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FINITE ELEMENT ANALYSIS OF GFRP COMPOSITE BRIDE DECK PANELS

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Abstract

Light weight and corrosion resistant FRP bridge decks are used as an alternative to conventional reinforced concrete (RC) bridge deck panels in the construction of new bridges and retrofitting of an existing bridges. The main objective of the present investigation is to study analytically the static behaviour of GFRP composite bridge deck panels upto failure under wheel load of Indian Road Congress Class A wheeled vehicle. SOLID45 and SHELL93 elements were used to model GFRP composite bridge deck panel and analyzed using the FEA software ANSYS. The effect of position of patch load on the static behaviour of bridge deck panels was also studied. The analytical results of maximum deflections and strains at factored load were compared with the specifications by the Ohio Department of Transportation, U.S.A. The maximum deflections and strains at failure load obtained from analytical study were compared with the experimental data. Based on this study it was concluded that the maximum deflections and strains at factored load obtained from analytical study satisfied the performance criteria specified by ODoT, U.S.A. The analytical results of maximum deflections and strains at failure load were 2% and 5% lower than the experimental data.

Keywords: Static Behaviour; GFRP Composite Bridge Deck Panels; Wheel load; Failure Load; Finite Element Analysis; Maximum Deflections and Strains

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INTRODUCTION

Fiber reinforced composites are currently being investigated for use in civil engineering applications for either repair, retrofit or as direct replacements for steel and reinforced concrete in bridge structures. The high strength to weight ratio and stiffness to weight ratios, corrosion and fatigue resistance of FRP composites make them attractive for use in the construction of new bridges and retrofitting of existing bridges. Besides the potential for lower life-cycle costs, FRP decks would be significantly lighter thereby effecting large savings in column and foundation costs, enabling the use of higher live load levels through replacement of heavier conventional decks. In addition, they have strong potential for use in areas where longer unsupported spans are necessary or where lower weight would translate to higher seismic resistance.

One of the main driving forces to use composites in bridge structure is to construct light and easy-to-erect deck systems. To achieve this, moderately thin walls and multi-cellular structures are usually employed in composite bridge decks. Despite the overall benefits of using FRP sections, these advanced composite materials are not yet widely used in practice. Often, standard materials like steel, concrete and timber are more economical in terms of material costs. Also, the material properties and behaviour of FRP composites are not as fully understood as conventional materials and therefore there are no standardized codes or specifications to govern their use. The application of FRP bridge deck systems for the construction of new bridges and retrofitting of existing bridges requires a thorough knowledge about the structural behaviour of these deck systems under traffic loads and environmental conditions. The main objective of the present investigation is to study analytically the static behaviour of GFRP composite bridge deck panels upto failure under wheel load of Indian Road Congress Class A wheeled vehicle. The effect of position of patch load on the maximum deflections and strains was studied. The analytical results were compared with the specifications by the Ohio Department of Transportation, U.S.A and experimental data.

Review of literature

Alagusundaramoorthy *et al*. (2003) analyzed the single and double span pultruded FRP bridge deck panels using ANSYS and compared the analytical results with the experimental results (Harik, 1999) and the performance criteria specified by Ohio Department of Transportation (ODoT). Aref and Parsons, (1999) presented a simplified procedure for an optimum design of fiber reinforced composite bridge deck.

Aref and Sreenivas, (2001) conducted field tests and studied the dynamic response of the first fiber reinforced polymer composite bridge built in USA. They developed a finite element model using MSC-PATRAN and analyzed using ABAQUS. Davalos *et al*. (2001) presented a combined analytical and experimental characterization of FRP honeycomb deck panels. They concluded that the equivalent orthotropic properties developed in their study could be used for the analysis and design of the FRP sandwich panel. Ehlen, (1999) examined the life cycle cost effectiveness of three FRP decks and compared with conventional concrete materials. Gan *et al*. (1999) evaluated different cross section profiles for pultruded deck panels with the reduced local stress and improved buckling strength. Harik *et al*. (1999, 2000) conducted static tests on three concrete deck panels made of concrete reinforced with glass fiber reinforced polymer rebars and externally bonded with GFRP rectangular tubular sections, three fiber glass composite bridge deck panels fabricated using the cell core technology in conjunction with SCRIMP, three pultruded FRP deck panels and three single span contact molding hand lay-up fiber glass composite deck panels and concluded that all FRP decks performed satisfactorily for AASHTO standard HS25 truck wheel load with the factor of safety of more than 5. Hayes *et al*. (2000) conducted static and fatigue tests on the composite bridge deck systems, assembled from glass/polyester pultruded components.

