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FATIGUE ANALYSIS OF GLASS FIBER REINFORCED POLYMER(GFRP) BRIDGE DECK PANELS

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ABSTRACT

Reinforced Concrete (RC) structures deteriorate due to several reasons including corrosion of steel. Once the bond between the concrete and steel is lost, the reinforcement becomes ineffective. There are several cases of failure of bridges due to this limitation of reinforced concrete. Glass Fiber Reinforced Polymer (GFRP) bridge deck panel is an alternative for conventional RC panel in bridges which remains unaffected by environmental attack.

The paper discusses the results of the analytical study on the fatigue behavior of GFRP bridge deck panels. Finite element software ANSYS is used for modeling and analysing multi-cellular GFRP bridge deck panels. The analysis shows good performance of GFRP panels under fatigue load.

NOMENCLATURE

N	Cumulative No. of standard axles to be catered for the design in terms of msa
D	Lane distribution factor
A	Initial traffic, in the year of completion of construction, in terms of number of commercial vehicles per day
F	Vehicle Damage Factor
N	Design life in years
r	Annual growth rate of commercial vehicles

1.INTRODUCTION

For several years, concrete structures have been regarded as permanent structures with their major advantages being considerable compressive strength, low maintenance and availability. However, it has been observed that many concrete structures are suffering deterioration for some reasons like corrosion. As a porous material, concrete allows fluids such as water, salt and de-icing chemicals to penetrate the concrete and attack the steel reinforcement. Corrosion of the steel reinforcement causes the steel to expand .The bond between the concrete and steel is lost and the reinforcement becomes ineffective. Glass FRP (GFRP) is gaining more popularity in construction of bridges, because bridge deck slabs are one of the most severely affected components in reinforced concrete structures. Since the material offers unique combination of high strength to weight ratio and stiffness to weight ratio, corrosion and fatigue resistance, improved long-term performance to environmental effects, lower maintenance cost, longer service life, lower life-cycle costs, it makes them attractive for use in the construction of new slabs and retrofitting and rehabilitation of existing slab panels, and also in place of other concrete structures.

Muthuraj and Subramanian, 2012 [1] conducted both experimental and analytical investigations on GFRP decks subjected to static loading with long span hinged and short span hinged conditions. The experimental model was one-third scaled model of a 3.75m bridge superstructure. Numerical simulation of GFRP decks has been carried out by using ABAQUS software. They found that the stresses and deflections were within permissible limits for the adopted cross-section.

Reddy et al., 2005 [2] studied the load–deflection behavior of GFRP composite deck panels under static loading. Three prototype GFRP composite deck panels were fabricated using hand lay-up process and tested under a factored load of AASHTO HS20/IRC Class A wheeled vehicle. The authors concluded that the maximum deflection under factored load obtained from both finite element analysis and experimental data are within a value of span/800 as specified in deflection criteria by Ohio Department of Transportation (ODOT), USA. Brea Williams [3] performed analyses using GFRP bridge decks consisting of three triangular modules bonded together and adhered to top and bottom pultruded plates as well as GFRP bars. Tedesco et al. [4] analyzed deteriorated reinforced concrete bridge girders repaired with externally bonded FRP laminates using finite element method. Static and dynamic analyses of the bridge were carried out for conditions before and after FRP repairing. Field load tests were performed before and after application of the FRP plates with trucks of known axle configuration and weight distribution. The authors concluded that the external bonding of FRP laminates to the bridge girders reduced the average maximum mid span girder deflections and stresses in reinforcing steel.

The aim of the present study is to evaluate the fatigue life of GFRP bridge deck panel under wheel loads. Different cross-sections were modeled in ANSYS. To select the best cross-section with minimum weight, static test on GFRP bridge deck panels was carried out under class A wheeled loading.

2. PROPERTIES OF GFRP

Common fibers in commercial use for production of civil engineering applications including composite-reinforced concrete are glass, carbon, and aramid[1]. Laminates are the most common form of fiber-reinforced composites used in structural applications. They are made by stacking a number of thin layers (lamina) of fibers and matrix and consolidating them into the desired thickness. Fiber orientation in each layer as well as the stacking sequence of the various layers can be controlled to generate a range of physical and mechanical properties. The major factors affecting performance of the fiber matrix composite are fiber orientation, length, shape and composition of the fibers, the mechanical properties of the resin matrix, and the adhesion or bond between the fibers and the matrix. Fibers are the principal load-carrying component in a fiber reinforced composite material. The effectiveness of fiber reinforcement depends on the type, length, volume fractions and orientation of fibers in the matrix.

