Experimental studies on multicellular GFRP bridge deck panels under static and fatigue loading

M P MUTHURAJ and K NITHYAPRIYA*

Department of Civil Engineering, Coimbatore Institute of Technology, Coimbatore 641 014, India
e-mail: m_p_muthuraj@rediffmail.com; nithyapriya83@gmail.com; priya8082000@gmail.com

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Abstract. This paper presents the experimental investigations carried out on hand lay-up prototype multicellular glass fibre reinforced polymer (GFRP) composite bridge deck panels under static and fatigue loading. Various sustainability aspects with regard to GFRP structural members were discussed. The aspects include (i) social development; (ii) environmental protection; and (iii) economic development. The GFRP material properties were evaluated by using (i) micromechanics; (ii) simplified composite micromechanics equations (Chamis); (iii) carpet plots; and (iv) equations proposed by Tsai–Hahn. GFRP members with various cross sections were tested to decide the better performance under flexural loading and found that GFRP with hollow section performs better. For the optimised cross-section dimensions, six multi-cellular GFRP composite bridge deck panels of size 1250 mm × 333 mm × 150 mm ($l \times b \times d$) were fabricated by hand lay-up process and tested for static and fatigue loading. It was observed from the experiment that during testing the bridge deck panel, no load shedding was observed even though the resin started cracking. At ultimate load, there was a loud cracking sound and the specimen load shedding occurred suddenly. Factor of safety for load and deflection was computed. From the fatigue experiments, it is observed that the percentage reduction in stiffness is approximately 12% for 500,000 cycles.

Keywords. Glass fibre reinforced polymer; bridge deck panel; static loading; fatigue loading; deflection; sustainability.

1. Introduction

Bridges are very important components of infrastructure development of a nation and are composed of several components such as decking slabs, girders, trusses, bearings, abutments and piers. Bridge deck is a structural component that distributes and transmits the live loads to the girders and then to the substructure of a bridge. The bridge decks require maximum maintenance because of corrosion and deterioration. Conventional materials and technologies, although suitable for bridge deck applications, lack in durability and fatigue for demanding applications, and in some cases are susceptible to rapid deterioration. 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. 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. 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. Due to low elastic modulus of GFRP materials, GFRP-reinforced sections exhibit higher deformability when compared to equivalent reinforced steel sections. Hence, the deflection criterion governs the design of intermediate and long spanning sections reinforced with GFRP bars [1–4]. Investigations on FRP bridge decks were conducted through laboratory tests on FRP deck components and field tests on FRP bridges [5, 6]. Alagusundaramoorthy and VeeraSudarsana Reddy [7] investigated the load–deflection behaviour of GFRP composite deck panels under static loading. Vovesný and Rottera [8] carried out analysis and design of a new bridge deck panel made of GFRP. Zhu and Lopez [9] presented results obtained from experimental and analytical study of a newly developed lightweight composite bridge deck system composed of pultruded trapezoidal GFRP tubes and outer wrap. From the analytical model, it was found that shear deformation must be considered for the accurate prediction of GFRP panels. Mara *et al* [10] examined the efficiency of GFRP system with

*For correspondence

traditional system and found that FRP decks contribute to potential cost savings over the life cycle of bridges and a reduced environmental impact. Ascione *et al* [11] presented experimental results on the mechanical performance of composite beams obtained by bonding GFRP rectangular pultruded panels by means of an epoxy structural adhesive. No significant loss of performance in terms of failure load is observed, but an increase of pre-failure stiffness was observed.

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. Brief description has been provided on sustainability of GFRP bridge deck panels. The main scope of the present investigation is to study the experimental behaviour of hand lay-up multi-cellular GFRP composite bridge deck panels under static and fatigue loading.