They found that the deck system met the necessary strength performance criteria and observed that strength and stiffness of bridge deck did not change even after 3 million cycles of fatigue load. Kitane *et al*. (2004) conducted static and fatigue tests on a scale model of a hybrid FRP concrete bridge superstructure. They concluded from the static test data that the bridge model meets the stiffness requirement and has significant reserve strength. Their fatigue test results showed that the structural system exhibited insignificant stiffness degradation after 2 million cycles. Qiao *et al*. (2000) conducted static tests on FRP deck/stringer bridge system for various load conditions. They presented a systematic approach for design analysis of FRP deck/stringer bridge systems. They correlated the experimental results with an approximate series solution and finite element model. Veera Sudarsana Reddy and Alagusundaramoorthy, (2003) carried out characterization of FRP composite materials with different resin systems and reinforcements and suggested guidelines for the selection of resin and reinforcement for making FRP bridge deck panels.

GFRP composite bridge deck panels

The cross section of the GFRP composite bridge deck panel used in this study is a 3-cell rectangular section with additional stiffeners connecting the web to the top flange of deck (Fig. 1). The length of the bridge deck panel was kept as 3000 mm. The width and depth of the deck was 1000 mm and 300 mm respectively. The larger dimension (length) of the GFRP bridge deck panel is kept perpendicular to the direction of the traffic. The dead load due to future surface wearing course on the deck was taken as 4950 N. The characterization of GFRP composites was carried out as per American Society for Testing and Materials (ASTM), British Standards (BS) and International Organization for Standardization (ISO) standards. The properties of GFRP composites were shown in Table 1.

Table 1. Properties of GFRP composites

Material properties	Value
Longitudinal modulus of elasticity (E_1)	23,476 MPa
Transverse modulus of elasticity (E_2)	19,515 MPa
Shear modulus (G_{12})	2,236 MPa
Tensile strength	313 MPa
Compressive strength	242 MPa
Bending strength	284 MPa
Shear strength	50 MPa
Poisson's ratio (υ_{12})	0.20
Ultimate strain (ϵ_{ult})	0.0102
Volume fraction of fibers (v_f)	0.38

Analysis of GFRP composite bridge deck panels

The static analysis of GFRP bridge deck was carried out using ANSYS, standard finite element software. Eight noded SOLID45 brick elements and SHELL93 elements with an orthotropic material option were used separately to model the bridge deck panel. The elements chosen for the analysis were having the capabilities of plasticity, creep, swelling, stress stiffening, large deflection and large strain. The bridge deck panel was simply supported over shorter spans and a rectangular patch load that represents IRC Class A wheeled vehicle was applied over a patch area of 500 mm x 250 mm at the center of the bridge deck panel as shown in Fig. 2. The convergence study has done for all FRP decks under the factored load of 83 kN. The size of the elements along the cross section was kept constant and they were refined along the span length of deck panel.