The FRP composites are characterized by their

1. Lightweight (20% of that of a comparable concrete deck slab)
2. High strength to weight ratio and high performance
3. Free formability, dimensional stability
4. Easy construction and handling
5. High corrosion and fatigue resistance
6. Short installation time

7. Minimal traffic interruption
8. High quality shop fabrication
9. Electrically Non-conductive
10. Attractive Appearance
11. Resists salt water, chemicals, acid rain, and withstand in most aggressive environment.

The strength properties of Fiber-reinforced polymers (FRP) collectively make up one of the primary reasons for which civil engineers select them in the design of structures. A material's strength is governed by its ability to sustain a load without excessive deformation or failure. When an FRP specimen is tested in axial tension, the applied force per unit cross-sectional area (stress) is proportional to the ratio of change in a specimen's length to its original length (strain). When the applied load is removed, FRP returns to its original shape or length. In other words, FRP responds linear-elastically to axial stress. Table 1 shows the material properties of GFRP.

TABLE 1: MATERIAL PROPERTIES OF GFRP

1	Longitudinal modulus of elasticity (E_l)	76000Mpa
2	Transverse modulus of elasticity (E_t)	42000Mpa
3	Poisson's ratio (ν_l)	0.264
4	Poisson's ratio (ν_t)	0.22
5	shear modulus (G_l)	59280MPa
6	Shear modulus (G_t)	30912MPa

3. GLASS FIBER REINFORED BRIDGE DECK PANELS

In bridges with steel or integrated reinforced concrete deck slab, the weight constitutes a considerable part of the load on the whole span. On the other hand, bridges with a wooden deck are light; but usually with a very low carrying capacity. In both cases the way to increase the load class of the bridge is by constructing the deck from fibrous composites in a polymer matrix - FRP. In the first case, it will be able to reduce the weight of the deck slab and relieve the main girders and /or other main structural elements of the structure, while in the second case it will be possible to increase its carrying capacity at a similar mass of the deck. The average weight of the load-carrying structures of a deck slab made of FRP composites ranges from 0.6 to 1.5kN/m^2 and a concrete one from 4.0 to 5.0kN/m^2 [5].To obtain composite elements with high, repeating properties it is necessary to keep a strict technological regime in the manufacturing process. It is difficult to obtain it at the construction site; therefore the elements of this type are usually prefabricated in manufacturing plants, transported to the destination and combined there. This allows speeding up the construction of the bridge and minimizing the related inconveniences, which is particularly important during the modernization of existing structures.

4. ASSEMBLAGE OF GFRP DECK PANELS

Over the past years GFRP panels have been increasingly used in decks of vehicular and pedestal bridges in both new construction and rehabilitation. In particular, multi-cellular decks show great potential due to number advantages that include lightness, strength, easy and rapid installation and improved durability under aggressive environment. Several joining techniques have been developed for the composites bridge deck, particularly at panel to panel connections. Schematic of the deck system is shown in Fig.1. Details of the joining techniques are available in [6].

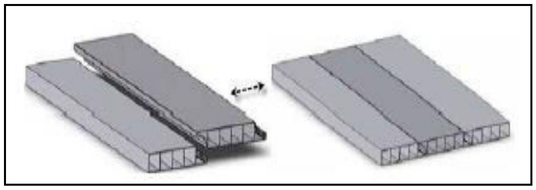

Fig 1.Deck Assembly

5. STATIC ANALYSIS OF GFRP BRIDGE DECK PANEL

The bridge deck is quite complex from the analysis point of view with a bond line thickness of approximately a millimeter and in plane deck dimensions of a metre.

Cross Sectional Profile

Different cross sections were analytically modeled in ANSYS to select the best cross section with minimum weight. The two types of cross sections adopted for the analysis is shown in fig. 2 and their dimensions are shown in Table 2.

