CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

The use of FRP as a primary structural material is developing rapidly in the construction industry. FRP materials have considerable advantages in terms of weight, strength and corrosion resistance. They have been used for several decades in the aerospace, automobile and marine industries, where they have developed a good track record in very adverse environmental conditions. However, the ‘product life cycle’ is much longer in civil engineering so uptake has been relatively slow, but FRP has been used in a number of bridges around the world. As production technology develops and design standards and guidelines become more generally available, these FRP materials will be used more widely to provide cost-effective alternatives to steel and concrete. Potential applications for FRP decks are new design, replacement of under-strength decks in existing bridges, and the provision of temporary running surfaces. In new bridge construction (pedestrian and vehicular), the FRP composite materials may be used in the entire structure (All Composite), or they could be used as structural members or components (Hybrid) and in existing structures their uses range from replacement decks, reinforcing rods and tendons to wraps for seismic upgrading of columns.

Composite fibre materials have been used since the mid-1980s, predominantly for strengthening purposes. Since the mid-1990s there has been an increase in their use, through pilot projects, in new hybrid and all-
composite constructions. A particularly impressive increase in the use of these materials has been observed since 1996/97 in bridge deck slabs, as reported by Black (2000). In recent years, a number of researchers have investigated the behaviour of FRP decks experimentally and analytically.

These promising materials deserve to achieve more widespread acceptance and applications. To achieve this, extensive literature review is carried out on various aspects related to FRP. The aspects include characterization, preparation of GFRP members, structural performance under static, fatigue and dynamic loadings, fire resistance, durability, analytical studies etc. Brief review on various aspects is summarized below.

2.2 LITERATURE REVIEW

2.2.1 Characterization

Christos (1993) developed a unified set of composite micromechanics equations of simple form to predict unidirectional composite (ply) mechanical properties using constituent material (fibre/matrix) properties. Using those set of micromechanics equations, it is possible to generate all the ply material properties needed for inputs to the structural analysis of composite structures.

Srivastava (1999) investigated the effects of water immersion on mechanical properties such as flexural strength; Inter-laminar shear strength and impact energy of aluminium tri-hydrate and polyethylene filled and unfilled quasi-isotropic glass fibre reinforced epoxy vinylester resin composites (GFRP). Inter-laminar shear strength and flexural strength were obtained with the variation of immersion time (0, 98, 158, 190 and 240 days) and weight percent of filler content (0, 5, 10 and 15). The author has concluded that the flexural strength, Inter-laminar shear strength and impact energy increased with increasing filler content in GFRP composites.
Immersion in water resulted in a significant increase of flexural strength, Inter-laminar shear strength and impact energy, increasing with immersion time. Aluminium tri-hydrate containing GFRP composites have shown higher values of flexural strength, Inter-laminar shear strength and impact energy than those of polyethylene filled and unfilled GFRP composites.

2.2.2 Maintenance, Rehabilitation, Strengthening, Repairs and Durability

Ghosh Karbhari et al (2007) provided details of investigation of strengthening efficiency of FRP rehabilitated bridge deck slabs through tests conducted on slab sections cut from a bridge just prior to demolition. The deck sections (one unstrengthened, and two strengthened using FRP composites) were subjected to routine traffic prior to removal and testing. The authors have concluded that the two rehabilitation schemes resulted in enhancement of capacity of the specimens in conjunction with a better load distribution resulting in the transformation of failure mode from punching shear to more ductile flexural failure. The specimen strengthened with wet layup based fabric strips had a strength enhancement of around 73% and the specimen strengthened with pultruded strips had a strength enhancement of around 59%, as compared to the control specimen.

Bjorn Taljsten (2004) presented a short summary on past and ongoing research in the area of plate bonding and concluded that considerable improvements in flexural behaviour can be achieved by employing innovative techniques such as prestressed NSRM (near surface mounted reinforcement) of rectangular carbon fibre rods and the use of cementitious bonding agents in combination with advanced composite materials.

