenance and up gradation, many research and studies have been carried out for utilization of these FRP materials in mainstream construction such as bridge deck. The deterioration and functional deficiency of existing bridge infrastructure made from conventional materials represent one of the most significant utilization challenges currently facing civil engineering community .In India, many bridge decks are in deteriorating conditions and needs attention for its strengthening or replacement. In addition, rapid growth in the volume and weight of heavy goods vehicles has led to serious problems and many older bridges no longer meet current design standards. The small dead load of approximately 20% of a concrete deck enables short installation times of the prefabricated panels with minimum traffic interface as well as a possible increase in the allowable live loads existing bridges via replacement of the heavy concrete decks. There is, therefore, a need for methods for replacing bridge decks to deal with structural deterioration and to increase load capacity without extensive and expansion bridge deck.

The issue of deteriorating of civil infrastructure is increasingly becoming a critical concern across the world. A 2001 report on America's infrastructure provided by the American Society of Civil Engineers shows that as of 1998, 29% of the nation's bridges were structurally deficient or functionally obsolete. To eliminate all bridge deficiencies of all the deficient elements in a bridge superstructure, the bridge deck perhaps requires the most maintenance.FRP bridge decks are believed to possess improved corrosion resistance. Their reduced weight enables rapid installation. In addition, the FRP material can be customized to dimensions of traditional decks and allows the economic reuse of existing support structures. To develop effective FRP deck systems, research pertaining to design and analysis of FRP decks should be fully considered. Analyzing an FRP bridge deck system requires full knowledge of the geometric properties and the material properties. The geometric properties are obtained in the design stage of the deck system. The material and mechanical properties of FRP decks are usually obtained though experimental characterization of the mechanical properties at the coupon, component, and full deck scale levels.

The benefits of using FRP bridge deck systems are summarized as follows:

Non-corrosive properties of FRP material can extend the service life of FRP bridge deck.

High quality results from well controlled factory environment.

Construction of FRP bridge decks is easier and faster than conventional bridge deck construction, which leads to less traffic control time, and less negative environmental impact.

Lightweight FRP bridge decks make it possible to increase the live load carrying capacity of a bridge without retrofitting its substructure.

Compared with conventional materials, FRP material has high strength but relatively low stiffness. Since the design of FRP bridge deck systems is based on stiffness requirements, this innovative bridge deck has a very high safety factor.

For the bridges in seismically active zones, lightweight FRP bridge deck is the optimal option because of its lower inertia force (Aref and Parsons, 2000).

II. DESCRIPTION OF FRP BRIDGE DECK

The structural behavior of a fiber reinforced polymer (FRP) web core skew bridge superstructure is studied in this two-part paper. The two-lane bridge is a simply supported superstructure with a 7.807m span, 10.071m wide and a 30 degree skew angle (Aref et al.2001). A Ritz-based static analysis procedure is described for fiber-reinforced plastic, skew bridge superstructure, or deck, with a parallel grid core. This is a simplified analysis method based on a transformed plate formulation and the classical Ritz method. The rib core bridge superstructure, or deck, is idealized as a homogeneous, orthotropic skew plate to which the Ritz method is applied to discretize the resultant, equivalent orthotropic skew plate (Aref et al.2005). Shell elements are used to model structures in which one dimension, the thickness, is significantly smaller than the other dimensions. Conventional shell elements use this condition to discretize a body by defining the geometry at a reference surface. In this case the thickness is defined through the section property definition. Conventional shell elements have displacement and rotational degrees of freedom. In contrast, continuum shell elements discretize an entire three-dimensional body.

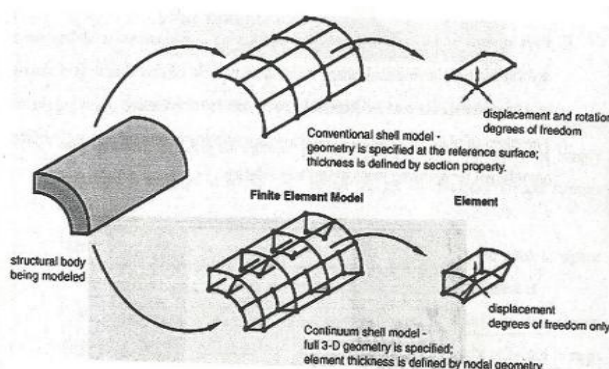


Fig 1 Conventional and continuum shell model

The thickness is determined from the element nodal geometry. Continuum shell elements have only displacement degrees of freedom. From a modeling point of view continuum shell elements look like three-dimensional continuum solids, but their kinematic and constitutive behavior is similar to conventional shell elements. According to the survey of Robinson (1985), the shell elements in ABAQUS are accurate and less sensitive to skew angle. In this work we used the S4R element (4-node doubly curved shell element, each node has six degrees of freedom) to model the top and bottom surface, while selected S4R5 element (4-node doubly curved thin shell element, each node have 5 degree of freedom) to model the web core. Both types of elements (S4R and S4R5) are reduced integration to avoid shear locking. ABAQUS shell elements assume that plane sections perpendicular to the plane of shell remain plane on the application of load.