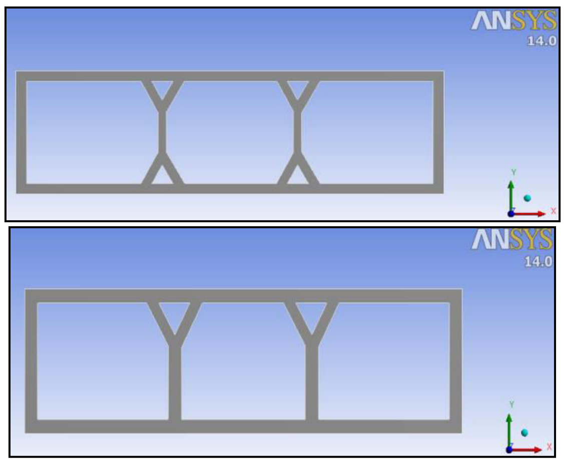

Fig. 2: ANSYS Models of Different types of cross section of GFRP bridge deck panel

Table 2: Dimensions of GFRP bridge deck panel

PARAMETER	MODEL(mm)
Length	3750
Width	1000
Depth	300
Thickness	20

Boundary Conditions

The bridge deck panel was assumed to be simply supported along the width. The boundary conditions were simulated by arresting the three translational degrees of freedom in x, y and z directions at one end (hinge support) and two translational degrees of freedom in y and z directions at the other end (roller support).

Static Analysis

The static test on GFRP composite bridge deck panel model was carried out under the simulated wheel load of IRC Class A wheeled vehicle as per IRC 6 [7]. The wheel load was applied as a rectangular patch load on the bridge deck panel. Two wheel loading arrangements over the plates of size 250mmx500 mmx15 mm were used to distribute the load on the deck. As per IRC, the Class A axle load is 114 kN .The dead load of wearing surface was input separately. The dynamic magnification factor was taken as 25% of the live load of the wheeled vehicle. The static tests were conducted under a load 456000N/m^2 ((57kN wheel load +25% of impact factor (for less than 9m)) applied over the bridge deck panel.

The cross-sections provided were found to be sufficient for resisting the stresses caused due to the design load. Fatigue analysis was performed on model 1.

6. FATIGUE ANALYSIS

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit and may be below the yield stress limit of the material. Fatigue occurs when a material is subjected to repeat loading and unloading.

Fatigue life, N_f, is defined as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs. Historically, most attention has focused on situations that require more than 10^4 cycles to failure where stress is low and deformation is primarily elastic.

In high-cycle fatigue situations, materials performance is commonly characterized by an S-N curve (stress-number of cycles) also known as a Wohler curve. This is a graph of the magnitude of a cyclic stress (S) against the logarithmic scale of cycles to failure (N).

Since S-N curves are typically generated for uniaxial loading, some equivalence rule is needed whenever the loading is multi axial. For simple, proportional loading histories, sine rule may be applied. For more complex situations, such as non-proportional loading, critical plane analysis must be applied.

Fatigue failures are caused by initiation and propagation of cracks when the cyclic stresses are applied. When the cyclic stresses are below certain value, (termed as fatigue limit /endurance limit), cracks do not initiate. In such cases, even existing cracks do not propagate. But, if the cyclic stresses are above the fatigue limit, cracks initiate after a certain number of cycles and then grow at a progressively increasing rate until complete fracture occurs.

The focus of fatigue analysis in ANSYS is to provide useful information to the design engineer when fatigue failure may be a concern. A stress-life approach has been adopted for conducting a fatigue analysis.

S-N curve is very important parameter in fatigue analysis because in case of bridges, deck slab directly sustains repeated moving wheel loads; it is one of the major bridge components susceptible to fatigue failure.After sample testing at various stress ranges, number of cycles causing failure is arrived. Based on that, S-N curve is plotted. The results are plotted as an S-N diagram usually on semi-log or on log-log paper, depicting the life in number of cycles tested as a function of the stress amplitude. The output of fatigue analysis is fatigue life.

