# OPTIMIZATION ON THE BEHAVIOUR OF GLASS FIBER REINFORCED PLASTIC BRIDGE DESK PANELS BY USING SIMULATION TOOL

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## ABSTRACT

*FRP strengthening of continuous beams. In the present study, an Numerical investigation is carried out to study the behaviour ofGFRP under static loading. The beams are strengthened with externally bonded glass fibre reinforced polymer (GFRP) sheets and also with unbonded GFRP using steel bolt system. Different scheme of strengthening have been employed. The experiment consists of (150×250×2300) mm. In recent years, high-performance Fibre Reinforced Polymer (FRP) composite materials have been identified as an excellent candidate for rehabilitating deteriorated bridges. One of the most promising applications for this high-performance material is bridge decking. In this pursuit for suitable materials, the FRP composites, has been demonstrated with great success for bridge applications, to solve some of the persistent problems associated with conventional construction using steel, reinforced concrete and pre-stressed concrete through extensive laboratory testing. FRP plate elements are used in bridge construction predominantly as deck slabs mainly because of their low self-weight, high corrosion and fatigue resistance, and very little installation time, resulting in minimal traffic interruption. Potential applications for FRP decks are new design, replacement of under-strength decks in existing bridges*

**Keywords***:* *ANSYS 13.0; GFRP; deboning failure;*

## INTRODUCTION

The deteriorating state of transportation infrastructure systems is a serious concern worldwide. The study of life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of repair. There is a growing interest among engineers to find cost-effective and durable technologies for bridge repair, rehabilitation and replacement. Different solutions are available to overcome this problem.

In recent years, high-performance Fibre Reinforced Polymer (FRP) composite materials have been identified as an excellent candidate for rehabilitating deteriorated bridges. One of the most promising applications for this high-performance material is bridge decking. In this pursuit for suitable materials, the FRP composites, has been demonstrated with great success for bridge applications, to solve some of the persistent problems associated with conventional construction using steel, reinforced concrete and pre-stressed concrete through extensive laboratory testing. FRP plate elements are used in bridge construction predominantly as deck slabs mainly because of their low self-weight, high corrosion and fatigue resistance, and very little installation time, resulting in minimal traffic interruption. Potential applications for FRP decks are new design, replacement of under-strength decks in existing bridges, and the provision of temporary running surfaces.

### FIBRE REINFORCED POLYMER COMPOSITES

FRP is a composite material made by combining two or more different materials. Composites exhibit the best qualities of the constituents and offer some qualities that neither constituent possesses, so that the resulting material has more useful applications than the constituent materials alone. Properties that are improved by composites include strength, durability, stiffness and fatigue life. A composite may be of any one of the following types: (1) Fibrous type having long fibres of one material embedded in a matrix of another material (2) Laminated type composed of layers of two or more different materials that are bonded together (3) Particulate type consisting of particles of one or more materials suspended in a matrix of another material. The FRP Composites considered in this work are herein limited to laminated type fabricated with thin fibres or filaments and bonded together in layers or lamina with a polymer matrix. The mechanical and physical properties of FRP are controlled by its constituent properties and by structural configurations at the micro level. Therefore the analysis and design of any FRP structural member requires a good knowledge of the material properties, which are dependent on the manufacturing process and the properties of constituent materials.

**FRP Composite Materials for Bridge Applications**

The applications of composites in bridges include construction of new bridges using composite bridge structural systems and repair or retrofit existing bridge structures. The first pedestrian FRP Bridge was built by the Israelis in 1975. Since then, others have been constructed in Asia, Europe, and North America. Many innovative pedestrian bridges have been constructed throughout the United States using pultruded composite structural shapes which are similar to standard structural steel shapes. Because of the light- weight materials and ease in fabrication and installation, many of these pedestrian bridges were able to be constructed in inaccessible and environmentally restrictive areas without having to employ heavy equipment. Some of these bridges were flown to the sites in one piece by helicopters; others were disassembled and transported by mules and assembled on site. The advancement in this application has resulted in the production of second generation pultruded shapes of hybrid glass and carbon FRP composites that will increase the stiffness modulus at very little additional cost.