2. Sustainability of GFRP structural members

The sustainability of FRP bridge deck panel is an important aspect. Although the initial cost of FRP deck is more, its sustainability is to be addressed by considering the advantages: lifetime cost, impact on the environment and society. Limited studies were conducted to verify the cost-efficiency and sustainability with reference to conventional bridge concepts. The widely used definition of sustainable development is that the ability to make sustainable development to satisfy the present needs without compromising the needs of the future. In general, the conventional design and construction of structures consider the cost, structural performance and structural design. Sustainability is related to three interrelated aspects, namely (i) social development; (ii) environmental protection; and (iii) economic development [10].

2.1 Social aspects

Thodesen *et al* [12] mentioned that social impact covers many aspects. Some of the aspects include (i) work-zone safety on site; (ii) user's convenience; and (iii) noise and dust emissions. In view of this, it was mentioned that the application of FRP bridge decks for construction and for rehabilitation of bridges has proved many advantages, namely, ease of handling and lightweight equipment which enhances safety for workers [13–15]. But care should be taken while using epoxy adhesives for deck panel connections. FRP bridge decks offer speedy construction, less delay in traffic during construction and increased safety. During bridge deck installation, vibrations and intensity of noise will reduce and enable fast installation. Dust emissions will be very less as the FRP decks are prefabricated. Though concrete decks are also prefabricated, dust emitted is higher compared to FRP decks.

2.2 Environmental aspects

To avoid negative environmental impact of bridge construction and improve sustainability, the following need to be considered [10]:

- reduce energy consumption;
- reduce emissions to water, air and soil;
- reduce waste generation/recover waste;
- reduce virgin material usage.

Life cycle approach is generally followed to evaluate energy consumption and emissions to water, air and soil. Carbon dioxide emission is one of the important aspects to be considered, as it is one of the causes for global warming. Important sources of energy and carbon dioxide emissions during the lifecycle of a bridge can be identified during the following activities [10].

- material extraction and production;
- transportation of materials/waste/employees during the construction, maintenance and disposal phases;
- on-site activities and equipment use during construction and demolition;
- traffic congestion and detours during construction and maintenance activities;
- possible energy recovery from recycling materials in the disposal phase.

Figure 1 shows the energy consumption of various materials, and it can be noted from figure 1 that FRP decks consume very lower energy as they generally contain glass fibres [16, 17].

Figure 1 also shows that the embodied energy consumption for concrete is less than that of GFRP, but the quantity of GFRP material required for a bridge deck is less than that for a concrete deck, as demonstrated by Daniel [18] and Resins *et al* [19]. Figure 2 reveals that a substantial saving in energy consumption when the bridge superstructure is made of glass fibre polymer materials [19].

Figure 3 clearly shows that the carbon emissions are less in case of FRP deck compared to bridges made of other materials [20].

Waste management is another key component of environmental sustainability. The concept of a waste hierarchy, which is the nucleus of waste minimisation strategies, is defined as follows [10]:

- waste prevention or reduction;
- re-use;
- material recycling;
- energy recovery;
- landfill/disposal.

FRP decks are generally prefabricated by various efficient manufacturing processes with minimal wastage. But re-use of the remaining FRP elements during manufacture or construction is very limited. Recycling of materials is

Figure 1. Energy consumption for production of different materials.

Figure 2. Comparison of energy consumption of a road bridge made up of various materials [19].

Figure 3. Comparison of carbon emissions for various bridges made of different materials [20].

essential for sustainability. Currently, production of FRP decks, which comprise glass fibres and thermosetting polymers, uses 100% virgin materials. It facilitates the minimum use of virgin materials for different products. Further, incineration of composites with energy recovery is a potential sustainable method for FRP waste management. It is mentioned in the literature that (i) incineration of FRP composites is overloading the incineration system due to

high calorific power and toxic emissions and (ii) dealing of FRP waste is in infancy now [10].