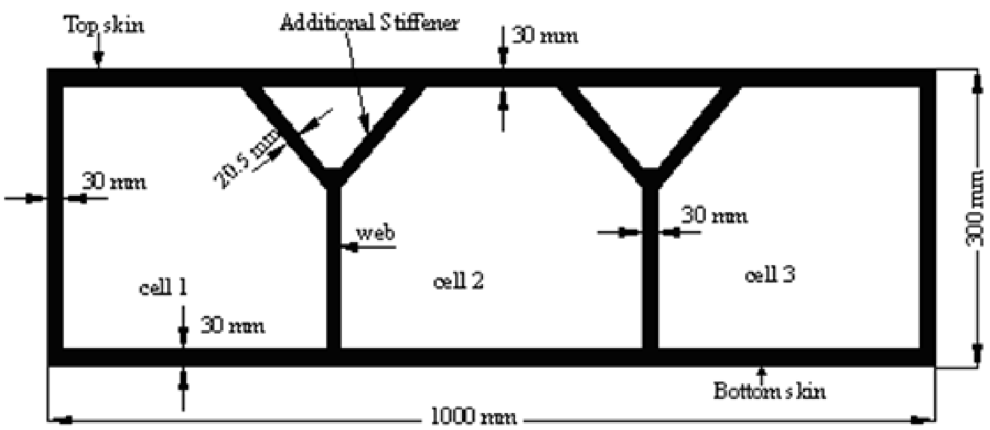

Fig. 1. Cross section of GFRP bridge deck panel

The convergence study was checked for the maximum stress of the deck along the longitudinal direction. Stress versus number of elements were plotted for all FRP deck panels. The optimum mesh was chosen from the graphs plotted. The effect of location of patch load on the static behaviour of bridge deck panels was also studied by shifting the patch load to the support and corner of the bridge deck panel (Figs 3 and 4). An incremental load was applied till the maximum strain in the bridge deck panel reached its ultimate strain and the corresponding load at ultimate strain was recorded as the ultimate load. The discretization of GFRP composite bridge deck panel using SOLID45 and SHELL93 elements were shown in Figs. 5 and 6 respectively.

The analytical results were compared with the specifications of ODoT, U.S.A. and experimental data. The performance criteria for deflection, flexure and shear specified by ODoT were given. The deflection limits for the FRP bridge deck panels are based on deflection calculations/limits for the conventional reinforced concrete decks. The deflection of the bridge deck panel is limited to span/800.The maximum allowable strain is limited to 20% of ultimate strain under factored load of LL+IM+DL, in which LL = live load, IM = Dynamic allowance factor for live load and DL = dead load. The maximum allowable dead load strain is limited to 10% of ultimate strain. This includes the weight of future surface wearing course.