El-Hacha et al (2001) summarized the strengthening works carried out with prestressed and non-prestressed laminates and concluded that the
serviceability of concrete beams and slabs strengthened with FRP laminates is improved when the laminate is prestressed. Beams strengthened with prestressed FRP laminates were reported to be stronger, and the yielding load is found to be significantly higher than for members strengthened with non-prestressed FRP laminates.

Similar studies on the application of FRP’s for structural repair and rehabilitation techniques column strengthening, beam strengthening using bonded FRP wraps and laminates as well as applications to masonry and other types of structures were carried by Triantafillou (1998), Neale (2000), Lees et al (2001). The techniques for upgrading of metallic structures with FRP composites were explained in detail by Hollaway and Cadei (2002). FRP material overlays or jackets were reported to be extremely effective in increasing the strength, ductility and stiffness of RC, masonry and timber structures.

Triantafillou (2001) reviewed the seismic retrofitting of RC elements and masonry walls by means of FRPs and has concluded that FRP in the form of jackets or overlays can be quite effective and economically viable in seismic retrofit applications. It has been reported that the FRP jackets enhance the shear strength and increase the confinement at plastic hinge or lap splice regions when applied to RC, and the FRP overlays increased the in-plane shear strength, reduced the shear deformations and enhanced the out-of-plane flexural strength considerably when applied to masonry walls.

Alampalli Sreenivas and Kunin (2002) described the replacement of a two lane reinforced concrete bridge superstructure in New York (Bennetts Creek bridge) which was deteriorated significantly by the use of deicing salts, by a FRP bridge superstructure. The superstructure was fabricated by VARTM from an E-glass stitched bonded fabric and vinyl ester resin and used a cell core system. It was designed for standard AASHTO loadings using
a FEA method. Proof load tests with HS25 truck loading was conducted with
the trucks placed at pre-marked positions on the bridge to maximize bending
moment. The maximum strain recorded was considerably less than the strain
expected as per analysis thereby indicating a higher load capacity. The
maximum deflection at mid-span was found to be less than 3.5 mm, which is
considerably less than the Span (L)/800 design limitation of 8.8 mm. The time
taken from closing of the deteriorated bridge to opening the new bridge was
about six months. Based on this the authors have concluded that the fibre-
reinforced polymers can be a cost- and time-effective alternative for replacing
short-span concrete slab bridges.

Harries and Moses (2007) studied the implication of RC to GFRP
deck replacement on superstructure stresses and concluded that GFRP decks
behave in a fundamentally different manner than RC decks and that the
substructure forces will be uniformly reduced due to the lighter resulting
superstructure. GFRP decks exhibited reduced composite behaviour and
reduced transverse distribution of forces as compared to comparable RC
decks, thereby offsetting the beneficial effects of a lighter deck structure and
resulting in increased internal stresses in the supporting girders.

Chiewanichakorn et al (2006) studied the behaviour of a truss
bridge, where an FRP deck replaced an old deteriorated concrete deck
experimentally and validated through finite element models. Finite element
model of the Bentley Creek Bridge was developed using the pre-processor
package, MSC PATRAN and the analysis was performed using the general
purpose FEA package, ABAQUS to determine fatigue life of the bridge when
subjected to dynamic loading caused by AASHTO fatigue live load. Fatigue
life of all truss members, floor-beams and stringers were determined based on
a fatigue resistance formula in the AASHTO-LRFD design specifications.
The numerical results agreed well with experimental results. The results have
shown that fatigue life of FRP deck system almost doubled when compared with the reinforced concrete deck system.

Soudki (1998) presented a state-of-the-art review on the use of fibre-reinforced polymer (FRP) reinforcement in prestressed concrete. A brief introduction to FRP composite materials was given followed by an overview of recent research work on various aspects of FRP prestressed concrete structural members. Concepts for analysis and design of members prestressed with FRP tendons were discussed and field demonstrations utilizing FRP prestressing reinforcement, were also presented.

Gilbert Nkurunziza et al (2005) provided details of the durability tests conducted by the authors and others on the latest generation of GFRP bars subjected to stresses higher than the design limits, combined with aggressive mediums at elevated temperatures, and have concluded that the strength reduction factors adopted by current codes and guidelines are conservative.