2.3 Economic aspects

Economic sustainability of any bridge can be measured only through life cycle cost (LCC) analysis. It was mentioned in the literature that use of FRP decks result in savings of social costs during construction and replacement activities, making FRP bridge decks more economical than concrete decks [21, 22]. Nystrom *et al* [23] demonstrated that FRP decks can thus be cost-effective alternative to conventional concrete decks, particularly for bridges located in urban areas with high traffic density.

3. Materials and methods

Epoxy resins (ERs) and isophthalic resin (ISO) are chosen as resin. Woven roving (WR) and chopped strand mat (CSM) are chosen as matrix for the present study. Table 1 presents the various properties obtained for E-glass fibre, ER and ISO. The properties include modulus of elasticity, volume fraction and Poisson's ratio.

The properties of GFRP composites depend on the properties of material constituents (i.e. reinforcing fibre and matrix) and the corresponding volume fractions. The following available methods were employed to evaluate the material properties of the composite [24].

- micromechanics;
- simplified composite micromechanics equations (Chamis);
- carpet plots;
- equations proposed by Tsai-Hahn.

The methods (i), (ii) and (iii) can be adopted for E-Glass–ISO composites and methods (i), (ii) and (iv) are suitable for E-Glass–ER composites.

3.1 Micromechanics

$$\text{Transverse modulus, } E_T = (E_f E_m) / [(E_m V_f) + (E_f V_m)] \quad (1)$$

$$\text{Longitudinal modulus, } E_L = (E_f V_f) + (E_m V_m) \quad (2)$$

Table 1. Properties of E-glass fibre, ISO and ER.

Properties	E-glass fibre	ISO	ER
Modulus of elasticity, N/mm ²	72,400	3450	5000
Volume fraction, V	33.33%	66.67%	66.67%
Poisson's ratio, ν	0.22	0.33	0.30

Longitudinal Poisson's ratio, $v_{LT} = (V_f v_f) + (V_m v_m)$ (3)

Transverse Poisson's ratio, $v_{TL} = v_{LT} x(E_T/E_L)$ (4)

Shear modulus, $G_{LT} = G_m \{ [(G_f/G_m)(1 + V_f) + V_m] / [(G_f/G_m)V_m + 1 + V_f] \}$
 where $G_m = E_m / [2(1 + v_m)]$
 $G_f = E_f / [2(1 + v_f)]$ (5)

3.2 Simplified composite micromechanics

Transverse modulus, $E_T = (E_f E_m) / [E_f - \sqrt{V_f}(E_f - E_m)]$ (6)

Longitudinal modulus, $E_L = (E_f V_f) + (E_m V_m)$ (7)

Longitudinal Poisson's ratio, $v_{LT} = (V_f v_f) + (V_m v_m)$ (8)

Transverse Poisson's ratio, $v_{TL} = v_{LT} x(E_T/E_L)$ (9)

Shear modulus, $G_{LT} = (G_f G_m) / [G_f - \sqrt{V_f}(G_f - G_m)]$
 where $G_m = E_m / [2(1 + v_m)]$
 $G_f = E_f / [2(1 + v_f)]$ (10)

3.3 Tsai Hahn's equations

Transverse modulus, $E_T = (V_f + \eta_{T1} V_m) E_f E_m / [E_m V_f + \eta_{T1} V_m E_f]$
 $\eta_{T1} = 0.516$ for ER and EGlass (11)

Longitudinal modulus, $E_L = (E_f V_f) + (E_m V_m)$ (12)

Longitudinal Poisson's ratio, $v_{LT} = (V_f v_f) + (V_m v_m)$ (13)

Transverse Poisson's ratio, $v_{TL} = v_{LT} x(E_T/E_L)$ (14)

Shear modulus, $G_{LT} = (V_f + \eta_{T2} V_m) G_f G_m / [G_m V_f + \eta_{T2} V_m G_f]$
 where $G_m = E_m / [2(1 + v_m)]$
 $G_f = E_f / [2(1 + v_f)]$
 $\eta_{T2} = 0.316$ for ER and EGlass (15)

Summary of the properties of the composite calculated by various methods is given in tables 2 and 3.