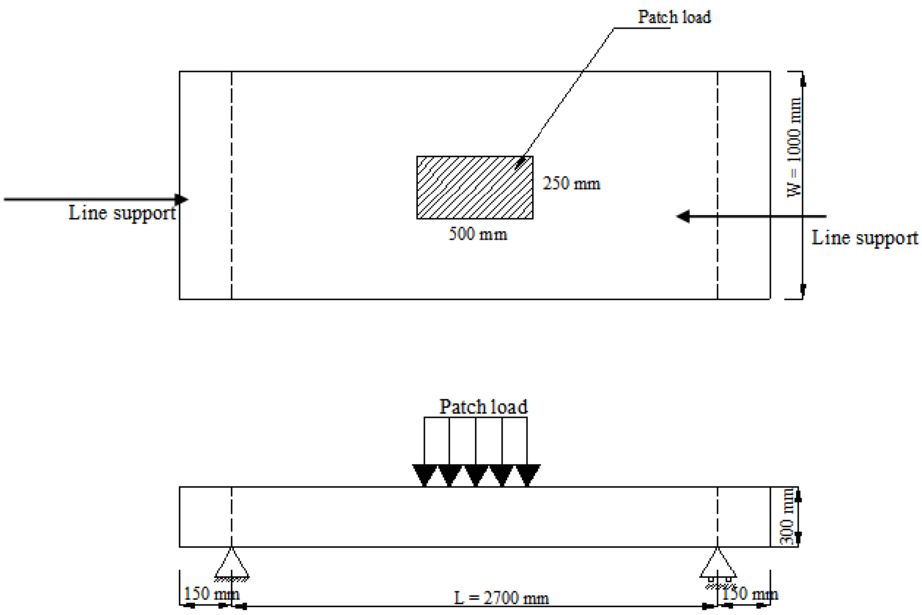

Fig. 2. Position of patch load at center of GFRP bridge deck panel

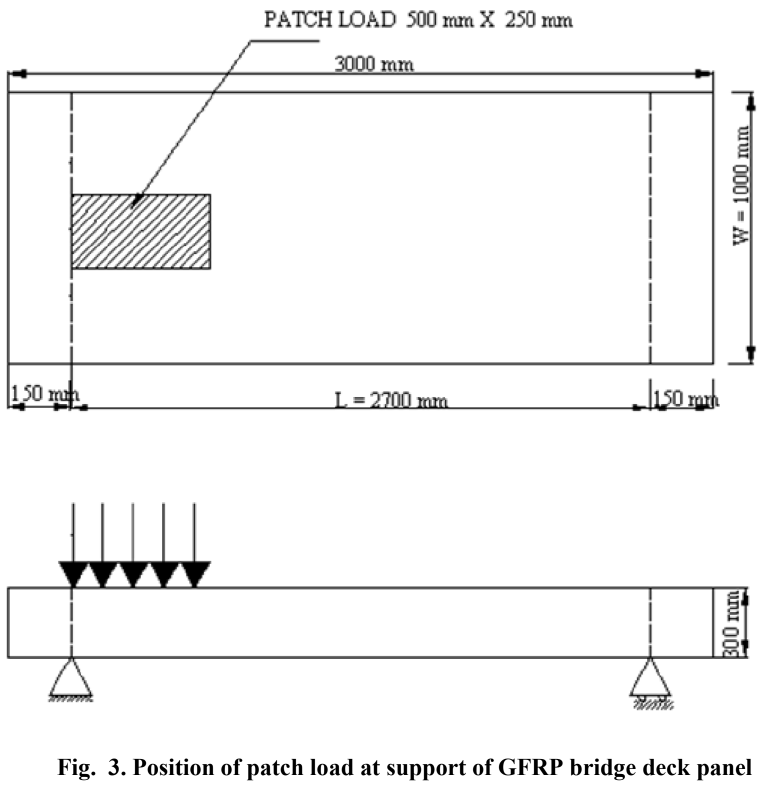

Fig. 3. Position of patch load at support of GFRP bridge deck panel

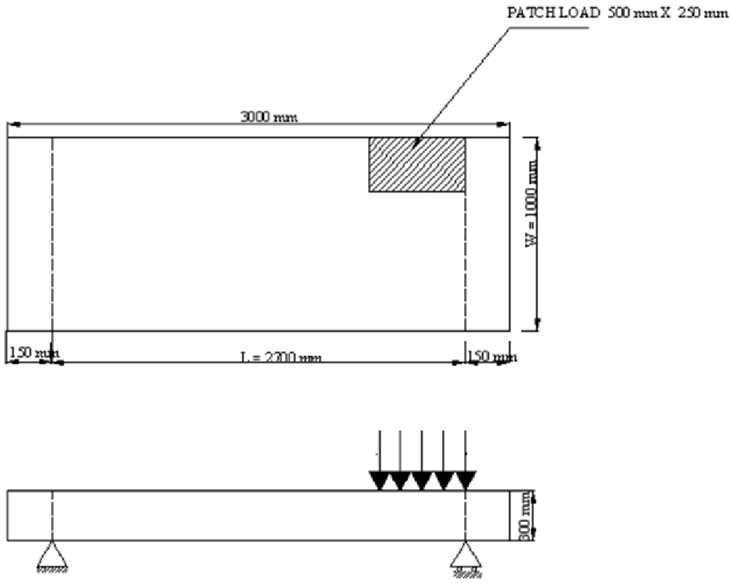

Fig. 4. Position of patch load at corner of GFRP bridge deck panel

The maximum factored load of 1.3[1.67(LL + IM) + DL] should be less than 50% of ultimate load capacity for FRP deck panels. Shear capacity should be equal to or greater than that of a reinforced concrete (RC) conventional deck panel. The maximum allowable shear for a factored load of 1.3[1.67(LL + IM) + DL] should be less than 45% of the ultimate shear load capacity for FRP deck panels. The ultimate load of bridge deck panel obtained from analysis was compared with experimental data. The static and fatigue tests were conducted on GFRP composite bridge deck panels in Structural Engineering Laboratory, Indian Institute of Technology Madras, India and the experimental data was used for comparison of the analytical results in this study. The first order optimization method available in ANSYS design optimization was used to optimize the weight of the GFRP composite bridge deck panels. In this method of optimization the constrained problem is transformed into an unconstrained one via penalty functions.

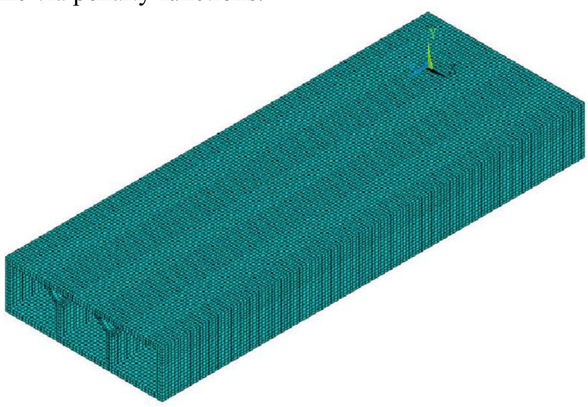

Fig. 5. Discretization of GFRP bridge deck panel using SOLID45 elements

Derivatives are formed for the objective function and state variable penalty functions, leading to a search direction in design space. Various steepest descent and conjugate direction searches are performed during each iteration until convergence is reached.