Atsuhiko Machida and Kyuichi Maruyana (2002) discussed the issues and solutions in developing design codes and standards for the use of fibre-reinforced polymer (FRP)-reinforced concrete structures and have compared different codes developed for strengthening of concrete structures with FRP. Methods of structural analysis; determination of design values; examination of flexural and shear capacity; precautions to ensure ductility or deformability; and calculations of deformation and development length have been presented. Authors concluded that all the three codes, JSCE, ACI and fib, use the same concept and adopt limit state philosophy, but differ in their exact expressions for calculating the respective strengths.

Thomas Keller et al (2006) studied the structural response of liquid-cooled multicellular GFRP slabs subjected to fire by comparing the results
from the numerical coupled thermo-mechanical models created using ANSYS multi-physics to the experimental results from large scale fire tests on loaded FRP slabs and concluded that the range of models developed are sufficient for the structural design of liquid-cooled FRP slab components with consideration of pre-fire, high-temperature, and damaged post-fire conditions. The agreement between predictions and experimental results has been reported to be good in most respects, with models usually producing slightly conservative predictions.

Kawada and Kobiki (2005) described the characteristics of a stress-corrosion crack in glass fibre reinforced plastics (GFRP) as a part of the study on long-term durability of polymer-matrix composites in hostile environments. Fragmentation tests were conducted on ECR-glass/vinylester and an E-glass/vinylester to investigate the degradation mechanism using a single fibre composite. Effects of environmental solution diffusion into a matrix on interfacial shear strength were also evaluated with immersion time. The maximum interfacial shear strength was observed to be influenced by matrix Young’s modulus. It was observed that the interfacial shear strength decreased as a function of the water absorption rate and it depended on the mechanical degradation of the matrix, and the interfacial shear strain decreased with time under the constant strain condition.

Bisby et al (2005) presented a review of the research conducted to investigate the fire performance of FRP materials for infrastructure applications. Details were also provided on the investigation to assess the performance of FRP-strengthened reinforced concrete slabs, beams, and columns in fire. It was mentioned that the FRP strengthened concrete structures can be protected to provide sufficient fire endurance and satisfactory fire performance for these members can be ensured, provided they are appropriately designed and adequately insulated.
Hamilton and Dolan (2000) carried out durability studies on FRP reinforcements for concrete and concluded that the normal environmental temperature domains of civil engineering structures, including freeze-thaw exposure, short-term exposure to salt water, alkali attack at low stress levels do not affect the bonded FRP response. It was suggested that coatings or fillers can be used to limit UV and ozone attack.

Hammami and Al-Ghuliani (2004) elucidated the evaluation of the durability and environmental degradation of glass fibre-reinforced composites based on vinylester resin when exposed to harsh climatic conditions, seawater and corrosive fluids. It was concluded that relatively high fibre content prevents the matrix from fully impregnating the fibre resulting in micro cracks and reduction in Inter-laminar shear strength when exposed to seawater, matrix expansion and occurrence of pits when exposed to water and corrosive fluids, and degradation at higher temperatures.

2.2.3 Analytical and Numerical Studies

Pisani and Marco (1998) performed a numerical investigation on the behaviour of beams pre-stressed with GFRP. The numerical method was checked by simulating the behaviour of 21 experimental tests. The same analyses were then repeated after changing the type of pre-stressing bonded, unbounded, internal, and external and the type of cable steel, GFRP. The conclusion based on the work is that GFRP or Aramid FRP tendons can satisfactorily replace steel strands to pre-stress beams placed in an unfavourable environment. GFRP cables were found to be reliable when dealing with external pre-stressing, while AFRP cables are suitable in bonded pre-stressing.