**ORGANISATION OF THE THESIS**

This thesis provides the introduction about FRP composite materials, methods of fabrication of composites and its application in the construction of bridges. Different cross sectional profiles of FRP composite bridge deck panels available in the literature are reported. Overall review of literature on FRP composite bridge deck panels. The various aspects include characterization, preparation of GFRP members, structural performance under static, fatigue and dynamic loadings, fire resistance, durability, analytical studies etc

**OBJECTIVES OF THE THESIS**

The objectives of the thesis are listed below

i) Evaluation of mechanical properties of FRP composites for flexural loading condition

ii) Characterization of FRP composite materials and selection the suitable resin and reinforcement for the fabrication of composite bridge deck panel as a flexural member

iii) Selection of proper geometrical profile for studies of GFRP bridge deck panels

iv) Fabrication of multicellular GFRP composite bridge deck panels by hand lay-up process

v) Static tests on GFRP composite bridge deck panels under flexural and shear loading conditions

**SCOPE OF THE PRESENT INVESTIGATION**

The main scope of the present investigation is to study experimental and analytical behaviour of hand lay-up multicellular GFRP composite bridge deck panels under static and fatigue loading conditions. The investigation is required because the number of advantages that the composite material posses compared to that of the other materials (steel and concrete) used in construction.

The scope of the study is to assess the composite behaviour of GFRP composite bridge deck system for the flexural and shear loading. The research results reported herein support the notion of employing a design approach, for a composite floor system, which is consistent with current practice related to concrete decking. The scope also includes that the choosing of proper geometry and material properties for FRP bridge-decks.

So for, there is no standard procedure for design and principles for the composite bridges. Here an attempt is made to make some principles and design standards for GFRP bridge decks. The guidelines for design principles are based on analytical and experimental works.

## LITERATURE REVIEW

**Amjad et al (2015)** analysed a hybrid GFRP - concrete multicellular bridge superstructure using the FE analysis software, ABAQUS, with the primary objective of examining the accuracy of FEA and to propose simple methods of analysis for predicting the static flexural behaviour of the hybrid FRP-concrete bridge superstructure. In the study, three trapezoidal GFRP (E-glass and Vinlyester) box sections bonded together to make up a one-lane superstructure, and a layer of concrete placed in the compression zone of those sections has been considered. It has been concluded that a linear FEA can accurately predict the static behaviour of the bridge superstructure under design live loads.

**Sreenivas et. al (2015)** studied the structural behaviour and failure modes of a glass fibre reinforced polymer web core skew bridge superstructure, using the standard FE analysis package ABAQUS and MSC PATRAN, and investigated the shear transfer capacity and the local buckling behaviour of the bridge superstructure. The conclusion based on the study is that the FRP bridge design is controlled by stiffness as reported by other researchers and when the superstructure deflection meets the AASHTO requirement, the allowable live load is approximately 2 times of HS-25 live load. It was established that when the superstructure deflection meets the AASHTO requirement, the Tsai-Hill index is far below the limit state (unit value).

**Upadyay and Kalyanaraman (2013)** considered the various factors that affect the FRP box-girder behaviour and developed a simplified, approximate and computationally efficient procedure for the analysis of single cell FRP box-girder bridges made of blade angle or T stiffened panels and validated the results by comparison with values available in literature and results obtained from FEA (MSC NASTRAN package). They considered the stresses due to longitudinal bending moment, shear force, torsion, distortion, shear-lag and transverse bending as well as instability of the flange under compression and web under shear to propose the simplified analysis method. It was mentioned that the simplified procedure is adequately accurate and very fast for effectively analyzing the FRP box sections in the preliminary and optimum design stages.

**King et al (2012)** outlined the Load and Resistance Factor Design (LRFD) of Fibre Reinforced Polymer composite (FRP) panel highway bridge deck. The deck would be of a sandwich construction where 152.4 mm × 152.4 mm × 9.5 mm square pultruded glass FRP (GFRP) tubes are joined and sandwiched between two 9.5 mm GFRP plates. The deck would be designed by Allowable Stress Design (ASD) and LRFD to support AASHTO design truckload HL-93. It was mentioned that there are currently no US standards and specifications for the design of FRP pultruded shapes including a deck panel therefore international codes and references related to FRP profiles will be examined and AASHTO-LRFD specifications will be used as the basis for the final design. Overall, years of research and laboratory and field tests have proven FRP decks to be a viable alternative to conventional concrete deck. Therefore, conceptualizing the design of FRP bridge decks using basic structural analysis and mechanics would increase awareness and engineering confidence in the use of this innovative material.

**Alagusundaramoorthy et. al(2018)** studied the load-deflection behaviour of GFRP composite deck panels under static loading. Three prototype GFRP composite deck panels each with a size of 3000mm × 1000mm × 300mm were fabricated using hand lay-up process and tested under a factored load of AASHTO HS20/IRC Class A wheeled vehicle. The deck panels were analyzed using the standard FE software, ANSYS. Maximum deflection and strain at factored load, and flexural and shear rigidities were calculated in the FE analysis and compared with the experimental data, and also with the specifications given by the Ohio Department of Transportation (ODoT), USA. From this study, it was concluded that the fabricated GFRP deck panels satisfied the performance criteria specified by ODoT and can be used in berthing structures, bridges in coastal regions, offshore oil platforms and also in seismic prone areas.

