DYNAMIC RESPONSE OF FIBRE REINFORCED POLYMER AND SRC COMPOSITE CABLE STAYED BRIDGES UNDER MOVING AND WIND LOADS

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Abstract - *Cable Stayed Bridge are typical long span bridge which are classified on the basis of longitudinal and transverse cable profile arrangements and pylon shapes. For the cable-stayed bridge chosen for the current study, composite materials are intended to use such as Fibre Reinforced Polymer and Steel Reinforced Concrete which is then compared with conventional Precast Concrete deck and it's important to accurately evaluate the deck and pylon deflection and all the forces and stress characteristics of the structural elements of cable stayed bridge. Hence, dynamic evaluation of varied components of such bridges gains more importance due to their geometric complexity. So, the aim of the study is to develop most efficient type of composite Cable stayed bridge under the dynamic moving load and static wind load and their load combinations as per IRC and EN1991-1-4 respectively as these loads are dominating in a typical cable stayed bridge than seismic loads. A 3-span continuous cable stayed bridge with diamond shaped pylons is considered and modelled in FEM software Midas Civil 2019. The results are discussed in terms of pylon displacement, cable forces, bending moment, torsion of composite deck. The results concluded that Fiber Reinforced Polymer composites deck gives the less critical values and is most efficient as compared to the steel reinforced concrete and conventional precast concrete deck cable stayed bridge.*

Key Words: Cable Profile Arrangement, Fiber Reinforced Polymer, Steel Reinforced polymer, IRC Loadings and their Load Combinations, Type of Pylon.

1.INTRODUCTION

Cable stayed bridges are aesthetically attractive and they are relatively lightweight, flexible and lightly damped structure and have larger span as compared to general bridges. Also, cable stayed bridges experience most flexibility than normal girder bridges. The structural efficiency and design of cable stayed is complex due to comprising of several structural components with individual stiffness and damping properties as both steel and concrete materials are in construction. Hence analysis of cable stayed bridges are done to estimate the dynamic response due to dynamic moving load and static wind load as the structure is light weight both the vehicular and the wind loads are predominating. There are two major structural advantages for achieving success in design of cable stayed bridges. Firstly, since variety of compact cables is self-anchored in an exceedingly cable stayed bridge, massive-scale anchorage isn't necessary as in an exceedingly conventional span. Secondly, the diagonally tensioned cables during a cable stayed bridge have greater rigidity and are less deflective than those of a suspension bridge, resulting in cost reductions.

For the cable-stayed bridge designated for the current analysis, composites materials are used such as Fibre reinforced polymers and steel reinforced concrete. Nowadays, many more industries have brought light on all the probabilities that Fibre Reinforced Polymer composites must offer, aesthetically and structurally speaking. These composites prevail for an extended period long back but their specific use of material in industries is current. When it involves the sector of bridge construction, alternatives to conventional materials, like steel, which mainly look after corrosion, fatigue, and also high maintenance problems. Thus, Fibre Reinforced Polymer composites research can state that it is one of the better replacements compared to conventional. FRP provides certain betterment which are lesser self-weight of the fabric, the dynamic effect of this composite bridges can be crucial. comparison for the cable-stayed bridge design, it's desirable to also design a bridge with traditional materials, during this case a steel-concrete composite bridge.

(Khalifa et al. 1996) described the assorted analysis and design aspects of a fiber reinforced plastic (FRP) bridge. The analysis is formed using three-dimensional (3-D) macro models of the bridge to explain its overall behavior under static and dynamic loads. (Adanur et al. 2011) studied the Fiber reinforced polymer (FRP) composites which provide many interesting features for existing and new bridges. Among these features are light weight, high stiffness-to-weight ratio and strength-to-weight ratios, damping abilities, and high resistance to environmental deterioration when properly designed and installed. (Xiong et al. 2011) introduced new forms of cable-stayed bridges with carbon fiber reinforced polymers (CFRP) stay cables and/or a CFRP deck. for every of the 2 CFRP components, namely, CFRP stay cables and CFRP deck, the key design parameters and style strategies were determined and therefore the appropriate value of every key design parameter was suggested. (Cho et al. 2013) observed the characteristics of axially loaded precast FRP-concrete composite decks which are examined through flexural tests so as to verify the applicability to cable stayed bridge. The deck of the bridge is of course subjected to high compressive forces. However, the precast Fibre Reinforced Polymer-concrete composite deck flaunts a little concrete section opposing to compression.