Hyeong-Yeol Kim et al (2003) proposed a modified Genetic Algorithm (GA) based process for the optimal design of GFRP bridge deck
having a pultruded cellular cross-section and surmised that the developed algorithm is capable of optimizing the structure and material for GFRP deck system simultaneously. The results of the optimization indicated that trapezoidal cross-section is an optimum shape for GFRP deck. The stiffness of deck was identified as a critical parameter for the design. The results of sensitivity analysis indicated that the geometrical design variables are more sensitive than those of materials and that the deflection profile was greatly influenced by the thickness of flanges, while the local buckling load was sensitive for the dimension of the web.

Aref and Parsons (1999) developed a simplified optimization procedure for a novel fibre reinforced plastic bridge system. The objective function considered in the study is the minimization of the weight of the bridge and constraint is that the vertical deflection should be less than L/800 as imposed by AASHTO. The design variables are the thickness of the plies. The bridge system has been modeled using a homogeneous, anisotropic Kirchoff plate that has the same global stiffness characteristics of the bridge system. Only the stiffness of the bridge has been considered during the design process as FRP design is usually governed by stiffness. The anisotropic plate has been discretized using the Ritz method. This provided a structural model that has been incorporated into a stiffness-based optimisation algorithm using the optimality criteria method. The authors have demonstrated the optimisation procedure by developing the solution for an 18.29-m long two-lane highway bridge and comparing the result with a detailed finite-element analysis. The resulting procedure has been reported to provide a useful design tool that can be used to produce a minimum weight design without resorting to finite-element analysis.

Amjad et al (2005) 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. The authors have suggested that a parametric study has to be conducted with different span lengths, different cross sectional heights, and so on, in order to generalize the result, as the result obtained in this study can be applied only to the particular hybrid bridge designed.

Sreenivas Alampalli (2005) 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). The shear stress failures at the interface of web-to-top or web-to-bottom surface do not occur prior other failure mechanisms and the deck has significant safety factor to resist shear failure, as reported by the authors.

Yin Zhang et al (2006) performed detailed finite element analyses to investigate the load distribution and the dynamic response of FRP deck bridges and compared the response of FRP deck and concrete deck bridges. It was concluded that the bridge deck types have seriously affected both load
distribution and dynamic response and that the lateral distribution factor values of FRP deck bridges are larger than those of concrete deck bridges. The dynamic response of FRP deck bridges was also noted to be larger than that of the concrete deck bridges. Authors observed the different dynamic performances between the FRP and concrete deck bridges and suggested that instead of imposing the same deflection requirement as conventional bridges (L/800), different serviceability control criteria by loosening the deflection requirement may be adopted for FRP deck bridges, as the design of FRP deck bridges is usually controlled by deflection requirements.

Upadyay and Kalyanaraman (2003) 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.

2.2.4 Experimental and Analytical Studies

Alagusundaramoorthy and Reddy (2008) 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.

Hyeong-Yeol Kim et al (2003) proposed an analysis and design procedure for a pultruded GFRP deck composed of unidirectional E-glass roving, continuous strand mat, woven fabric, and vinylester, and also have explained shear pocket confinement method of deck-to-girder connection. To assess the material properties, material tests were performed on the coupon specimens that were cut from the pultruded plates. Decks having thin-walled
rectangular, triangular and trapezoidal cross sections were analyzed to design a viable cross-sectional profile of the deck. A simply supported beam subjected to single wheel load (DB24 truck load 1.3 times heavier than AASHTO's HS20 truck load) at centre was considered to assess the structural characteristics of the deck profiles based on the deflection limit of L/800. Ultimate safety factor of five and a safety factor of two against local buckling provided in the FHWA's Advisory were employed. The results indicated that, overall, the deck profile having a rectangular-shaped cellular profile gave favorable structural performance than others.

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.

Salim et al (1997) proposed a new design concept for short span FRP composite deck and stringer bridges, based on a first order shear deformation macro-flexibility (SDMF) orthotropic plate solution. Experimental studies were also carried out to obtain the stiffness coefficients. The FRP decks considered consisted of contiguous thin-walled box sections which were fabricated by bonding side by side pultruded thin walled box beams which were placed transversely over FRP composite stringers. It was concluded that the experimental and analytical results presented in the study
can assist in the development of efficient FRP sections and simplified equations for new and replacement highway bridge decks.