**Ki-Tae Park et al (2005)** determined the optimum geometry for bridge decks and properties of the GFRP material by carrying out three-dimensional numerical modeling and evaluated the performance of GFRP (E-Glass - Vinylester) cellular deck modules fabricated using the pultrusion method, based on the results of optimisation, by conducting several tests such as fibre direction flexure test, transverse direction test, buckling test, and load weighting test in actual scale. Authors observed that most failures took place at the joint between flange and web. It was also noticed that the factor of safety against buckling is more than five. In addition, the failure load of FRP decks is found to be three times larger than the axial load of design truck load DB- 24, as specified in the Korean specification.tool for the practicing engineer in predicting, in an average sense, the inelastic response of composite laminates due to damage accumulation.

**Julio Davalos et al (2001)** described a combined analytical and experimental characterization of FRP honeycomb panels. The core consisted of in-plane sinusoidal cells extending vertically between top and bottom face laminates. A combined micro / macro mechanics were used to predict face laminate elastic properties, and the core equivalent properties were obtained by a homogenization technique combined with an energy method and a mechanics of materials approach. The analytical model predictions were found to correlate well with the FE modeling (using ANSYS 5.5) and experimental results. It was concluded that the equivalent orthotropic properties developed in the study can be used in design analyses of FRP sandwich panels used for highway bridge decks.

**Kumar et al (2001)** conducted three and four point bending tests on three different pultruded hollow square GFRP tubes and their assemblies for bridge deck panel. A preliminary design model of each test specimen was developed and analyzed using FEA. It was mentioned that the experimental results showed good correlation with analytical results and indicated that the web-flange junction was the principle location of failure of GFRP tubes.

**Baolin Wan et al (2015)** investigated the main parameters that affect the analysis and design of a GFRP composite bridge deck on steel girders in South Carolina, through computer models developed using ANSYS 7.0. Authors validated the computer models with in situ measurements and experimental data and observed that there was good correlation. The deck was found to deform locally when the supporting girder structure is excessively stiff. It was observed that fewer girders or larger girder spacing decreased the overall bridge stiffness resulting in more effective distribution of the deck deformations and so girder spacing plays a key role on the performance of the deck.

**Thomas Keller and Martin Schollmayer (2016)** examined the structural in-plane tensile performance of a pultruded GFRP bridge deck system, perpendicular to the pultrusion direction both numerically using ANSYS and experimentally. The investigation was carried out with regard to the use of the deck as the compositely acting top chord of hybrid bridge main girders in negative moment regions. The deck properties determined on the system level comprised of the in-plane tensile stiffness and capacity, as well as a limit of elastic behaviour. Exceeding the elastic limit signified local damage in the adhesive bond of the deck joints. The experiments were shown that creep deformations in the FRP deck due to in-plane tensile loading are negligible and not determinant to design. The results of the model enabled the interpretation of the damage initiation and failure behaviour and so the authors have suggested that the elastic behaviour could be modeled with an orthotropic two-dimensional FE model.

**Reddyet. al (2016)** studied the behaviour of GFRP composite highway bridge deck panels under static loading. 3-cell rectangular section with additional stiffeners connecting the web to the top flange of the deck was fabricated. A rectangular patch load that represents the IRC Class A wheeled vehicle was applied at the centre of the bridge deck panel and tested under factored load upto failure. Maximum deflection and strain at factored load and load at failure obtained from FEA using ANSYS were compared with the specifications by the Ohio Department of Transportation (ODoT), USA. The maximum deflection under factored load satisfied the deflection criteria specified by ODoT.

**Almansour and Cheung (2010)** analyzed all-advanced composite bridge superstructure (E-glass - Vinylester) formed from laminated FRP box girder and chopped FRP deck slab. The bridge had two lanes of 3.75 m each and its performance was examined for Canadian highway bridge design code with a non-linear anisotropic FE model and compared to a traditional slab on prestressed concrete bridge. Maximum deflection of the bridge for all laminate design cases were within the acceptable range, the distribution of deformations being unsymmetrical. The increase of the laminate thickness resulted in decreasing the resultant displacement field, increasing natural frequencies and decreasing the Tsai-Hill Failure Function. The results indicated that its deflection is higher than the short term deflection of the slab on prestressed girder bridge but close to the long term deflection of that same bridge and that the AAC gives lower flexural natural frequencies than those of the slab on prestressed concrete girder bridge.