2. FRP Composites:

Fibre reinforced polymer composite material has two main structural elements which are resins and fibres itself. And, the properties not only depend on those of it constitutes but also on the geometry of FRP i.e. the fibre to the resin ratio and the bonding between the two components also the direction of the fibres.

Fibre reinforced polymer composite which is also called as fibre reinforced plastic composite which has two main structural elements one is fibre and other is resin. Property of FRP not only depends on the constituents used but also depends on the geometry of composite, also fibre-resin ratio, direction of fibres and the adhesions between two constituents. In longitudinal direction fibres have a very high tensile strength thereby providing adequate stiffness and desired material strength to the finished product. Also, the capacity of Uni directional laminates in transverse direction is much lesser. This states that the stiffness and strength of FRP material depend on how the fibres are aligned. These composites are made up of high-performance fibres which are embedded with a polyester matrix. Carbon, glass and aramid are the most commonly used fibres in the FRP and phenols, formaldehyde resins, polyester, vinyl ester and lastly epoxy

FRP consists of high-performance fibres embedded with a polymer matrix. Various fibres which are used in FRP are carbon, glass and aramid and polymers used are phenol formaldehyde resins, epoxy, vinyl ester and lastly polyesters

These composites can have different pattern of fibre arrangement within the polymer which are as follows.

- 1D orientation where the fibres are oriented in x-direction only;
- 2D orientation, where the fibres are aligned either oriented or in a particular manner in both x & y direction;
- 3-D arrangement, Where the fibres are randomly oriented in all three directions i.e. in (X, Y, Z) direction.

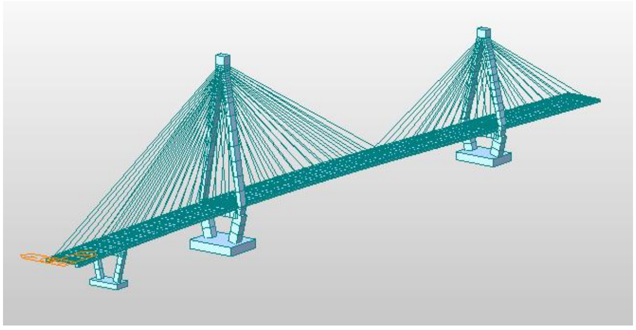

Figure 1. 3D FEM Modelling of Cable stayed bridge.

1.2 Bridge Configuration

Table -1: Composite Cable stayed bridge configuration

Bridge type	Four span cable stayed bridge
Bridge length	46.5+113.5+260.0+100.0 = 520.0 m.
Bridge width	24.0 m.
Deck Type	1. FRP Composite deck.
	2. SRC Composite deck.
	3. Conventional PSC deck.
Pylon shape	Diamond shape.
Number of cables	52×2 pair = 104.
Transverse arrangement	Double plane.
Number of lanes	6

Types of models considered for present study

There are 3 models which are considered for the current study.

1. Model 1: Fibre Reinforced Polymer deck arrangement of Cable Stayed Bridge.

2. Model 2: Steel Reinforced Concrete deck arrangement of Cable Stayed Bridge.

3. Model 3: Conventional Concrete deck arrangement of Cable Stayed Bridge.

Fibre Reinforced Polymer deck:

Model 1 is of fibre reinforced polymer deck of span 520m and pylon height of 80m. Material properties used for FRP deck are mentioned in below table 2 and Anisotropic structural properties of carbon fibre reinforced polymer are mentioned in table 3 and other material properties for composite cable stayed bridge are mentioned in table 4

Table -2: Anisotropic CFRP material properties

Name	Type	Elasticity (kN/m²)	Poisson ratio	Thermal (1/[C])	Density (kN/m³)	Mass Density (kN/m³/g)	Material Type
Main Concrete	Concrete	2.74E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Sub Concrete	Concrete	2.61E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Cable	Steel	2.06E+08	0.3	1.20E-05	77.00	7.85	Isotropic
CFRP	Composite	2.30E+07	0.18	1.8E-05	17.46	0.00	Anisotropic

Name	Type	Elasticity (kN/m²)	Poisson ratio	Thermal (1/[C])	Density (kN/m³)	Mass Density (kN/m³/g)	Material Type
Main Concrete	Concrete	2.74E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Sub Concrete	Concrete	2.61E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Cable	Steel	2.06E+08	0.3	1.20E-05	77.00	7.85	Isotropic
CFRP	User Defined	2.58E+07	0.32	1.96E-05	77.10	0.00	Anisotropic