Preliminary studies were carried out on open and closed sections of GFRP purlins with the primary objective of

Table 2. Material properties of the E-Glass–isophthalic polyester composite.

Property	Micromechanics	Simplified composite micromechanics	Carpet plots (WR)	Carpet plots (CSM)
E_x (GPa)	26.433	26.433	26.71	14.92
E_y (GPa)	5.055	7.664	7.70	14.82
G_{xy} (GPa)	2.44	2.90	3.03	5.29
v_{xy}	0.293	0.293	0.296	0.41
v_{yx}	0.056	0.085	0.085	0.41

Table 3. Material properties of the E-glass–epoxy composite.

Property	Micromechanics	Simplified composite micromechanics	Tsai Hahn's equation
E_x (GPa)	27.467	27.467	27.467
E_y (GPa)	7.250	10.810	6.49
G_{xy} (GPa)	3.44	4.09	4.40
v_{xy}	0.293	0.293	0.293
v_{yx}	0.077	0.115	0.050

assessing the suitability of GFRP as a flexural member. GFRP purlins of the following cross sections were investigated under two-point loading condition. Figure 4 shows the geometrical details of various GFRP cross-section profiles.

- I section
- Channel section
- Angle section
- Hollow rectangular section

The following procedure was adopted for the preparation of GFRP members by hand lay-up method.

- Dimensionally correct moulds capable of replicating the surface finish to the required degree of excellence were used.
- The surface of the mould is first polished, if required, and treated with a suitable mould release agent such as wax and poly vinyl alcohol (PVA) to prevent the moulding resin from sticking to the mould surface.
- A layer of ER is applied directly to the mould surface to form a gel coat of 0.5–2 mm thickness. Gel coats may produce a good surface finish; enhance the durability and corrosion resistance of the moulding by reducing the absorption of water and solvents into the materials during exposure in service.
- On gel-coating the mould, if required, the next stage of the operation is to build up the laminate. This is done by applying a sheet-reinforcing material on to the gel-coated mould surface, then by applying liquid resin by brush and working the resin into the reinforcement to

Figure 4. Various cross-section profiles.

ensure complete infiltration, wetting and expulsion of pockets of air.

- When one layer is applied all over the mould surface, subsequent layers are placed until the required amount of reinforcement is in place.
- The whole assembly is then left until the resin gels at which point overhanging reinforcement is conveniently trimmed off. This can be done with the knife just after gelation but would require more elaborate machine saws or grinders after curing.

Figure 5 shows preparation of GFRP specimens, typical finished profiles and a typical tested specimen.

The members were tested for flexure under two-point loading and the deflections were measured using deflectionometers. The average flexural strength obtained for various GFRP sections are presented in table 4. From table 4, it can be noted that the flexural strength is very high for the case of hollow GFRP section compared to other profiles.

Figure 6 presents typical plots of load–deflection behaviour of various GFRP profiles.

From figure 6, it can be inferred that GFRP flexural member with hollow section resisted for more deflection compared to other profiles. The average modulus of elasticity for GFRP is found to be 27.12 N/mm^2 , and it is far less compared to steel. The experimental results indicated that GFRP material is brittle, and failure is due to sudden cracking, not by yielding like steel. Unit weight of flexural member is found to be 1620.6 kg/m^3 .

Preliminary analysis was carried out on various models created by using general-purpose finite element software ANSYS by applying Indian Road Congress (IRC) class A loading to optimise the cross-sectional profile that can be used for the fabrication of the experimental models.

The optimised cross section consists of a three-cell section with additional stiffeners connecting the web to the top flange (figure 7). The thickness of the top flange, bottom flange and the exterior webs is kept as 60 mm. The thickness of additional stiffeners is kept as 45 mm. The experimental models used in this investigation are a 1:3 scale model of a 3.75 m bridge superstructure. The dimensions of

the prototype and one-third scaled model of the bridge deck panel are given in table 5.