**Prakash Kumar et al (2014)** investigated the structural performance of a FRP bridge deck fabricated from pultruded square hollow glass and carbon FRP tubes bonded using epoxy adhesive and mechanically fastened together using screws. Fatigue and failure tests were conducted and the values of deflection and strain as obtained from FE model were shown good correlation with the experimental values. The deflection and strain histories were shown linear elastic bending and shear behaviour and the net central deflections ranged within the allowable limits of length / 800. The fatigue test results indicated that there was no reduction in strength or stiffness after 2 million cycles of fatigue loading in excess of the design wheel load. The failure load was about 4 times the design wheel load.

**REINFORCEMENT FORMAT**

The reinforcement fibres are generally available in the form of a tow, or in a band. In some processing operations (e.g. filament winding), tows, or rovings, of continuous fibres are converted directly into the component. Following forms of GFRP are generally available:

1. CSM (Emulsion)
2. CSM (Powder)
3. WR
4. Spray - up Rovings
5. SMC Rovings
6. Assembled Rovings
7. Direct Roving

Among these forms, deals with CSM (Emulsion) and WR.

**FUNCTIONAL RELATIONSHIP OF POLYMER MATRIX TO REINFORCING FIBRE**

The matrix gives form and protection from the external environment to the fibres. Chemical, thermal, and electrical performance can be affected by the choice of matrix resin. But the matrix resin does much more than this. It maintains the position of the fibres. Under loading, the matrix resin deforms and distributes the stress to the higher modulus fibre constituents. The matrix should have an elongation at break greater than that of the fibre. Re-alignment. Both of these design approaches inevitably reduce the load-carrying capability of the molded part and will probably also adversely affect its cost effectiveness. On the other hand, in the case of a complex part, it may be necessary to resort to shorter fibres to reinforce the molding effectively in three dimensions. In this way, quasi-isotropic properties can be achieved in the composite. Fibre orientation also influences anisotropic behaviour.

**MATRIX RESINS**

There are mainly three different types of matrix materials- organic polymers, ceramics and metals. Thermosetting polymer resins are the type of matrix material commonly used for civil engineering applications. Polymers are chain like molecules built up from a series of monomers. The molecular size of the polymer helps to determine its mechanical properties. Polymeric matrices have lowest density, hence, produce lightest composite materials. A major consideration in the selection of matrices is the processing requirement of the selected material.

**PARTICULATE FILLERS**

Particulate fillers are not reinforcements in the sense that stiffness and strength of the resin are greatly enhanced, but they are widely used in composite formulations. Typical fillers are the various forms of chalk (calcium carbonate), silica aerogels, glass ballotini**,** glass and polymer micro balloons, and carbon black. Their main function is to modify the matrix resin and especially to improve the surface finish. Since resins are very expensive, it will not be cost effective to fill up the voids in a composite matrix purely with resins. Fillers are added to the resin matrix for controlling material cost and improving its mechanical and chemical properties. Fillers are added to a polymer matrix for one or more of the following reasons:

**PERFORMANCE CRITERIA**

From the literature review, it has been observed that the design of GFRP bridge deck panels is driven by stiffness and hence maximum deflection is the governing criteria in design. The loads imposed on the bridge decks include dead load, which includes the self-weight and weight of future surface wearing course, and the live load imposed in the form of wheel load. These loads should be factored up suitably to account for impact and variation in material properties. The deflection produced by this factored load must be less than the limiting value of deflection. AASHTO has set up a deflection limit of Span / 800 for FRP bridge deck panels.

**IRC CLASS A LOADING**

According the specifications given by the Indian Roads Congress (IRC 6 - 2000), IRC class A loading is to be normally adopted on all roads on which permanent bridges and culverts are constructed. The IRC class A train of vehicles is shown in Figure 6.1