Zureick (1997) examined the previously published works on the analytical and experimental investigations pertaining to the behaviour and design of fibre reinforced polymeric pultruded members and pointed out that though the subject was exploited to some degree, reliable design criteria are still absent and that there is a need to understand the experimental behaviour and to develop predictive analytical tools that incorporate the anisotropic, heterogeneous character of the material, and the poorly characterized load and environmental conditions.

Pizhong Qiao et al (2000) presented a systematic approach for analysis and design of all FRP deck/stringer bridges. This design approach included the analyses of ply (micromechanics), panel (macromechanics), beam or stringer (mechanics of laminated beam), deck (elastic equivalence model), and finally combined deck/ stringer system (series approximation technique). The actual deck fabricated by bonding box beams side-by-side has been experimentally tested and analyzed by a finite element model developed using NISA software package, to verify the accuracy of orthotropic material properties. It was concluded that this design analysis approach can be efficiently used to design bridge systems and also to develop new design concepts for single-span FRP deck/stringer bridges.

Barbero and Lonetti (2001) developed a model to predict stiffness reduction and stress redistribution due to damage of laminated polymer composites. Classical lamination theory was generalized for the case of a continuously damaging material using concepts from continuous damage mechanics. The damage model was validated with experimental results for various laminates built with aramid/epoxy, T300/5208, and T300/914 carbon/epoxy. It was concluded that the model has the potential to be a useful
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.

Burgueno et al (2001) conducted dynamic tests on large scale FRP composite bridge superstructure systems. The superstructure consisted of concrete filled filament wound circular carbon/epoxy girders and an E-glass/polyester deck as the representative of a bridge section. Authors assessed the global and local response of the system under dynamic loading and concluded that the results obtained from the plane-grillage finite element model correlated well with the experimental results for mode shapes and frequencies.

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 (2005) 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 (2006) 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 composite 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.

Reddy and Alagusundaramoorthy (2006) 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 up to 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 (2004) 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. It was summarized from the studies that the design of bridge deck using pultruded glass and carbon FRP tubes met with the necessary strength and deflection design criteria as defined in the AASHTO specifications and installed the bridge in the University of Missouri campus.

Amjad Aref et al (2005) studied the structural behaviour of a sandwich type GFRP (E-Glass and Vinylester) web core two-lane skew bridge superstructure, simply supported with 7.807m span, 10.071m wide and a 30° skew angle, using the Finite Element packages MSC PATRAN and ABAQUS, and validated the results by field testing (Load tests). The comparisons of the field testing and numerical simulation results have shown a good agreement. Based on the results the authors have concluded that FEA is a feasible and robust tool, having excellent accuracy to simulate the structural behaviour of GFRP bridge deck, and have suggested that it can be used to study the load-carrying capacity and failure modes.

Carrion et al (2005) developed finite element models to represent beam and column test frames comprising box sections connected together with monolithic GFRP cuff connections. Model mechanical properties (both stiffness and strength) for the member and connection composite materials were determined from tests on the composite constituent materials and on composite lamina coupons. Damage was investigated in the models by employing the Tsai-Wu failure criterion. The models were validated with respect to stiffness and strength by comparing to the experimental test frame behaviour. It was mentioned that the frame stiffness and cuff damage patterns are well represented for the case of pultruded fibre reinforced plastic (PFRP)
members connected by GFRP cuff connections of various thicknesses and hence employed the models for the improved design of connections.

Lee et al (2007) presented the experimental characterization of the flexural performance of pultruded GFRP decks under static loading. Several tests were carried on single module and adhesively bonded modules. The specimen details such as dimensions, material properties and fibre architecture are given. Numerical verification was performed by using the general purpose finite element package ABAQUS. Experimental set-up, instrumentation, testing procedure, failure modes and the results of these experiments were discussed in detail.