Six multi-cellular GFRP composite bridge deck panels of size $1250 \text{ mm} \times 333 \text{ mm} \times 150 \text{ mm}$ ($l \times b \times d$) were fabricated by hand lay-up process using the following combination of materials.

- E-Glass fibres in the form of CSM and ISO – 2 Numbers
- E-Glass fibres in the form of WR and ISO – 2 Numbers
- E-Glass fibres in the form of WR and ER – 2 Numbers

The following are notations for the six multi-cellular GFRP composite bridge specimens made in laboratory and they are tested as stated:

Flexure	Shear
CSIS1—CSM and ISO	CSIS2—CSM and ISO
WRIS1—WR and ISO	WRIS2—WR and ISO
WRER1—WR and ER	WRER2—WR and ER

Two rectangular patch loads were applied symmetrically over the deck and the maximum deflection under each panel under the factored load is obtained. The static tests of GFRP bridge deck panels were carried out under the simulated wheel load of IRC class A vehicle, with short span hinged condition to obtain the maximum bending moments and bending stresses. The bridge deck panel was loaded from zero to an ultimate load in short span hinged condition to find the flexural strength. The shear capacity of the bridge deck panel was also studied by loading the bridge deck panel up to ultimate load under the long span hinged condition. The details of the experimental set-up, instrumentation, loading pattern and the failure modes are explained as follows.

The overall view of the test set-up is shown in figure 8. The loading frames were connected to the strong test floor. A hydraulic jack was used for applying load. Proving ring of 300 kN capacity was used for loading. Two-point

Figure 5. Preparation of GFRP specimens and behaviour of typical GFRP specimen.

Table 4. Flexural Strength of various sections.

Section	MI	Flexural strength, N/mm ²
Hollow rectangle	89,514.67	279.29
I section	89,002.67	200.25
C section	81,194.67	190.86
Angle section	47,133.24	180.39

loading was applied on the model. The span length (1250 mm) of the bridge deck panel was kept parallel to the primary beam of the loading frame. The simply supported boundary conditions were simulated using the line supports as shown in figure 8.

Deflections were measured at critical locations using LVDT (figure 9). As per IRC, the class A wheel load is 114 kN, and this load is scaled down to 38 kN. The dead load of future wearing surface was calculated. The dynamic allowance factor was taken as 30% of the live load of the wheeled vehicle. Static tests were conducted under a factored load of 50 kN (38 kN wheel load + 11.4 kN – 30% of impact factor (assumed) + 0.6 kN dead load including future wearing surface) applied over the bridge deck panel from zero to factored load of 50 kN and further to ultimate.

The load was increased gradually from zero to a factored load of 50 kN. The deflections were measured at 10 kN intervals, at the mid-span of the GFRP deck panel and at the middle, inner and outer edges of the steel plates using LVDT. Load versus deflection graph was drawn from the measured data. For the GFRP fabricated from CSIS1, the maximum deflection obtained from the experiment is 5.34 mm and is found to occur at the centre of bridge deck. For the GFRP

fabricated from WRIS1, the maximum deflection obtained from the experiment is 7.14 mm and is found to occur at the centre of the bridge deck. For the GFRP fabricated from WRER1, the maximum deflection obtained from the experiment is 6.63 mm and is found to occur at the centre of bridge. The failures for all cases are similar to that of the flexural member failure, since the effect is similar to one-way slab (uniaxial bending) and the aspect ratio is 3.75. For the GFRP fabricated from CSIS2, the maximum deflection obtained from the experiment is 0.361 mm and is found to occur at the centre of steel plate where the load is applied. For the GFRP fabricated from WRIS2, the maximum deflection obtained from the experiment is 0.531 mm and is found to occur at the centre of the steel plate. For the GFRP fabricated from WRER2, the maximum deflection obtained from the experiment is 0.487 mm and is found to occur at the centre of steel plate where the load is applied. The failure is similar to local shear failure of slab, since the aspect ratio is 0.267.