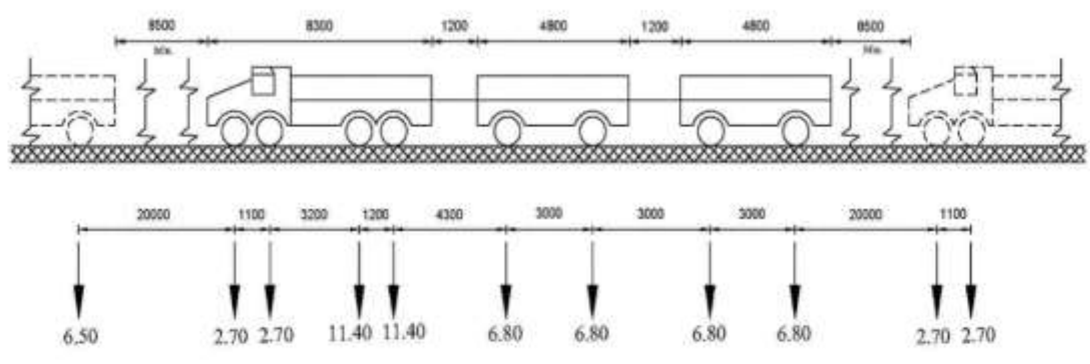



**Figure 6.1 IRC class A train of vehicles (axle loads in tones, linear dimensions in m)**

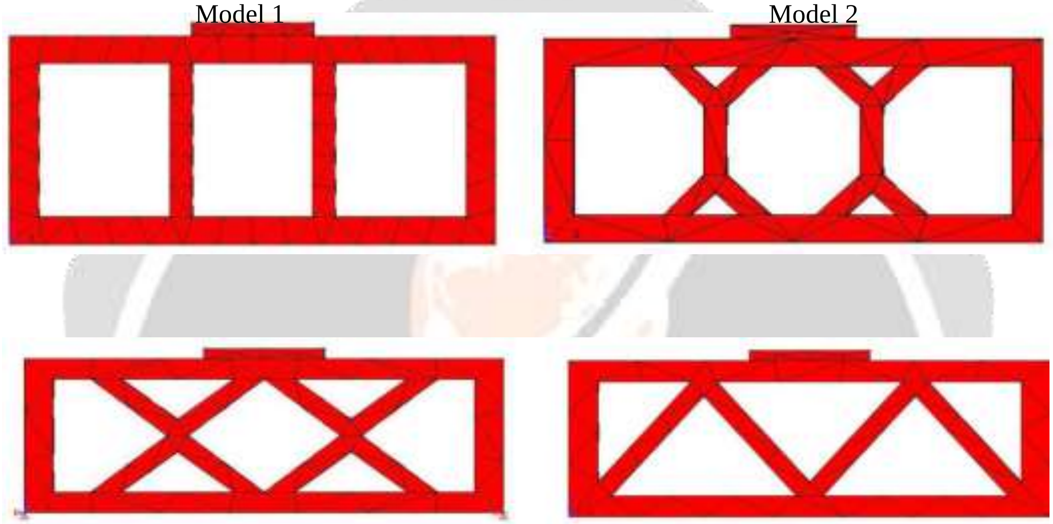
To obtain the maximum bending moment and shear force, the maximum wheel load should be considered as shown in Figure 6.2. The ground contact area for the maximum axle load of 114 kN as specified in IRC 6 - 2000 is 500 mm perpendicular to the direction of motion and 250 mm parallel to the direction of motion. The minimum clearance to be ensured between the outer edge of the wheel and the inner face of the kerb is 150 mm for all carriage way widths.

The width of a single lane carriage way is 3.75 m and that of two lane carriage way is 7.5 m as per IRC 5 - 1998. The ground contact area for the maximum axle load and the distances between the wheels in both directions has been indicated

**SELECTION OF CROSS SECTIONAL PROFILES**

Multi-cell box sections are commonly used in deck construction because of their light weight, efficient geometry, and inherent stiffness in flexure and torsion. Also, this type of deck has the advantage of being relatively easy to build. It can either be assembled from individual box-beams or manufactured as a complete section. Various cross sectional profiles of multicellular bridge deck panels available in the literature were selected and analyzed for IRC Class A wheel load using ANSYS, the standard FEA software. The cross sections considered for analysis are shown in Figure 6.4.

Model 1 Model 2



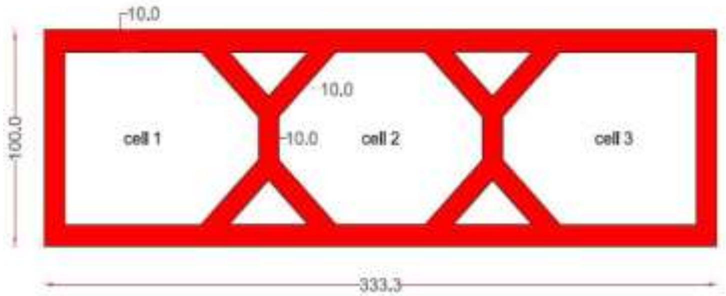
Model 3 Model 4

The analysis is on the cross sectional profile of the fourth model with varying thicknesses of flanges, webs and stiffeners as shown in Figure 6.5.