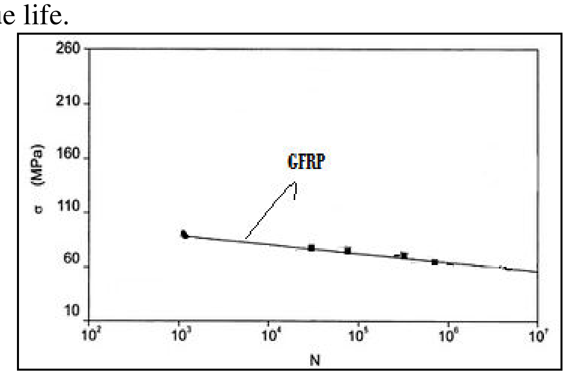

Fig 3:S N curve for GFRP

Fig 3 Shows the S N Curve for GFRP material based on an experimental study conducted by Grellmann and Seidler [8]. The S–N diagram shows the usual trend that as the fatigue stress increases, the fatigue life decreases.

Methodology for Fatigue Analysis

1. SOLID 186 element is used for modeling of the deck which is defined by eight nodes having three degree of freedom (translations in x, y and z-directions) at each node with orthotropic material properties.
2. S-N curve of the material is given as the input.
3. Stress locations where fatigue stress is required have to be mentioned.
4. Zero reversed loading is specified to create alternating stress cycles and perform a stress-life fatigue analysis.
6. Von – Mises stress is used to compare against fatigue material data.
7.Perform stress and fatigue calculations.
8. Fatigue life cycle is obtained from this analysis.
9. A contour plot of the factor of safety with respect to a fatigue failure at a given design life is also obtained.

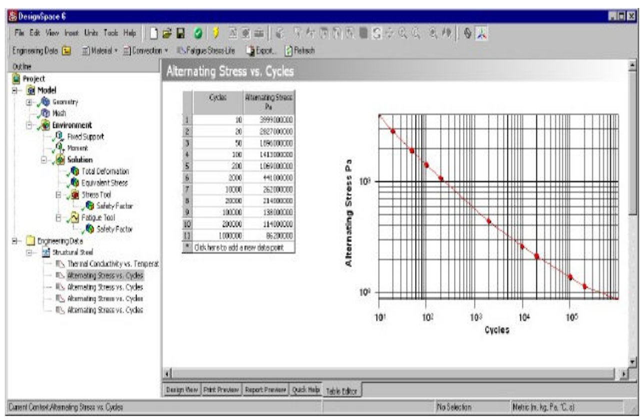

Fig 4 Screen shot showing a user editing fatigue data in ANSYS.

Fig. 4 shows the fatigue data input in ANSYS as per the SN curve.

Fatigue Analysis Results

The analysis is carried out till the failure of the model. The result is obtained in terms of fatigue life**.** The stress concentration was found to occur at the centre of the rectangular patch load as that of static analysis. The minimum fatigue life was found to occur at the centre of the rectangular patch load as the stress concentration was maximum in the same area. Life distribution shows the location of maximum and minimum life. The fatigue life was found to be 100million cycles.

The fatigue life can also expressed in terms of number of years. The design traffic is considered in terms of cumulative number of standard axle to be carried during the design life. As per IRC 37 (2001)[9], cumulative number of standard axle is given by

$$N = \frac{365A(1+r)^{n} - 1}{r} DF \qquad (1)$$

where N, A, D, F and r are as defined earlier. The corresponding values adopted are 100msa, 5228CV/day, 0.75, 4.5 and 0.075. As per the analysis, the fatigue life is obtained as 66 years corresponding to 100 million cycles. The standard fatigue life of RC bridge deck panel is 38 years corresponding to 10 millions.

Hence, it can be inferred that GFRP bridge deck panel offers good resistance against fatigue failure.

7. CONCLUSIONS

GFRP have proved as an innovative construction material for use as bridge deck panel, due to its numerous advantages including light-weight and corrosion-resistance. Static analysis of GFRP bridge deck panels have been carried out by several researchers. Its performance under fatigue loads is evaluated in the present study in terms of number of cycles and equivalent design life. From, the limited study conducted on panels of size (3.75m x 1.0m), it can be concluded that GFRP deck panel is a suitable alternative for RC panels. Further research on large number of models of varying panel sizes, cross-sections and support conditions, is required to confirm the result.

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