Steel Reinforced Concrete deck:

Model 2 is of steel reinforced concrete deck of 520m span and width of 24m. in steel reinforced concrete steel plates of fe540 are embedded into the concrete grade of M45 all the material type and properties of steel reinforced concrete used are given in table 6

Table -3: Isotropic SRC material properties

Material Type	Standard	DB	Elasticity (kN/m²)	Poisson	Thermal (1/[C])	Density (kN/m³)	Mass Density (kN/m³/g)
SRC (Steel)	IS(S)	Fe540	2.05E+08	0.3	1.20E-05	76.98	7.85
SRC (Concrete)	IS(RC)	M45	3.35E+07	0.20	1.00E-05	23.60	2.41

Conventional PSC deck:

Model 3 is of conventional precast concrete deck of same span and width as compared to model 1&2. Concrete of grade M45 is used for pylons and deck and all the material type and properties of Conventional PSC is given in the table below.

Table -4. Conventional PSC material properties

Name	Type	Elasticity (kN/m²)	Poisson ratio	Thermal (1/[C])	Density (kN/m³)	Mass Density (kN/m³/g)	Material Type
Main Concrete	Concrete	2.74E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Sub Concrete	Concrete	2.61E+07	0.167	1.00E-05	24.50	0.00	Isotropic
Cable	Steel	2.06E+08	0.3	1.20E-05	77.00	7.85	Isotropic

A 3-span continuous Cable Stayed Bridge is considered for the study which have 520 m of total span (260m central span and 1st side spans of 160m and 2nd side span of 100m) and 80 m of Asymmetrical diamond shaped Pylon. The deck is 2 cell FRP & SRC section of 24m wide and 1.6m depth. Two plane systems of transverse arrangement of cable profiles is considered. 2 number of pylons are placed at 260 m centre to centre with 52 number of cables at each pylon.

2. LOADINGS:

Loads to be considered while arriving at the appropriate combination for carrying out the analysis of FRP & SRC type of composite cable stayed bridge are as follows:

1) Self-Weight (DL).
2) Superimposed Dead Load (SIDL).
3) Pretension forces.
4) Moving Load (ML).
5) Wind Load (WL).

All the above loads are calculated as per IRC 6(2014) and wind load is calculated by EN1991-1-4 and applied to the FRP, SRC and PSC deck type cable stayed bridge models in FEM Software (Midas Civil 2019).

Self-Wight (DL):

Self-weight is nothing but the total dead load of structure which contains superstructure and substructure elements. Girders, cross girders, cables, and pylon are superstructure elements and the elements below the superstructure are substructure that are pylon below the deck and foundation.

Superimposed Dead Load (SIDL):

Additional dead loads are nothing but the loads like barriers, footpath and kerbs etc. these loads are generally taken as 0.5 kN/m².

Calculation for SIDL is as follows
Assume, Asphalt Density = 2380 kN/m², Wearing Coat = 80 mm
SIDL Load = 23.8 x 0.08 = 1.904 kN/ m²
Total SIDL Load = 1.904 + 0.5 = 2.404 kN/m²
Total Width of Deck = 24m
SIDL Load along deck = 24 x 2.404 = 57.70 kN/m
The top layer of a road surface is wearing course. The 80mm of wearing course is considered and applied to the deck as UDL by taking 22 kN/m². The additional load is applied to the deck as UDL. The SIDL is carried out due to crash barrier.

Pretension forces:

The initial step of analyzing a composite cable-stayed bridge is to calculate the initial cable prestressing forces for the end bridge with WC and SIDL. The general method of finding out these initial prestressing forces is by the Unknown Load

Factor (ULF) option in FEM software MIDAS Civil 2019 which is described in Figure 2. While performing linear analysis load combinations for the unit pretension loads and the respective dead load should be defined.

The initial cable forces are calculated by described method for Fibre reinforced polymer, steel reinforced concrete and conventional concrete deck type of cable stayed bridges as shown in Figure 3.

These initial cable forces are applied to all model (FRP, SRC & PSC) types respectively with different load for further analysis.