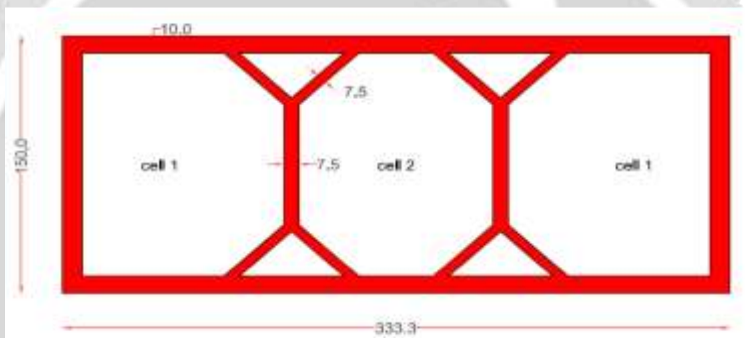
**Table 6.1 Deflection values for various models**

| **Model** | **Deflection (in mm)** |
|---|---|
| Model – 1 | 6.50 |
| Model – 2 | 5.64 |
| Model – 3 | 2.49 |

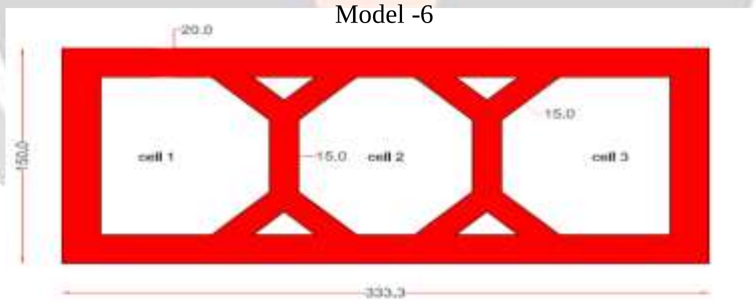
| | |
|---|---|
| Model – 4 | 2.34 |




Model -5




Model -6




Model -7

**ANALYSIS OF GFRP COMPOSITE BRIDGE DECK PANEL**

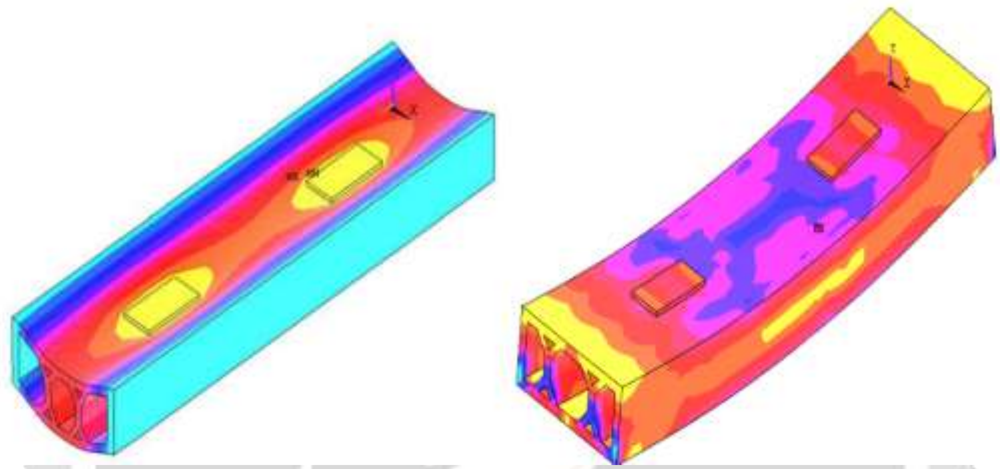
The GFRP bridge deck panel having the dimensions as specified above was analyzed by assigning the orthotropic material properties corresponding to the composites composed of the following materials.

- E-Glass fibres in the form of CSM and ISO

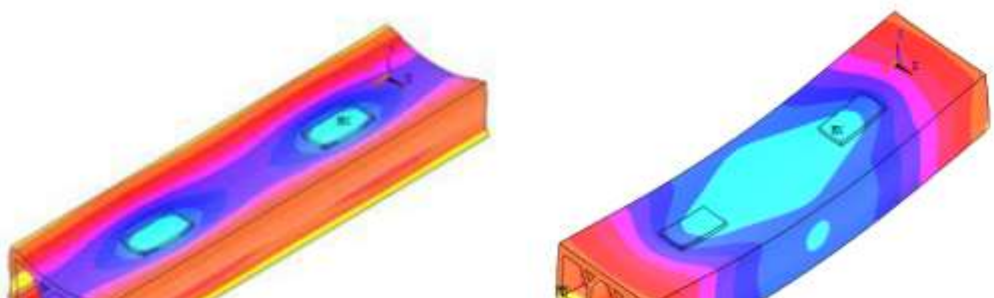
- E-Glass fibres in the form of WR and ISO
- E-Glass fibres in the form of WR and ER

The followings are notations for the six multi-cellular GFRP composite bridge are considered for analytical purpose and they are tested analytical using ANSYS as stated below