Some simplifying assumptions are consistently made while producing finite element models. A general attitude towards these is to make as few as possible and to make them in a manner that they do not affect the correctness of the analysis

1.Top skin, web core and bottom skin does not slip from the joints on the application of load i.e. hard contact is used
2.camber is omitted

III. MODELING OF FRP BRIDGE DECK

Modeling is done in following manner:- 1) Rectangular laminated plate and skew plate of (1x1)m analyzed with aspect Ratio=1

2) Rectangular laminated plate and skew plate of (1x2)m analyzed with aspect Ratio=2

3) FRP Bridge Deck of (7.807x10.071)m and FRP Bridge deck of (1x4)m analyzed applying uniform pressure of 1000pa and IRC Class AA Loading .using ABAQUS V 6.10

ABAQUS is used to describe the static load behavior of laminated rectangular plates with different orientation and aspect ratio. The results obtained are compared with some published results and found satisfactory.

Table 1
Material properties

E_l	E_t	G_{lt}	μ_{lt}	Density
23.0 GPa	18.0 GPa	9.0 GPa	0.25	1826 Kg/m ³

Table 2
Geometric Properties

W In m	L In m	D In m
10.076	7.786	0.623

In this section, a rectangular and skew FRP bridge deck is taken into consideration for analysis. Before finding the stresses; deflection of decks are compared with already published results for validation. The uniform pressure of 1000 Pa is applied on the top of deck in downward direction.

IRC Class AA Loading: Ground contact length of the track is 3.6 m and nose to tail length is 7.2 m. The nose to tail between two successive vehicles shall not be more than 90 m. The Class AA loading is to be adopted for bridges located within certain specified municipal localities and specified highways. As the span of bridge is more than 5.3 m, minimum clearance is taken as 1.2 m from free loading edge and same has been incorporated in the ABAQUS model. For maximum deflection, loading condition has been kept at the centre of bridge.

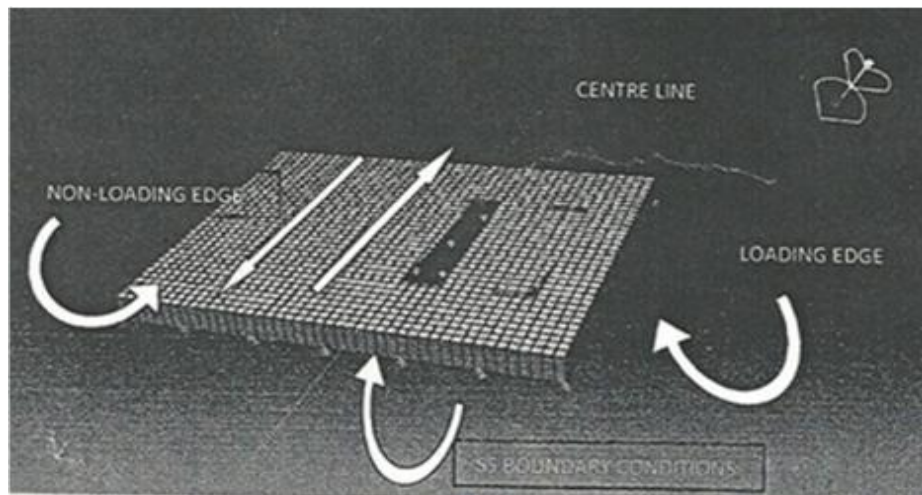


Fig.2 FRP bridge deck with class AA tracked loading at centre with simply supported boundary condition

For the purpose of applying 350KN on the track portion in ABAQUS, this loading has been converted into pressure by multiplying with track area, so the uniform pressure of 0.1143N/mm² has been applied on each track portion to simulate the IRC Class AA tracked loading.