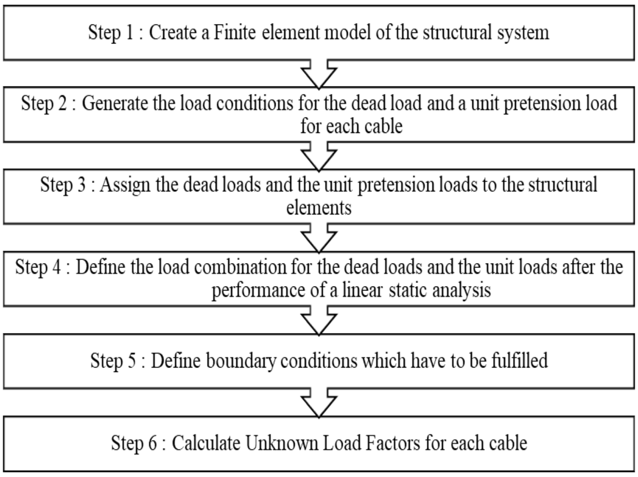

Figure 2. Flowchart for ideal cable prestress calculation

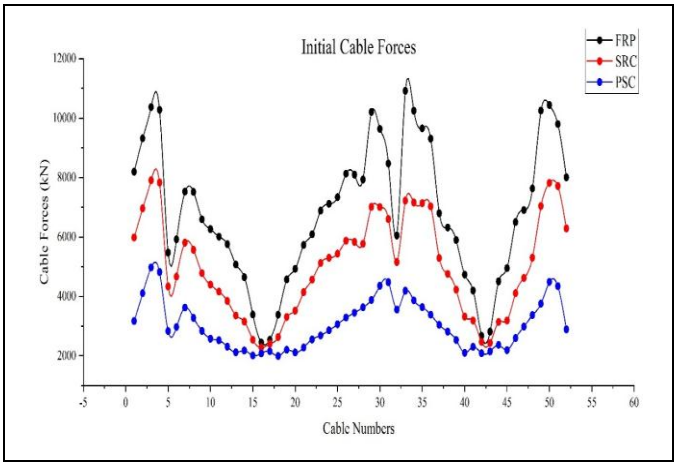

Figure 3. Initial Cable Forces at Equilibrium Condition

Dynamic Moving Live Load (ML):

The Moving loads are design live loads which are given in IRC 6(2014). The term live load is nothing but the load that moves along length of the particular span. The loads are categorized based on their configuration and intensity.

In a present study, number of lanes are 6. For these 6 lanes, 3 live load cases are described in Cl. No. 204.3, Table No. 2, IRC 6(2014). They are

1. Case I: Class A + Class 70R - 6 Lanes.
2. Case II: Class A + Class 70R Wheeled - left 3 Lanes.
3. Case III: Class A + Class 70R Wheeled - right 3 Lanes.

The above moving load cases are defined with giving the traffic line lanes as per their eccentricity from the centre of deck. The eccentricity of these lanes is carried out according to clearance distance from the deck, gauge distance and centre to centre distance between vehicles as per mentioned in Clause No. 204, IRC 6(2014).

Wind Load (WL):

The basic wind velocity V_b is defined in EUROCODE (EN 1991-1-4) as a function of the wind direction and time of year at 23 m above ground of terrain category 0.
$Z_e = 23 + 0.8 = 23.8$ m
The wind velocity is calculated using equation 4.1 section 4.2

$$V_b = C_{dir}.\, C_{season}.\, V_{b,0}$$

Where $V_{b,0}$ is the characteristic 10 minutes mean wind velocity at 10 m above the ground level for terrain category II. Which is defined in EN 1991-1-4 as the fundamental value of the basic wind velocity.

In the following calculations the basic wind velocity is considered as $V_b = 44.00$ m/s.

$$V_b = C_{dir}.\, C_{season}.\, V_{b,0} = 1.0 \times 1.0 \times 44 = \mathbf{44\ m/s}$$

Peak Velocity Pressure

The peak velocity pressure $q_p(z)$ at height z is given by the expression below;

$$q_p(z) = [1 + 7.l_v(z)]0.5\rho V_m^2(z) = c_e(z).q_b$$

$$q_p(23.8\text{ m}) = [1 + 7(0.299)] \times 0.5 \times 1.25 \times 24.22^2$$

$$= 4226.457\text{kN/m}^2 = \mathbf{4.227}\ \boldsymbol{kN/m^2}$$

Wind force acting in X-direction

$$F_{wk} = q_p(Ze)C_{f,x}.A_{ref,x}$$

$$F_{wk} = 4.227 \times 1.3 \times 2.6 = \mathbf{14.2873}\ \boldsymbol{kN/m}$$

Results for Dynamic moving analysis

1. Deck deflection due to Dynamic moving load.

- Composite Material used in the current study is FRP, steel reinforced concrete and conventional concrete. As the self-weight of FRP is very less, thereby causing very fewer bending moments thus bending moment in the deck was not critical.