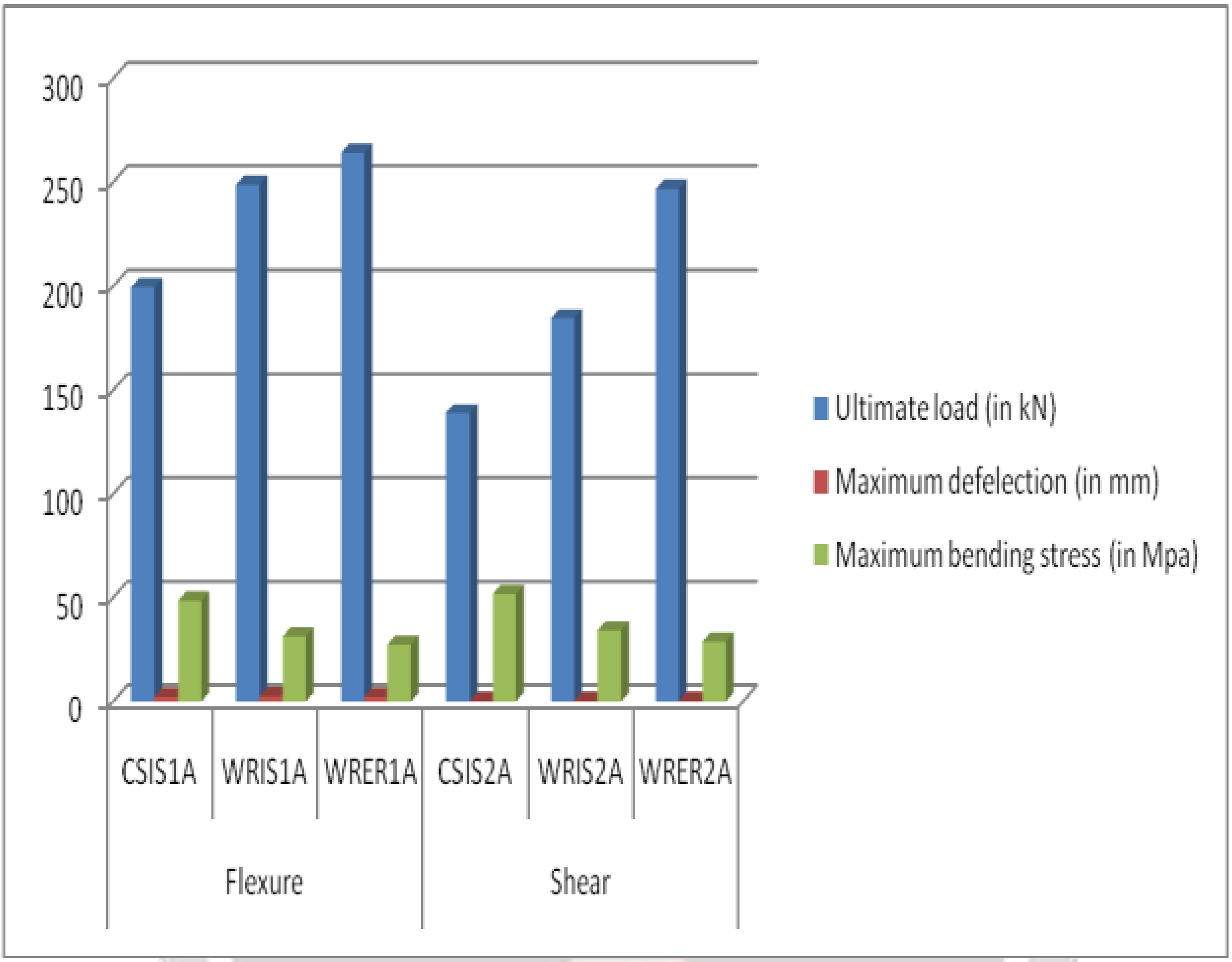
**Deflected shape of the GFRP bridge deck panel (WRIS2A and WRIS1A)**



**Deflection contour of the GFRP bridge deck panel (WRIS2A and WRIS1A)**



The experimental observations are mainly included the measurement of deflections which will indirectly indicates the strength / stiffness of the member The best cross section is arrived at based on the mathematical model of GFRP bridge deck developed by using ANSYS. Since bending stress is low, the deflection is considered as a parameter for further studies.