Each iteration is composed of subiterations that include search direction and gradient (derivative) computations. In other words, one first order design optimization iteration will perform several analysis loops. Compared to the subproblem approximation method, this method is more computationally demanding and more accurate.

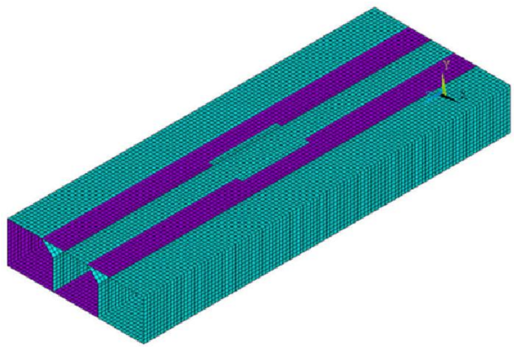

Fig. 6. Discretization of GFRP bridge deck panel using SHELL93 elements

The first order iterations continue until either convergence is achieved or termination occurs. These two events are checked at the end of each optimization iteration. Convergence is assumed when comparing the current iteration design set to the previous set and the best set. The cross section of the bridge deck panel was expressed in terms of thickness parameters such as t1 and t2 (Fig. 7).

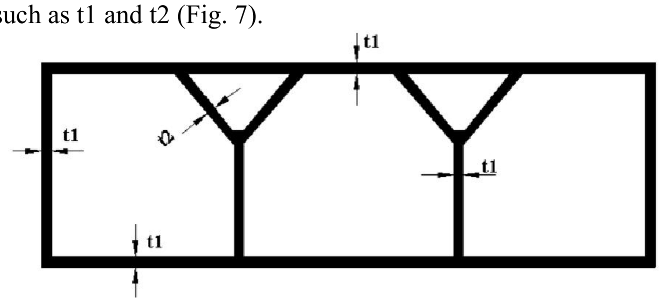

Fig. 7. Cross section of GFRP bridge deck panel in terms of parameters

The thickness parameters of GFRP composite bridge deck panel were taken as the design variables in the optimization process.

RESULTS AND DISCUSSION

The maximum deflections and strains at factored load at the bottom of the bridge deck panel were obtained from the analysis when the position of patch load at center, support and corner of the bridge deck panel (Tables 2 and 3).

The maximum deflections and strains at failure load of GFRP bridge deck panel were obtained using ANSYS (Table 4). The deflection and strain contour plots of a bridge deck panel under a factored load using SOLID45 and SHELL93 elements were presented (Figs. 8, 9, 10, and 11).

The load vs deflection and load vs strain curves at midspan and quarterspan at the bottom of the bridge deck panel were shown in Figs. 12, 13, 14 and 15 respectively. All the curves followed the linear trend upto a factored load.