- To check the overall deflection, the deck system here is designed as a single span beam on the supports. This was done in MIDAS Civil 2019 as it was not possible by hand calculation
- The maximum deflection is limited to $\frac{L}{350}$, [NOTE: L can be taken as the length of the clear span]

Comparison of deck deflection is made of FRP, SRC, PSC deck were FRP deck have least deflection of 0.173m following with the SRC and PSC of 0.2m and 0.29m respectively.

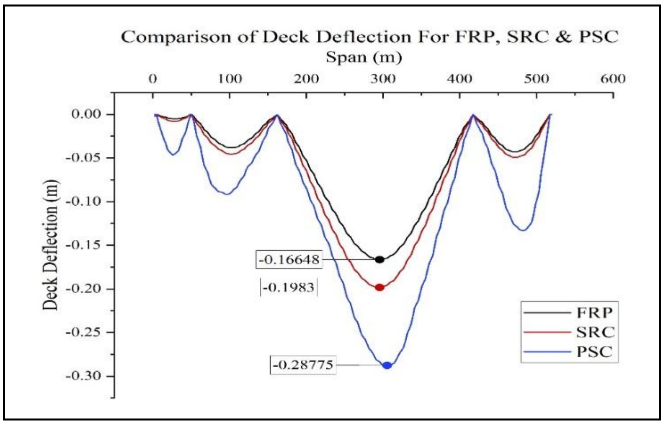

Figure 4. Comparison for Deck deflection for FRP, SRC & PSC

2. Pylon deflection due to moving load

In terms of displacement of pylon, the comparison is made between Fibre reinforced Polymer, Steel Reinforced concrete and Precast Concrete deck of cable stayed bridge. Figure shows the maximum displacement in pylon of FRP, SRC and PSC deck cable stayed bridge. The maximum displacement of deck is occurred in conventional type of cable stayed bridge of 105.6539 mm. Composite have nearly around 37.5% less values of pylon deflection as compared to Conventional PSC cable stayed bridge.

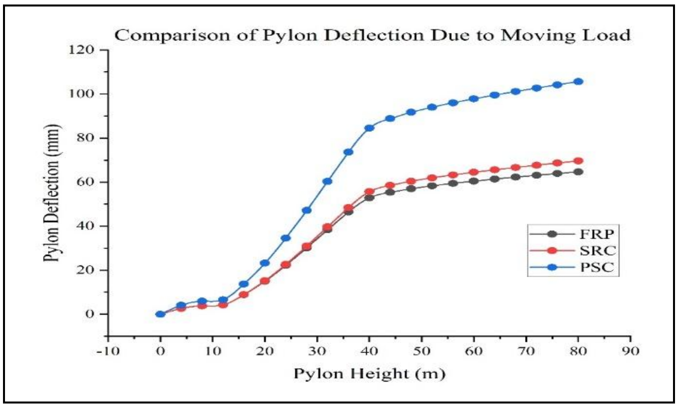

Figure 5. Comparison of Pylon Deflection due to Moving Load

3. Axial forces in deck due to moving load

Figure shows maximum axial forces generated in the deck elements of FRP and SRC deck arrangements which are compressive in nature. The maximum axial force is occurred in SRC arrangement followed by FRP deck. And when compared with the conventional deck maximum axial force is found out to be in PSC cable stayed bridge by increase of 43.8%

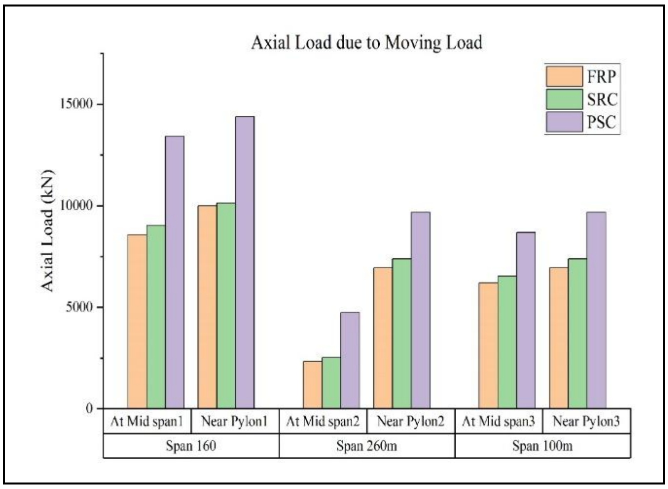

Figure 6. Comparison of Axial Load in deck due to Moving Load

Results for static wind analysis.