**CONCLUSION**

A comprehensive outcome of the investigations carried out for static and fatigue behaviour multicellular GFRP composite bridge deck panels under IRC wheel loads is presented in this dissertation. The objectives have been directed primarily towards the study of the following aspects;

**FUTURE SCOPE**

Although the work presented in the dissertation is extensive, still some more studies are to be done in this area for further understanding. The possible research investigations are given below:   Stress versus number of cycles to failure (S-N curve) could be developed for GFRP bridge deck panel Durability studies could be conducted on GFRP specimens at different scales and ages Real time monitoring could be conducted to demonstrate the efficacy of the methodologies developed Appropriate codal provisions are to be brought out to the material/structural/construction engineering community

**REFERENCES:**


- Albert F. Daly and John R. Cuninghame, “Performance of fibre-reinforced polymer bridge deck under dynamic wheel loading”, composites: part A, Vol.37, pp.1180-1188, 2006.
- Aixi Zhou, Jason, T.C., Anthony, B. T., John, J. L. and Thomas E.C.,“Laboratory and field performance of cellular fibre reinforced polymer composite bridge deck systems”, Journal of composites for construction, Vol.9, No.5, pp.458-467, 2005.
- Aixi Zhou and Thomas Keller, “Joining techniques for fibre reinforced polymer composite bridge deck systems”, Composite Structures, Vol.69, No.3, pp.336-345, 2005.
- American Concrete Institute Committee, “State-of-the-Art Report on Fibre Reinforced Plastic Reinforcement for Concrete Structures”, Vol.440, 1996.
- Amjad J. Aref, “Hybrid Fibre Reinforced Polymer concrete bridge deck systems”, A thesis report, 2009.
- ANSYS, “ANSYS release 13.0 Documentations”, Version 13.0, Swan analysis system, Inc. 2012.
- Aref, A.J. and Alampalli, S., “Vibration Characteristics Of A Fibre-Reinforced Polymer Bridge Superstructure”, Composite Structures, Vol.52, pp.467-474, 2001.
- Aref, A.J. and Parsons, I.D., “Design Optimisation Procedures For Fibre Reinforced Plastic Bridges”, Journal of Engineering Mechanics, Vol.125, No.9, pp.1040-1047, 1999.
- Atsuhiko Machida and Kyuichi Maruyama, “Design code development for fibre-reinforced polymer structures and repairs”, Progress in structural Engineering and Materials, Vol.4, No.2, pp.145-160, 2002.
- Barbero, E. J. and Lonetti, P., “Damage Model for Composites Defined in Terms of Available Data”, Mechanics of Composite Materials and Structures, Vol.8, No.4, pp.299-316, 2001.
- Bisby Luke, A., Green Mark, F. and Kodur Venkatesh, K.R., “ Response to fire of concrete structures that incorporate Fibre Reinforced Polymer”, Progress in structural Engineering and Materials, Vol.7, No.3, pp.136-149, 2005.
- Bjorn Taljsten, “Fibre Reinforced Polymer strengthening of concrete Structures: new inventions and Applications”, Progress in structural Engineering and materials, Vol.6, No.3, pp.162-172, 2004.
- Bouguerra, E.A., Ahmed, S., El-Gamal, B. and Benmokrane, “Testing of full-scale concrete bridge deck slabs reinforced with fibre-reinforced polymer bars”, Construction and Building Materials, Vol.25, No.10, pp.3956-3965, 2011.
- Burgueno, R., Karbhari, V. M., Frieder, S. and Kolozs, R. T., “Experimental Dynamic Characterisation Of An FRP Composite Bridge Superstructure Assembly”, Composite Structures, Vol.54, pp.427-444, 2001.
- El-Hacha, R., Wight, R. G. and Green, M. F., “Prestressed fibre-reinforced polymer laminates for strengthening structures”, Progress in Structural Engineering and Materials, Vol.3, No.2, pp.111-125, 2001.
- Federal Highway Administration (FHWA), “FRP decks and superstructures: current practice”, 2002.
- Ghosh, Kumar, Karbhari and Vistap M., “Evaluation of strengthening through laboratory testing of FRP rehabilitated bridge decks after in-service loading”, Composite Structures, Vol. 77, No.2, pp.206-222, 2007.
- Gilbert Nkurunziza, Ahmed S. Debaiky, Patrice Cousin and Brahim Benmokrane, “Durability of GFRP Bars – A Critical Review of The Literature”, Journal of Progress In Structural Engineering and Materials, Vol. 7, No.4, pp.194-206, 2005.
- Hamiliton, H.R. and Dolan, C.W., “Durability of FRP reinforcements for Concrete”. Progress in Structure Engineering Materials, Vol. 2, pp. 139-145, 2000.
- Hammami, A. and Al-Ghulilani, N, “Durability and Environmental degradation of Glass – Vinylester Composites”, Polymer Composites, Vol.25, No.6, pp.609-616, 2004.