IV. COMPARISON OF RESULTS AND DISCUSSIONS

Comparison of deflection between published results and present results have been illustrated for validation purpose. Similarly new results for stresses are obtained for laminated composite plates and bridge decks.

Rectangular laminated plate and skew plate of (1x1)m with aspect Ratio=1

Table 3
Comparison of results

Sr.No.	Skew angle	Location	FE Result in mm (Aref et.al.2001)	FE Result in mm (present study)
1	90	W_{max}	2.40	2.90
		W_c	2.22	2.02
2	60	W_{max}	1.95	2.12
		W_c	1.60	1.89

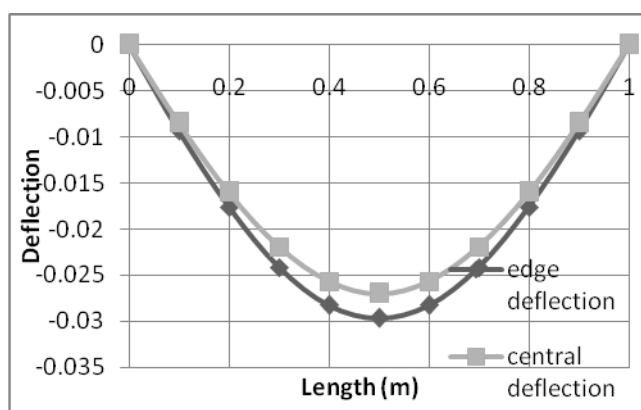


Fig.3 Deflection of Rectangular plate at edge and centre

Table4
Stresses For Cross Ply (0/90/90/0), Plate with aspect ratio one

Skew Angle	Values	$S_{11}(N/mm^2)$	$S_{22}(N/mm^2)$	$S_{12}(N/mm^2)$
90	Max.	7.65	0.47	0.23
	Min	0.34	0.013	-0.23
60	Max.	6.61	0.73	0.03
	Min	-1.15	-0.053	-1.24

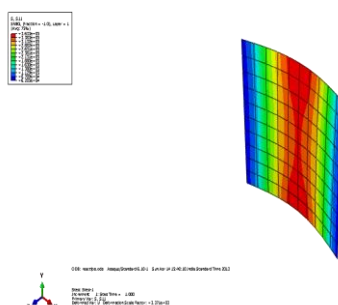


Fig. 4 S_{11} stresses for rectangular

From Table 4 and pictures shown in Figure 4,5,6,7 &8, it is clear that S_{11} normal stress in x-x direction is decreasing with the increase in skew angle. But on the outer side S_{22} normal stress in y-y direction shows increased Values on the increased of skew angle. Minimum value for S_{22} has shown deteriorating effect at the corners which obtuse angle is i.e. decreasing on the increase of skew angle similarly S_{12} shear stress in x-y direction decreasing trends on the increase of skew angle. The obtuse angle edge has shown deterioration of S_{12} at 60 degree

Rectangular laminated plate and skew plate of (1x2) m with aspect Ratio=2

Now considering composite laminated plate with aspect ratio two and keeping all other parameters as case I, deflections are compared with already published results .table 5, show such comparison of deflection and found satisfactory.

**Table 5
Comparison of Results**

Sr.No.	Skew angle	Location	FE Result in mm (Aref et.al.2001)	FE Result in mm (present study)
1	90	W_{max}	37.45	37.45
		W_c	36.20	36.19
2	60	W_{max}	30.52	30.99
		W_c	28.27	28

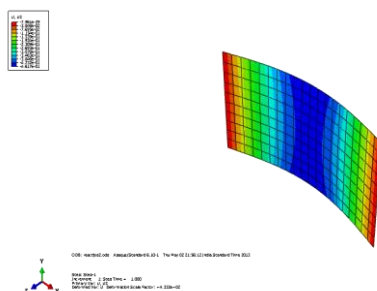


Fig. 5 Deformed shape showing maximum and central deflection for Case II (Rectangular plate)

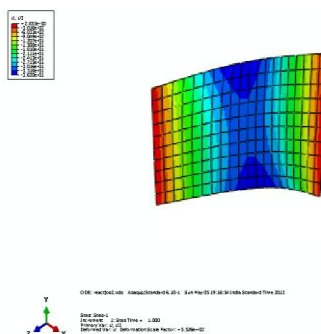


Fig.6 Deformed shape showing maximum and central deflection for Case II (Rectangular Skew plate)