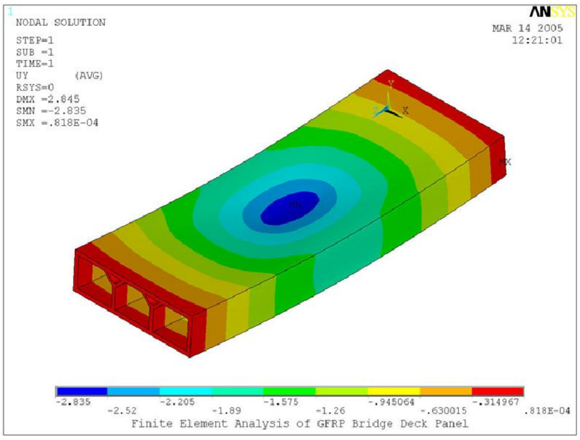

Fig. 8. Deflection contour of GFRP bridge deck panel using SOLID45 element

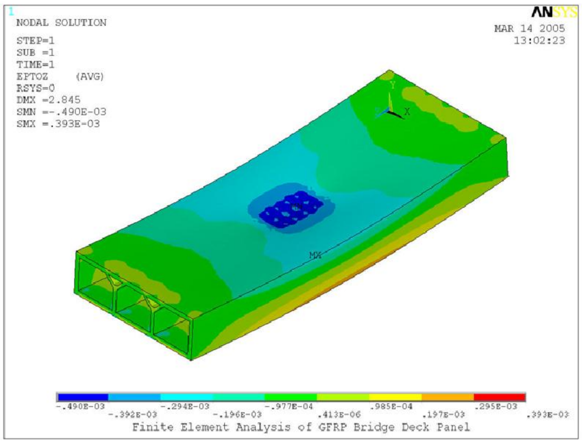

Fig. 9. Strain contour of GFRP bridge deck panel using SOLID45 element

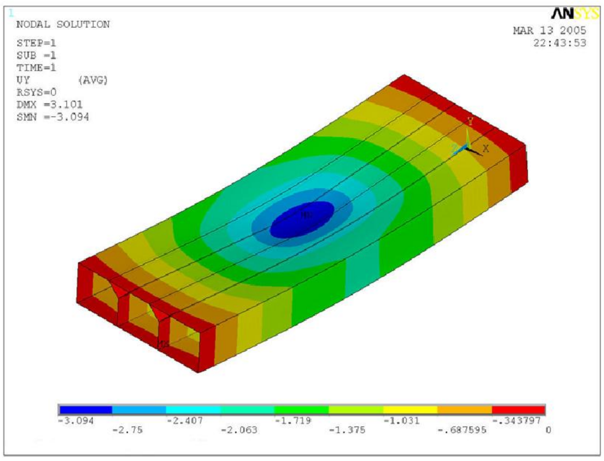

Fig. 10. Deflection contour of GFRP bridge deck panel using SHELL93 element

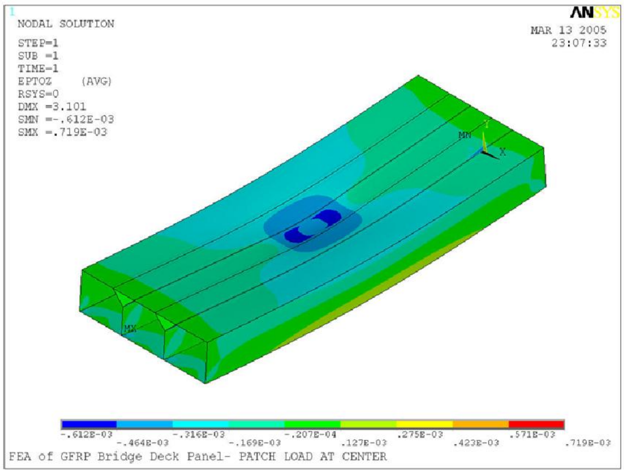

Fig. 11. Strain contour of GFRP bridge deck panel using SHELL93 element

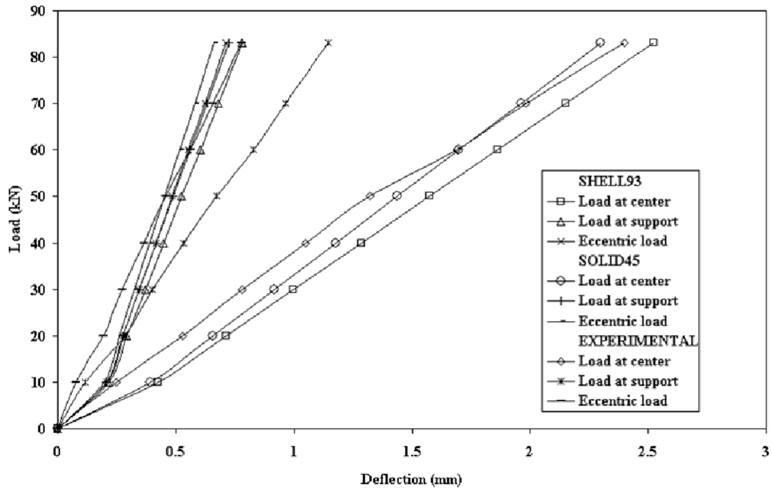

Fig. 12. Load vs deflection at midspan of GFRP bridge deck panel

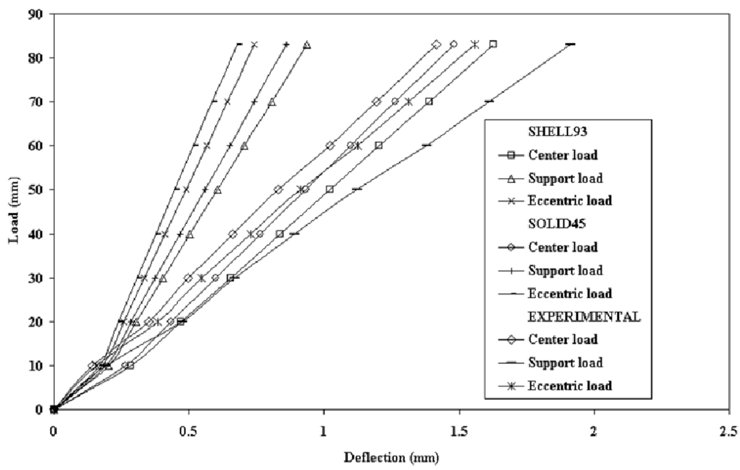

Fig. 13. Load vs deflection at quarterspan of GFRP bridge deck panel