Deck deflection.

- The maximum deflection is limited to $\frac{L}{350}$, [NOTE: L can be taken as the length of the clear span]
- Comparison of deck deflection is made of FRP, SRC, PSC deck were FRP deck have least deflection of 4mm following with the SRC and PSC of 7mm and 16.3mm respectively. [NOTE All the deck have passed the maximum deflection check]
- Pylon deflection.

In terms of displacement of pylon, the comparison is made between FRP, SRC and PSC Deck of cable stayed bridge due to static wind loads. Figure shows the maximum displacement in pylon of FRP, SRC and PSC deck cable stayed bridge. The maximum displacement of pylon is occurred in conventional PSC type of cable stayed bridge of 30mm. Composite have nearly around 20% less values of pylon deflection as compared to Conventional type of cable stayed bridge In Pylon, PSC cable stayed bridge has maximum displacement.

As both moving load and wind load in cable stayed bridge are predominating thus combination of both moving load and wind load results should be governed at the same time.

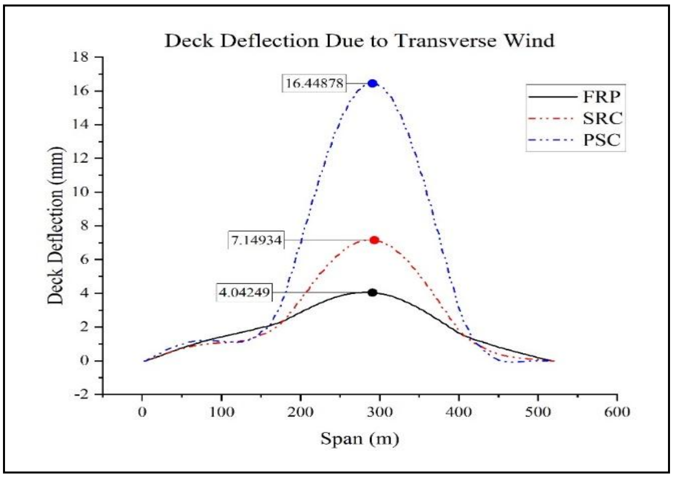

Figure 8. Deck deflection due to transverse wind

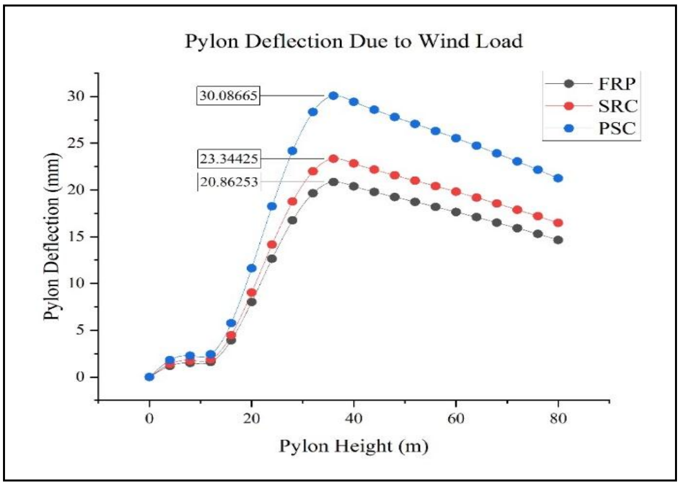

Figure 9. Pylon deflection due to transverse wind load

Results for Moving Load and Wind Load (ML+WL)

1. Deck deflection

- Figure show the deck deflection along the span for both the moving and wind load cases for FRP, SRC and PSC decks. Where, FRP deck have least deflection of 0.19978m following with the SRC and PSC of 0.23811m and 0.34563m respectively. [NOTE All the deck have passed the maximum deflection check]

- Composites have 31% lesser deck deflection as compared to the conventional PSC cable stayed bridge.