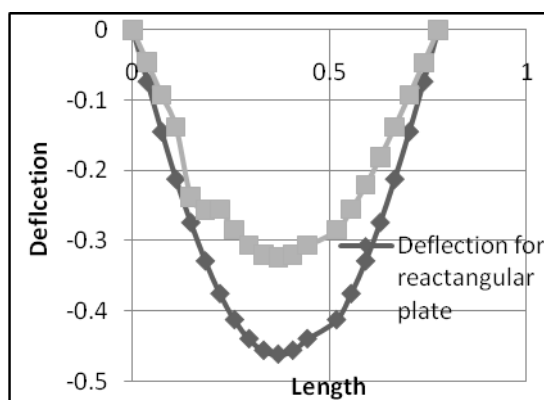


Fig.7 deflection of rectangular plate and skew plate

From graph shown in fig 3, it can be implied that deflection is more at edge compared to central portion (same trend as Rectangular plate of 1X1 m). This is probably because of its unsupported free position at the edge whereas central area is confined by the adjoining portion; hence less deflection can be seen

Table 6
Stresses for (0/ 90/ 90/ 0), plate with aspect ratio two

Skew angle	Values	S_{11} (N/mm ²)	S_{22} (N/mm ²)	S_{12} (N/mm ²)
90	Max.	29.91	1.454	0.75
	Min.	0.70	0.022	-0.76
60	Max.	25.38	2.11	0.070
	Min.	-5.836	-0.097	4.76

The nature of stresses develop by changing the skew angle is shown in Table 6, the trends shown by the normal and shear stresses is same as that of case-I. So it can be concluded that by increasing the skew deflection of plate, S_{11} and S_{12} decreases whereas S_{22} increases. One more intersecting fact can be predicted that shear stress S_{12} concentration is maximum at the centre at the acute angle section of the plate.

FRP Bridge Deck of (7.807x10.071) m

In this section, a rectangular and skew FRP bridge deck is taken into consideration for analysis. Before finding the stresses; deflection of decks are compared with already published results for validation. The uniform pressure of 1000 Pa is applied on the top of deck in downward direction. The deflection results are tabulated in Table 7

Table7

Comparison of deflection for bridge deck

Sr.No.	Skew angle	Location	FE Result in mm (Aref et.al.2001)	FE Result in mm (present study)
1	90	W_{max}	9.44	9.68
		W_c	8.50	8.47

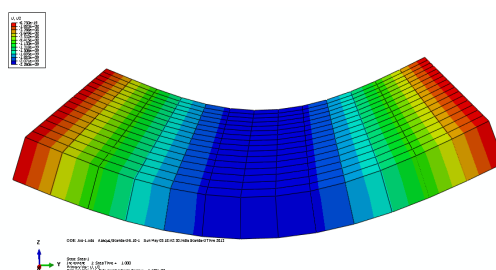


Fig.8 visualization of deflected shape and deflection values at different location with max and mini value

Normal stress, S_{11} in x-x direction decreases on the increase of skew angle. Whereas, S_{22} in the y-y direction increases on the increase of skew angle. Shear stress, S_{12} , does not show considerable change on change of skew angle. The top skin of central portion is under compression while bottom skin of central portion is under tension.

Table8
Stresses for rectangular bridge deck

Skew angle	Values	S_{11} (N/mm ²)	S_{22} (N/mm ²)	S_{12} (N/mm ²)
90	Max	9.16	4.42	5.84
	Min	-1.22	-8.79	-3.80

D) FRP Bridge Deck of (1x4)m

In this section, a rectangular and skew FRP bridge deck is taken into consideration for analysis. Before finding the stresses; deflection of decks are compared with already published results for validation. The uniform pressure of 1000 Pa is applied on the top of deck in downward direction. The deflection results are tabulated in Table 9

Table 9
Comparison of deflection for bridge deck

Sr.No.	Skew angle	Location	Check for deflection Span /800	FE Result in mm (present study)
1	90	W_c	5.00	4.96