While testing the bridge deck panel, no load shedding was observed even though the resin started cracking. A faint cracking sound was heard due to fracture of the mat fabric inside the cells and also a loud cracking sound was heard when the load reached the ultimate capacity of bridge deck panel with sudden specimen load shedding. The fracture of specimens proves its brittle nature. The rupture of fabric was found at the junctions of the triangular stiffeners (as shown in figure 10) in all the three cells. Other failure patterns can be seen in figures 11 and 12.

After releasing the load, no fabric rupture was seen on the portion of the deck where the patch load was applied. The specimen returned to its original shape as soon as the applied load was released, and it almost looked like an

Figure 6. Typical load versus deflection plots for various GFRP cross sections.

untested specimen. This shows the elastic behaviour of the bridge deck panel. Hence, to avoid brittle failure, a significant safety factor should be introduced in the design of GFRP bridge deck panel.

The factored load-carrying capacity and the ultimate load-carrying capacity for all the three models for both long edge and short edge supported hinge conditions are presented in table 6.

Figure 7. Cross-sectional profile of one-third scaled model.

Table 5. GFRP bridge deck panel dimensions.

Parameter	Prototype (mm)	Model (mm)
Length	3750	1250
Width	1000	333.33
Depth	450	150
Flange and outer web thickness	60	20
Inner web thickness	60	15
Additional stiffeners	45	15

Based on ultimate loads obtained from the experiments, the factor of safety for load can be calculated. For the GFRP bridge deck panel fabricated from CSIS2, ultimate load-carrying capacity of the section is found to be 132.7 kN, which means that it can carry 2.7 times more load than IRC-6 loading. Similarly, for the GFRP bridge deck panel fabricated from WRIS2, the factor of safety for load is 3.5 and for WRER2 combination, the factor of safety is 4.8. The factor of safety obtained for all the three models with respect to ultimate load and deflections are shown in tables 6 and 7, respectively.

From tables 6 and 7, it can be observed that the best model is the one fabricated from WR and ER. Load versus deflection plots for all the cases are found to be linear, elastic and brittle. Similarly, the load versus deflection plots for shear loading are also found to be linear, elastic and

brittle. The nature of failure is typical punching shear failure or sometimes local shear failure.

4. Experiments under fatigue loading

Two GFRP bridge deck panels were tested under constant amplitude fatigue loading. The panel dimensions are same as mentioned in figure 7 and table 5. WR and ER were selected for the fabrication of GFRP composite bridge deck panels. Two rectangular patch loads are applied symmetrically over the deck, and the maximum deflection under each panel under the factored load is obtained. In the case of fatigue loading, the boundary condition is short span hinged and the loading range is 5–50 kN. The minimum load is 5 kN, and the maximum load is 50 kN. The load ratio is 0.1. Deflection is measured at the centre of the

Figure 9. Location of LVDT.

Figure 8. Test set-up of the bridge deck panel.

Figure 10. Failure pattern at the junctions of the triangular stiffeners.

Figure 11. Failure pattern inside the mid-cell of GFRP bridge deck panel (CSMIS1).

Figure 12. Typical failure pattern (rupture of fabric) of GFRP bridge deck panel (WRER1).

Table 6. Factored and ultimate load-carrying capacity.

Models		Factored load-carrying capacity (kN)	Ultimate load-carrying capacity (kN)	Factor of safety for load
Flexure	CSIS1	50	194.8	3.9
	WRIS1	50	235.1	4.7
	WRER1	50	252.6	5.1
Shear	CSIS2	50	132.7	2.7
	WRIS2	50	175.8	3.5
	WRER2	50	238.6	4.8

Table 7. Factor of safety for deflection.