2.2.5 Experimental Studies

Moon et al (2009) investigated the fatigue behaviour of the foam-filled GFRP bridge deck in the transverse direction which is an intermediate type between the modular type deck and the sandwich type. Four different types of the specimens were prepared and tested with different stress ratios. The failure mode and the change in stiffness by the foam inside the deck were reported. The role of the foam was very clear. It was observed that it reduced the damage accumulation in the web-flange joint efficiently. Compared to the reference case which was not filled, the endurance of limit of the foam-filled deck was remarkably increased.

Albert Daly and John Cuninghame (2006) carried out full scale static and fatigue tests to study the performance of GFRP cellular decks under local wheel loads on a 4 m span model bridge and concluded that FRP components can provide a robust bridge solution complying with the general requirements of the UK design code, capable of resisting local wheel loads due to heavy vehicles for at least 30 - 40 years without structural damage. Authors mentioned that measurement of surface strain is not a satisfactory
method of characterizing the strength of FRP panels under high test loads. Based on the results obtained, the authors suggested that a simple test simulating a single wheel load will be sufficient.

Thomas Keller and Herbert Gurtler (2005) described the quasi-static and fatigue performance of hybrid bridge girders composed of cellular FRP bridge decks and steel girders. The FRP bridge deck was connected adhesively to the steel girders and acted as the top chord of the hybrid section. Composite action between FRP bridge decks and steel girders increased the stiffness and the deflections of hybrid girders reduced considerably. The adhesive bond between the FRP bridge deck and steel girders was reported to have behaved well under quasi-static and fatigue loading. The bond did not fail and showed no damage after 10 million fatigue cycles. An overall ductile failure mode of the hybrid girder system has been achieved. The authors have commented that the serviceability limit state governs the design of adhesively bonded hybrid FRP-steel girders and so have suggested that the established design methods for steel-concrete composite bridges with a few modifications can be used.

Aixi Zhou and Thomas Kellar (2005) studied the laboratory and field performance of multicellular fibre-reinforced polymer FRP composite bridge deck systems produced from adhesively bonded pultrusions. Two methods of deck contact loading were examined: a steel patch dimensioned according to the AASHTO Bridge Design Specifications, and a simulated tyre patch constructed from an actual truck tyre reinforced with silicon rubber. The results from both laboratory and field tests indicated that the unsupported edges are prone to failure and, therefore, not recommended for practical design and construction. The failure mode was localized and dominated by transverse bending failure of the composites under the simulated tyre loading as opposed to punching shear for the AASHTO recommended patch load. It
was concluded that the FRP decks made from adhesively bonded pultrusions are viable for highway bridge deck structures.

Reddy and Alagusundaramoorthy (2006) examined the behaviour of GFRP composite highway bridge deck panels under fatigue loading. Two multicellular prototype GFRP composite bridge deck panel of 3000mm length, 1000mm width, 300mm depth was fabricated using contact moulding process. Fatigue load ranging from 10kN to 83kN and 83kN to 400kN were applied at a frequency 1Hz for 2 million fatigue cycles. The reduction in stiffness of bridge deck panels after completion of 2 million fatigue cycles was found to be 7% and 14% under fatigue load ranges of 10kN to 83kN and 83kN to 400kN.

Susumu Kumagai et al (2005) carried out an experimental study on the fatigue damage behaviour of GFRP woven laminates in terms of stiffness degradation and residual strength under cyclic loading at low temperatures (around 10°C). Uniaxial, load-controlled, tension-tension fatigue tests were conducted at room and low temperatures. The applied stress versus cycles to failure (S-N) relationships and fatigue limits were obtained for the GFRP woven laminates and the micro crack evolution due to fatigue loading was characterized using optical microscopy. Temperatures were also measured using a thermocouple embedded in the center of the specimens. The conclusions based on the study were that the observed S-N diagrams showed the decrease in fatigue life with increase in fatigue stress and that the primary damage mechanism at low temperature was micro cracks in transverse fibre bundles.