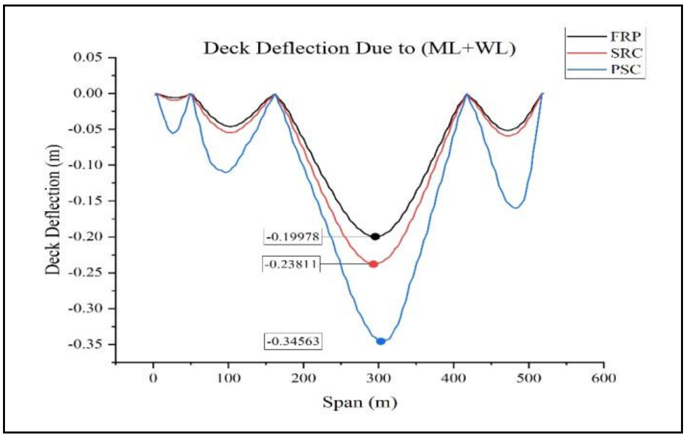

Figure 10. Deck Deflection due to ML+WL

2. Cable forces

Figure shows the comparative results between the FRP, SRC and PSC deck type of cable stayed bridge in terms of cable forces due to both moving load and wind load, by taking all required loads and load combinations, which are occurred in all type of arrangements. The maximum cable force arrived in conventional deck type of cable stayed bridge which is of 2548.362 kN Comparatively lesser values of cable forces can be seen in the composites used.

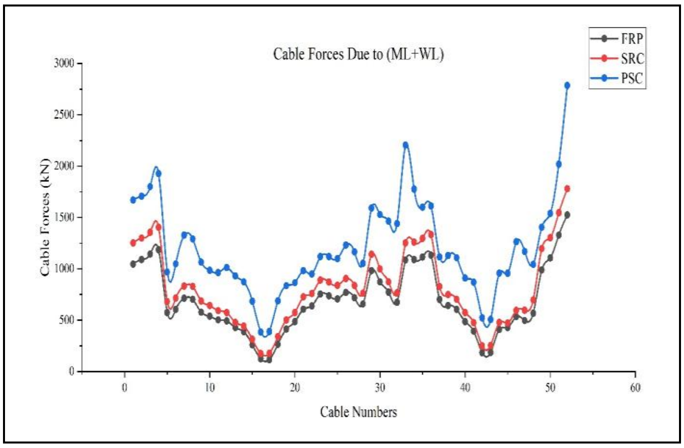

Figure 11. Cables Forces due to ML+WL

3. Pylon deformation.

For the deformation of pylon, the comparison is made between Fibre reinforced Polymer, Steel Reinforced concrete and Precast Concrete deck of cable stayed bridge due to combination of moving and static wind load. Figure shows the maximum displacement in pylon of FRP, SRC and PSC deck cable stayed bridge. The maximum displacement of pylon is occurred in conventional PSC type of cable stayed bridge of 126.901mm. Composite have nearly around 32.11% less values of pylon deflection as compared to Conventional type of cable stayed bridge.

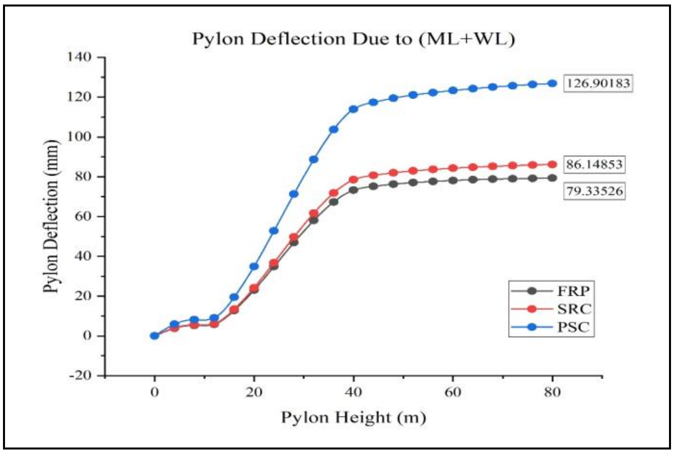

Figure 12. Pylon Deflection due to ML+WL

4. Pylon reaction

Figure shows the comparison of pylon reaction due to moving load and static wind load where the maximum reaction can be seen in PSC cable stayed bridge following with the SRC and FRP deck bridges. This clarifies that the composite decks absorb the stresses efficiently as compared to conventional cable stayed bridge. Also, in composites the Fibre reinforced polymer deck have relatively lesser values of support reactions than the SRC. Thus, making FRP best suitable composites in cable stayed bridge.