Models		Ultimate deflection, in mm	Deflection for working load in mm	Factor of safety for deflection
Flexure	CSIS1	2.17	0.71	2.04
	WRIS1	2.45	0.74	2.12
	WRER1	2.21	0.56	2.80
Shear	CSIS2	0.31	0.15	2.78
	WRIS2	0.43	0.12	3.53
	WRER2	0.37	0.11	3.74

Table 8. Fatigue test results.

Cycles	Deflection (mm)	
	Panel 1	Panel 2
1	0.297	0.283
10	0.297	0.283
50	0.297	0.283
100	0.297	0.283
500	0.297	0.283
1000	0.297	0.283
5000	0.297	0.283
10,000	0.333	0.312
20,000	0.337	0.323
30,000	0.450	0.428
40,000	0.528	0.516
50,000	0.594	0.583
60,000	0.718	0.683
80,000	0.885	0.823
100,000	0.921	0.846
150,000	0.995	0.948
200,000	1.021	0.993
300,000	1.059	1.010
400,000	1.081	1.020
500,000	1.106	1.060

panel. Table 8 shows the results obtained under fatigue loading. Frequency of loading is 1 Hz. From table 8, it can be noted that the maximum deflection occurs at 500,000

Figure 13. Number of cycles versus average reduction in stiffness.

cycles. Figure 13 presents the average stiffness degradation with respect to number of cycles. From figure 13, it can be noted that reduction in stiffness is linear up to 300,000 cycles, subsequently there is steep increase in reduction of stiffness up to 11.91%. Further, it can be noted that the GFRP bridge deck panel performance under fatigue loading is beyond the low cycle fatigue. However, more experiments are to be carried out under fatigue loading with different magnitudes of constant amplitude loading, load ratios and frequencies to generate S–N curve.

5. Concluding remarks

Experimental investigations were carried out on hand lay-up prototype multi-cellular GFRP composite bridge deck panels under static and fatigue loading. Sustainability aspects with regard to GFRP structural members were discussed in brief. The aspects include (i) social development; (ii) environmental protection; and (iii) economic development. The properties of GFRP composites depend on the properties of material constituents (i.e. reinforcing fibre and matrix) and the corresponding volume fractions. The material properties were evaluated using (i) micromechanics; (ii) simplified composite micromechanics equations (Chamis); (iii) carpet plots; and (iv) equations proposed by Tsai–Hahn. GFRP members with various cross sections were tested to determine better performance under flexural loading and found that GFRP with hollow section performs better. For the optimised cross-section dimensions, six multi-cellular GFRP composite bridge deck panels of size 1250 mm × 333 mm × 150 mm (l × b × d) were fabricated by hand lay-up process and tested for static and fatigue loading. While testing the bridge deck panel, no load shedding was observed even though the resin started cracking. A faint cracking sound was heard due to fracture of the mat fabric inside the cells and also a loud cracking sound was heard as soon as the applied load reached the ultimate capacity of the bridge deck panel and sudden specimen load shedding. Factor of safety for load and deflection is computed. From the fatigue

experiments, it is observed that the percentage reduction in stiffness is approximately 12% for 500,000 cycles.