Suzuki et al (2000) employed an advanced acoustic emission analysis method to study the dynamics and sequence of micro fractures in uni-directional glass fibre reinforced plastics. GFRPs (with 60 % fibre) with different interfacial qualities were prepared by adding a small amount (4 or
8 wt %) of paraffin wax into vinylester matrix without affecting much the mechanical properties of the matrix. The orientation dependence of both the P-wave velocity and attenuation were accurately measured by the laser ultrasonic method, and incorporated into the acoustic emission analysis of visco-elastic media. The P-wave velocity and attenuation were not significantly changed by wax addition, but have shown strong orientation dependence. The authors have reported that three fracture modes namely fibre and matrix fracture, fibre debonding and fibre disbonding were observed. For the GFRP without wax, the fibre fracture occurred prior to another fracture types at low load, but the fibre debonding preceded the fibre fracture for GFRP with the addition of wax.

Aixi Zhou and Thomas Keller (2005) discussed the design requirements, characteristics, performance, advantages and disadvantages of developed FRP deck connection techniques and provided design principles for adhesively bonded joints and also for mechanical fixing and hybrid joints involving cutouts. Composite action, structural redundancy and system ductile characteristic were described as the main objectives when designing hybrid or adhesive-bonded FRP deck-support connections for bridge superstructures. The mechanical techniques for connecting FRP deck panels were found to vary according to the levels of joining. It was noted that in the component level, adhesive bonding is the most efficient way and because of their advantages, adhesive bonding and hybrid joining are promising connecting techniques for system level connections.

Turvey (2000) carried out a detailed overview of the testing that was undertaken on two principal types of bolted connection i.e., axially loaded and moment connections between PFRP sections. The limited guidance on the design/analysis of these two types of connection was briefly
reviewed. Some types of connection testing required in the future was suggested. Some of the issues which may impact on these tests were also mentioned.

Hollaway and Cadei (2002) estimated the cost savings over steel, when fibre reinforced composites are used for rehabilitation works. It was mentioned that though the fibre composites are 4 to 20 times as expensive as steel in terms of unit volume, cost savings of the order of 17.5% can be achieved compared with steel, when FRP material is used, and installation costs and traffic management costs are included. Two kg of FRP material was reported to replace 47 kg steel on an equal strength basis.

Nicolas and Liu (2011) carried out experiments to increase the stiffness of a commercial GFRP honeycomb sandwich panel through the inclusion of steel within the cross section. GFRP-steel hybrid parametric studies were conducted to evaluate improvements on the GFRP honeycomb deck panel stiffness. Possible configurations included the embedment of steel plates within the face sheets and the placement of steel tubes within the core. Core stiffness analyses were also performed, leading to the development of the steel hexagonal honeycomb core concept. An experimental study, including large-scale beam tests, was conducted. The large-scale tests were performed to assess the equivalent flexural and shear stiffness, comparing the hybrid steel core concept and the current GFRP core design. From the large-scale beam test results, an overall stiffness increase was observed.

Bouguerra et al (2011) presented an experimental study by investigating the behaviour of FRP-reinforced concrete bridge deck slabs under concentrated loads. A total of eight full-scale deck slabs measuring 3000-mm long by 2500-mm wide were constructed. The test parameters were: (i) slab thickness (200, 175 and 150 mm); (ii) concrete compressive strength (35 - 65 MPa); (iii) bottom transverse reinforcement ratio (1.2-0.35%); and
(iv) type of reinforcement (GFRP, carbon Fibre reinforced Polymer (CFRP), and steel). The slabs were supported on two parallel steel girders and were tested up to failure under monotonic single concentrated load acting on the center of each slab over a contact area of 600 x 250 mm to simulate the footprint of sustained truck wheel load (87.5 kN CL-625 truck). All deck slabs failed in punching shear. The punching capacity of the tested deck slabs ranged from 1.74 to 3.52 times the factored load (Pf) specified by the Canadian Highway Bridge Design Code (CHBDC) CAN/CSA S6-06. Besides, the ACI 440.1R-06 punching strength equation greatly underestimated the capacity of the tested slabs with an average experimental-to-predicted punching capacity ratio (Vexp/Vpred) of 3.17.