Table 2. Deflections in GFRP bridge deck panel when patch load at center, support and eccentric

Position of load	Maximum deflection at factored load (mm)						
	Midspan				Quarterspan		
	SOLID45	SHELL93	Experimental	ODoT	SOLID45	SHELL93	Experimental
Center	2.301	2.525	2.400	3.375	1.481	1.627	1.415
Support	0.723	0.783	1.146	3.375	0.861	0.936	1.910
Eccentric	0.662	0.713	0.778	3.375	0.677	0.741	1.556

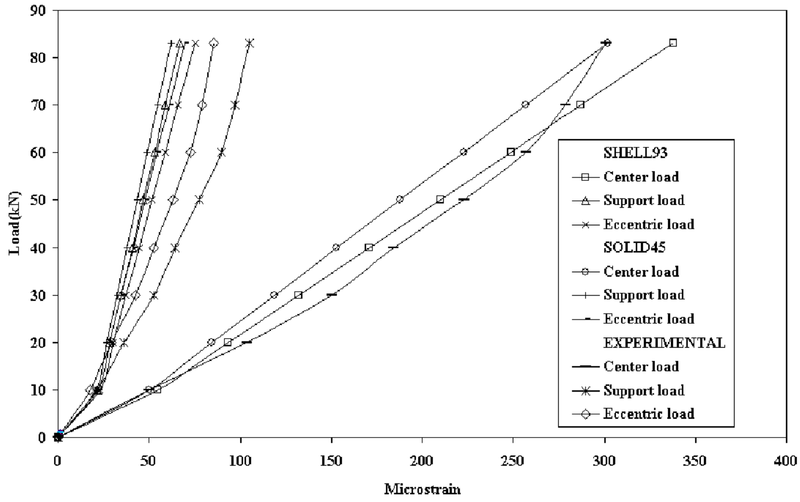

Fig. 14. Load vs strain at midspan of GFRP bridge deck panel

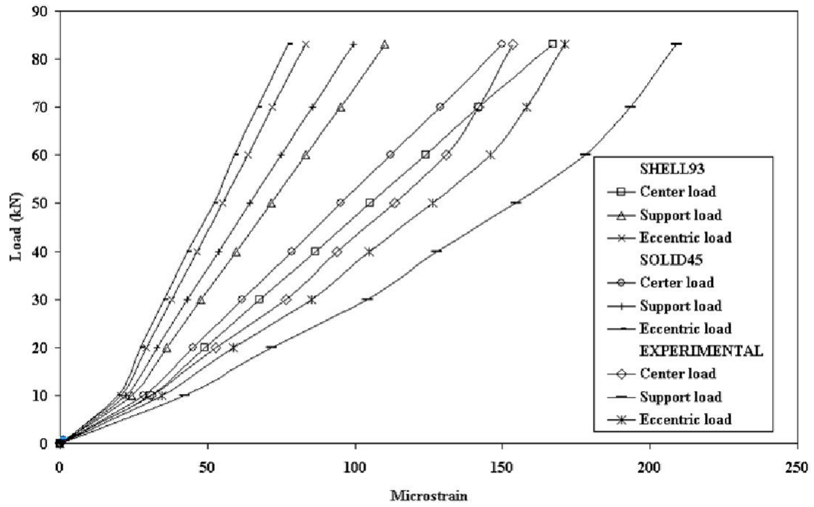

Fig. 15. Load vs strain at quarterspan of GFRP bridge deck panel

Table 3. Strains in GFRP bridge deck panel when patch load at center, support and corner