References

- [1] AASHTO (American Association of State Highway and Transportation Officials) 2000 *Standard specifications for design of highway bridge*. Washington, DC, USA
- [2] ACI-440 2008 Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures, *American Concrete Institute (ACI)*, Committee 440, Michigan, USA
- [3] CAN/CSA-S6-00 2005 Canadian highway bridge design code, *Canadian Standards Association*, Mississauga, ON, Canada, pp. 706
- [4] El-Salakawy E F, Benmokrane B, El-Ragaby A and Nadeau D 2005 Field investigation on the first bridge deck slab reinforced with glass FRP bars constructed in Canada. *J. Compos. Construct.* ASCE 9(6): 470–479
- [5] Shenton H W and Chajes M J 1999 Long-term health monitoring of an advanced polymer composite bridge. In: *Proceedings of the SPIE—The International Society for Optical Engineering* 3671: 143–151
- [6] Turner M K, Harries K A, Petrou M F and Rizos D 2004 In situ structural evaluation of a GFRP bridge deck system. *Compos. Struct.* 65(2): 157–165
- [7] Alagusundaramoorthy P and VeeraSudarsana Reddy R 2008 Testing and evaluation of GFRP composite deck panels. *Ocean Eng.* 35(3–4): 287–293
- [8] Vovesný M and Rottera T 2012 GFRP bridge deck panel. *Proced. Eng.* 40: 492–497
- [9] Zhu J and Lopez M M 2014 Performance of a lightweight GFRP composite bridge deck in positive and negative bending regions. *Compos. Struct.* 113: 108–117
- [10] Valbona Mara, Reza Haghani and Peter Harryson 2014 Bridge decks of fibre reinforced polymer (FRP): a sustainable solution. *Construct. Build. Mater.* 50: 190–199
- [11] Francesco Ascione, Geminiano Mancusi, Saverio Spadea, Marco Lamberti, Frédéric Lebon and Aurélien Maurel-Pantel 2015 On the flexural behaviour of GFRP beams obtained by bonding simple panels: an experimental investigation. *Compos. Struct.* 131: 55–65
- [12] Thodesen C C, Krigsvoll G, Nilssen K and Bridget O Brien Thodesen 2012 Comparative analysis of best practices: review of existing methods and development of an indicator suite for pantura goals. Pantura, SINTEF, Norway
- [13] Knippers Jan, Pelke Eberhard, Gabler Markus and Berger Dieter 2010 Bridges with glass fibre-reinforced polymer decks: the road bridge in Friedberg, Germany. *Struct. Eng.Int. J. – International Association for Bridge and Structural Engineers (IABSE)* 20(4): 400–404
- [14] Lee S W, Hong K J and Kim J I 2008 Use of promising composite ‘Delta Deck’ for various composite deck bridges. In: *Proceedings of Fourth International Conference on FRP Composites in Civil Engineering (CICE2008)*, Zurich, Switzerland
- [15] Sams M 2005 Broadway bridge case study: bridge deck application of fiber reinforced polymer. Journal of the Transportation Research Board, Washington DC
- [16] Hammond G and Jones C 2008 *Inventory of carbon and energy (ICE)*, version 1.6a, University of Bath
- [17] Suzuki T and Takahashi J 2005 Prediction of energy intensity of carbon fiber reinforced plastics for mass-produced passenger cars. In: *Proceedings of the Ninth Japan International SAMPE*, symposium
- [18] Daniel R A 2010 A composite bridge is favoured by quantifying ecological impact. *Struct. Eng.Int. J.—International Association for Bridge and Structural Engineers (IABSE)* 20(4): 385–391
- [19] Resins B D D C et al. 2009 LCA COMPOSITBRUG Eindrapport (2e versie) VERTROUWELIJK, BECO Groep, Vestiging Rotterdam, mei 2009
- [20] Zhang C, Amaduddin M and Canning L 2011 Carbon dioxide evaluation in a typical bridge deck replacement project. In: *Proceedings of the Institution of Civil Engineers—Energy*. 164(4): 183–194
- [21] Ehlen M A 1999 Life-cycle costs of fiber-reinforced-polymer bridge decks. *J. Mater. Civil Eng.* 11(3): 224–230
- [22] Sahirman S, Creese R C and Ganga Rao H V S 2008 *FRP bridge deck life cycle cost analyzer*. In: *Proceedings of the International symposium on Life Cycle Civil Engineering*, Varenna, Lake Como, Italy
- [23] Nystrom H E, Watkins S E, Antonio Nanni P E and Murray S P E 2003 Financial viability of fiber-reinforced polymer (FRP) bridges. *J. Manag. Eng.* 19(1): 2–8
- [24] Design Data 1990 *Fibre glass reinforced plastics*. FGP Limited, Mumbai