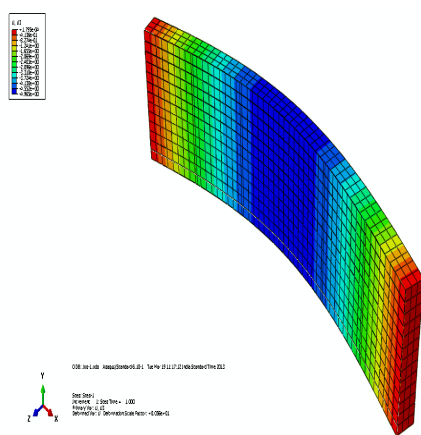


Fig.9 Deflections for rectangular bridge deck

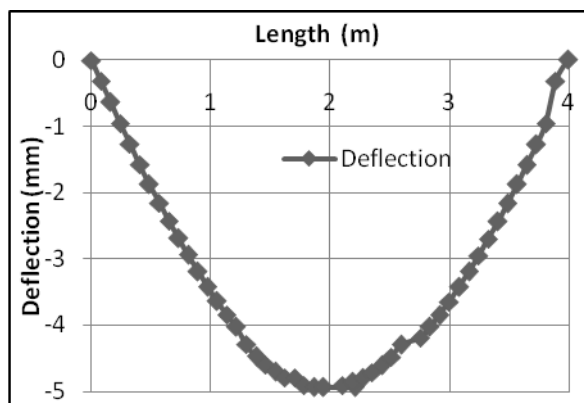


Fig.10 deflection of rectangular plate

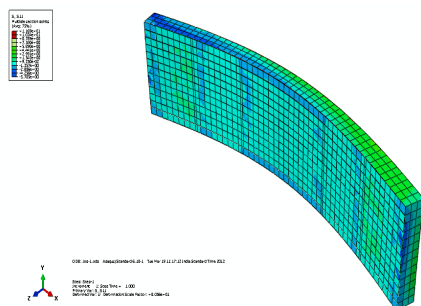


Fig.11 In plane normal stresses S11for rectangular bridge deck

From the summary presented in Table 10, it is observed that by the increase of web core thickness deflection has reduced dramatically. The possible reason for decreasing the deflection is, as top and bottom skin goes away from neutral axis, it allows the increase of sectional modulus (I/y) of the deck resulting reduction in deformation. Where I = Moment of Inertia and y = Distance of neutral axis from extreme fiber

As elastic modulus of FRP section is low as compared to steel, the scope of increasing the stiffness of structure lies in moment of inertia only. And this can be achieved by increasing the depth of the core material. As maximum deflection is inversely proportional to the modulus of elasticity and moment of inertia i.e. flexural rigidity (EI), increase in depth decreases the maximum deflection keeping the FRP properties unchanged.

Table 10
Summary of results for parametric study

Thk. mm	Deflection		S ₁₁		S ₂₂		S ₁₂	
	W _{Max}	W _c	Max	Min	Max	Min	Max	Min
623	18.3	7.4	17.1	-28.4	18.1	-22.7	16.3	-7.4
800	11.8	3.6	14.0	-27.6	16.1	-18.7	16.6	-6.5
900	9.5	2.8	12.2	-24.5	14.2	-17.3	15.6	-6.6

From Table 10, it is also observed that normal stresses (S_{11} and S_{22}) decreases on the increase of depth of web core whereas shear stress (S_{12}) shows not much difference as in- plane stresses does not depend on depth of deck.

IV. CONCLUSION

- [1] A finite element model based on ABAQUS gives extensive information regarding the behavior of different types of bridge decks including the sandwich web core system, used in the present study.
- [2] It is observed that, in case of symmetric cross ply laminated plate having simply supported boundary conditions subjected to uniform pressure, two in-plane normal stresses (S_{11} and S_{22}) and in-plane shear stress (S_{12}) increases with the increase of aspect ratio. Same trend has been observed in case of deflection. In all cases, deflection is found maximum at centre of the free edge as compared to centre of the plate.
- [3] In the case of symmetric cross ply, for the same loading deflection increases with the increase of aspect ratio
- [4] When the skew of plate is increased (from 90^0 to 60^0), deflection is found to be decreased. S_{11} and S_{12} decrease with the increase of skew angle whereas S_{22} increases. The S_{11} at obtuse angle edge for skew plate is found to be decreasing. This is may be due to the fact that most of the in- plane shear stress gets distributed near the acute angle edges.
- [5] In case of FRP bridge deck subjected to uniform pressure, deflection is found to be maximum at centre of free edge as compared to centre of bridge deck. It shows that stiffness is less at free edge allowing it to deflect more compared to the confined central portion of deck.
- [6] In case of FRP bridge deck subjected to uniform pressure ,normal stress S_{11} and shear stress S_{12} decreases with the increase of skew angle (from 90 to 60) whereas S_{22} increases. The top skin of the deck is always in compression and bottom skin is in tension on the load at the top surface.
- [7] Parametric study on FRP bridge deck having simply supported boundary conditions at the supporting edges subjected to IRC Class AA loading reveals that deflection(w) decreases on the increase of thickness of deck normal stresses decreases on the increase of thickness
- [8] The FRP Skew bridge deck has been found to be an efficient configuration since by changing the thickness of web core only the optimum design can be achieved with little efforts in ABAQUS which saves time and heavy calculations. This is also been revealed in the parametric study presented in this work

Lastly the use of FRP bridge deck structures may be recommended to replace/rehabilitate the distressed bridge decks and to upgrade the live load rating of bridges in India.