Position of load	Maximum strain at factored load						
	Midspan				Quarterspan		
	SOLID45	SHELL93	Experimental	ODoT	SOLID45	SHELL93	Experimental
Center	0.000302	0.000338	0.000301	0.00204	0.000150	0.000167	0.000153
Support	0.000062	0.000067	0.000105	0.00204	0.000099	0.000110	0.000209
Corner	0.000069	0.000075	0.000086	0.00204	0.000077	0.000083	0.000171

The analytical values of maximum deflection and strain at midspan and quarterspan using SOLID45 element under a factored load when position of load at center of bridge deck panel were 4% lower and 0.3% higher and 4.6% higher and 2% lower respectively than the corresponding experimental values. The analytical results of maximum deflection and strain at midspan and quarterspan using SHELL93 element under a factored load when position of load at center of bridge deck panel were 5% and 12.3% and 15% and 9% respectively higher than the corresponding experimental data. The failure load of bridge deck panel obtained from analytical results using SOLID45 and SHELL93 elements was 7% higher and 1% lower respectively than the experimental results.

The maximum deflection at failure load of bridge deck panel using SOLID45 and SHELL93 elements were 3.6% and 2% lower than the corresponding experimental value. The maximum strain at failure load of bridge deck panel using SOLID45 and SHELL93 elements were 8% and 4.9% lower than the corresponding experimental data. The analytical results such as failure load, maximum deflection and strain at failure load obtained using SHELL93 element were in close agreement with the corresponding experimental data when compared the results of SOLID45 element. It is suggested to use SHELL93 element for modeling of GFRP bridge deck panel. GFRP composite bridge deck panel was optimized and the optimized parameters were presented in Table 5. The weight of optimized deck was compared with the actual deck and the reduction in weight of GFRP composite deck panel due to optimization was calculated (Table 5).

- The decrease in weight of the GFRP bridge deck panel due to optimization was found to be 6%.

Table 5. Optimized parameters and weight of GFRP bridge deck panel

Parameter	Value of parameter (mm)		Weight (N)		% decrease in weight
	Actual deck	Optimized deck	Actual deck	Optimized deck	
t1	30.0		4112		
t2	20.5				

Summary and conclusions

The static analysis of GFRP composite bridge deck panels was carried out using the standard finite element software ANSYS. The analytical results of maximum deflections and strains were compared with ODoT specifications and experimental data. The following conclusions were drawn based on the analytical study carried out in this investigation.

- The maximum strain at factored load obtained from finite element analysis using SOLID45 and SHELL93 elements was within the 20% of the ultimate strain specified by ODoT, USA.
- The analytical value of maximum deflection using SOLID45 and SHELL93 elements under factored load of GFRP bridge deck panel was within span/800 as specified in the deflection criteria specified by ODoT, USA.
- The analytical values of maximum deflection and strain at midspan and quarterspan using SOLID45 element under a factored load when position of load at center of bridge deck panel were 4% lower and 0.3% higher and 4.6% higher and 2% lower respectively than the corresponding experimental values.
- The analytical results of maximum deflection and strain at midspan and quarterspan using SHELL93 element under a factored load when position of load at center of bridge deck panel were 5% and 12.3% and 15% and 9% respectively higher than the corresponding experimental data.
- The values of maximum deflection and strain at midspan and quarterspan under factored load when the position of patch load at support and eccentric were lower than the corresponding experimental data and the limits specified by ODoT.
- The failure load of bridge deck panel obtained from analytical results using SOLID45 and SHELL93 elements was 7% higher and 1% lower respectively than the experimental results.
- The maximum deflection and strain at failure load of bridge deck panel obtained using SOLID45 and SHELL93 elements were 3.6% and 8% and 2% and 4.9% lower than the corresponding experimental values.
- The analytical results such as failure load, maximum deflection and strain at failure load obtained using SHELL93 element were in close agreement with the corresponding experimental data when compared the results of SOLID45 element.
- It is suggested to use SHELL93 element for modeling of GFRP bridge deck panel because the failure load, deflections and strains at failure load can be estimated very close to the experimental values using less number of finite elements for modeling the bridge deck panel and with reduced computational time.

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