Zi et al (2008) investigated the static behaviour of an orthotropic bridge deck made of GFRP and polyurethane foam experimentally. The bridge deck consisted of GFRP unit modules with rectangular holes filled with foam to improve the structural behaviour in the transverse direction. It was found that the structural behaviours in the transverse direction such as the nominal strength, stiffness, etc. were greatly improved when the GFRP bridge deck was filled with foam. Because of the low mass density of the foam used in this study, the bridge deck was still light enough while the structural properties were improved significantly. The longitudinal response of the GFRP deck was improved with the foam. The strength was increased about 20% but the elastic modulus was not improved.

2.3 OBSERVATIONS FROM LITERATURE REVIEW AND NEED FOR THE PRESENT INVESTIGATION

Based on above literature review on various aspects related to GFRP, the following observations are made.
FRP composite deck panels are effectively used in the construction of offshore structures such as pontoons, floating docks, oil drilling platforms, ocean thermal energy conversion systems and harbour structures due to their excellent corrosion and fatigue resistance, high strength to weight ratio and stiffness to weight ratio and less maintenance cost.

Bridge decks made of FRP are beneficial for maintenance purposes and ease of the replacement of the deck to accommodate any increased traffic demand.

The reason for use of GFRP is its low self-weight in comparison of strength and stiffness and high resistance against weather influenced degradation resulting in long life. Using GFRP for the construction of the bridge deck leads to lightweight construction that can pass the required wheel load. Lightweight design is appreciated for temporary bridge which is expected to be transported and assembled often on places of current need. Long durability and resistance against weather degradation also reduces maintenance costs of bridge deck. Design of deck panel will be done on the base of loading experiments and FEM analysis. The main use of GFRP bridge deck panel is for temporary bridge but it is possible to extend its use on permanent or movable bridges.

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.

It was believed that there is merit in combining durable FRP decks with stiffer conventional bridge girders.
Furthermore, parametric studies in experimental procedures are time consuming and prohibitively expensive. Computer simulations based on advanced methods, such as the finite element method (FEM), are reliable and cost effective alternatives in structural analysis for the study of structural response and performance. FEM procedures have been successfully employed in research studying the performance of FRP bridge decks or their components.

There is a need to evaluate the long-term structural behaviour and durability of FRP deck systems in order to obtain comprehensive data for preparing the future design, manufacturing and construction materials.

GFRP bridge decks do not have to be solid sections. They are fabricated in the form of thin walled structures with empty space inside.

Response to thermal change is slightly different than for concrete and steel and requires special consideration when an FRP deck is used on a concrete or steel superstructure or when FRP is used for a superstructure.

FRP material properties like strength and stiffness naturally degrade over time. The resultant tendency to creep must be addressed in the design. Appropriate strength reduction factors need to be used to ensure adequate stiffness over the entire service life of the structure.

In literature, it is observed that only few researchers made an attempt to study the static and fatigue behaviour of pultruded multicellular FRP composite bridge deck panels. The major concern for the construction industry all over the world is the cost of pultruded bridge deck systems is
approximately five times the cost of hand lay-up bridge deck systems. It can be noted that the cost of multicellular hand lay-up FRP composite bridge deck systems is cheaper than the bridge deck systems manufactured by other processes. Further, it is observed that the research investigations carried out on hand lay-up FRP composite bridge decks under static and fatigue behaviour of prototype decks are scanty. In view of this, it is necessary to fabricate and test multicellular hand lay-up FRP composite bridge deck systems under static and fatigue loading. This motivated the study on the behaviour of FRP composite bridge deck systems made up of hand lay-up process.

2.4 OBJECTIVES OF THE PRESENT INVESTIGATION

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

vi) FEA of Three Dimensional GFRP composite bridge deck panels using general purpose finite element software.
vii) Comparison of the analytical results with the experimental observations

viii) Study of fatigue behaviour of GFRP composite bridge deck panels upto 500,000 cycles (At a rate of 100 vehicles during the peak hour) under flexural loading

ix) Formulation of guidelines for the design of GFRP composite bridge decks

2.5 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.