➤ **FUTURE SCOPE OF STUDY**

- The present work can be extended to study the dynamic as well as buckling behavior of the proposed bridge structure.
- The effect of slip between the interface of top skin, web core and bottom skin may also be included in the proposed FE model.
- Experimental studies may be carried out to validate the results obtained in this study.

REFERENCES

- [1] Aref, A. J., and Chiewanichakorn, M. (2002), "The analytical study of fiber reinforced polymer deck on an old truss bridge." *Rep., Transportation Research and Development Bureau, and Transportation Infrastructure Research Consortium, New York State.*
- [2] Aref, A. J., Chiewanichakorn, M., and Alnahhal, W. I. 2004. "Temporal thermal behavior and damage simulations of FRP deck." *Rep., Transportation Research and Development Bureau, and Transportation Infrastructure Research Consortium, New York State.*
- [3] Aref, Alampalli, and Yihong (2001), "Ritz-based static analysis method for fiber reinforced Plastic rib core skew bridge superstructure." *Journal Of Engineering Mechanics.*450-459
- [4] Aref, Alampalli, and Yihong. (2004), "Performance of a fiber reinforced polymer web core skew bridge superstructure. Part I: field testing and finite element simulations." *Composite Structures 69 (2005).*, 491–499
- [5] Aref, and Alampalli, (2001), "Finite-element analysis of a fiber reinforced polymer bridge superstructure." *Rep., Transportation Research and Development Bureau, and Transportation Infrastructure Research Consortium, New York State*
- [6] Dr. Nahla K. Hassan and Dr. Emile Shehata. (2004), "Development of FRP Bridge Decks an Analytical Investigation."
- [7] Ishan srivastava, Dey, Chakrabarti, and Bhargava (2003), "Structural optimization of FRP web core decks." *(ASCE)CC.1943-5614.*
- [8] Methee Chiewanichakorn,(2000), "An Analytical Study of an FRP Deck on A Truss Bridge." *Transp.Reserch and development Bureau,NY 12232.*
- [9] P. Alagusundaramoorthy, I. E. Harik, and C. C. Choo(2005),"Structural Behavior of FRP Composite Bridge Deck Panels" *ASCE1084-702(2006)11,384-393*
- [10] P.K. Gupta, K. Singh and A. Mishra,(2010),"Parametric study on behavior of Box-Girder Bridges using Finite Element Method." *Asian Journal of civil engineering*, vol. 11(1), 135-148
- [11] Piyush K. Dutta, Soon-Chul Kwon and Roberto Lopez-Anido (2003) "Fatigue performance evaluation of FRP composite bridge deck prototypes under high and low temperatures." *US Army Cold Regions Research & Engineering Laboratory. ERDC, Hanover, NH 03755*
- [12] Prakash Kumar and K. Chandrashekhara,(March 2001), "Structural Performance of FRP Bridge Deck."
- [13] Prasun K. Majumdar, Zihong Liu, John J.Lesko, and Tommy Cousins.(2007) "Analysis of Cellular FRP Composite Bridge Deck Utilizing Conformable Tire Patch Loading." *Composites and polycon 2007.*,523-532
- [14] Robinson and Pizhong. (2006), "Modeling and Characterization of Honeycomb FRP Sandwich Beams in Torsion." *Composites: Part B,Engineering J.*,27(3),295-305
- [15] Vistasp M.Karbhari, Joannie, and Reynaud (2005), "Critical gaps I durability data for FRP composites in civil Infrastructure." *Proceedings Of The 45th International Sample Symposium and Exhibition, science of advanced materials and process.*
- [16] Wael I. Alnahhal, Methee Chiewanichakorn, J. Aref and Sreenivas Alampalli (2006), "Temporal Thermal Behavior and Damage Simulations of FRP Deck." *ASCE 1084-702(2006)11,452-464*
- [17] Zureick, Abdul-Hamid., Shih, Ban-Jwu., and Munley, E. (1997), "Fiber-Reinforced Polymeric Bridge Decks." *Structural Engineering Review*, 7(3), 257-266.