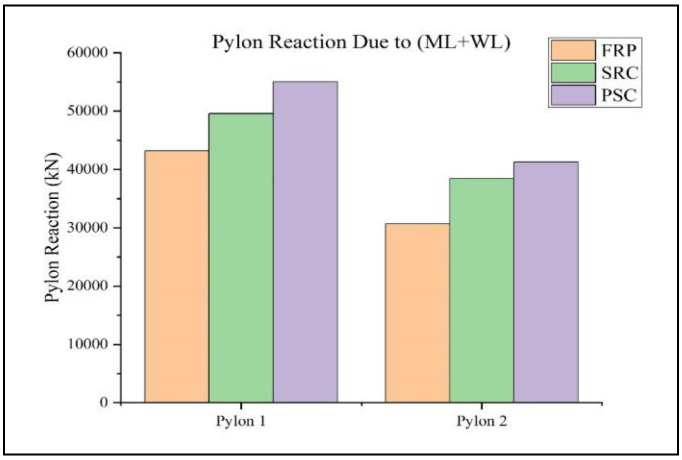

Figure 13. Pylon Reaction due to ML+WL

5. Axial Load in deck

Figure shows maximum axial forces generated in the deck elements of FRP and SRC deck which are compressive in nature due to moving and static wind load. The maximum axial force is occurred in SRC deck followed by FRP deck. And when compared with the conventional PSC deck maximum axial force is found out to be in PSC cable stayed bridge by increase of 43.8%. Thus, stating that FRP deck relatively has lesser value of axial load generated in deck

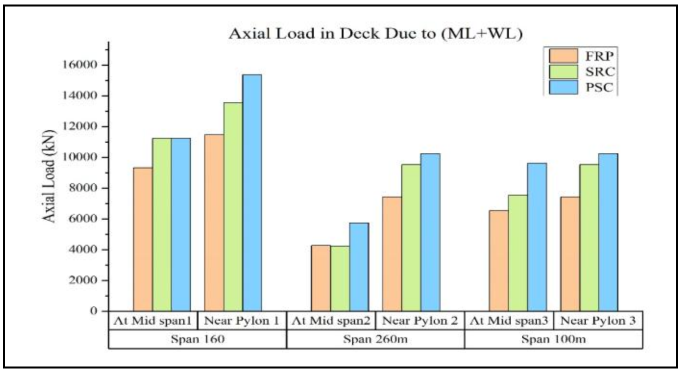

Figure 14. Axial Load in Deck due to ML+WL

6. Torsion in deck.

Figure 16 shows the maximum torsion in deck. The maximum torsion in deck is occurred in PSC deck followed by SRC and FRP deck of cable stayed bridge. FRP deck has 11.11 % lesser values than SRC and 29.41% lesser values of torsion in deck than PSC deck.

7. Bending moment in deck

Figure 17 shows maximum bending moment occurred in FRP, SRC & PSC cable stayed bridge at relative span of 160 m, 260 m, & 100 m. The maximum bending moment occurred is in SRC deck followed by FRP & PSC deck of cable stayed. The bending moment in the deck of SRC has 11.56 % more values than FRP deck and 14.28 % more values than PSC deck of cable stayed bridge.

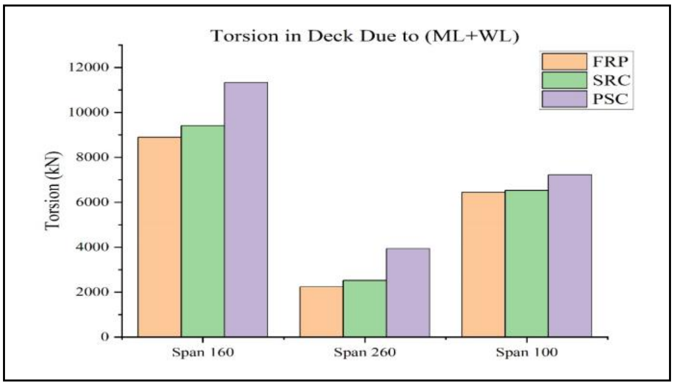

Figure 16. Torsion in Deck due to ML+WL

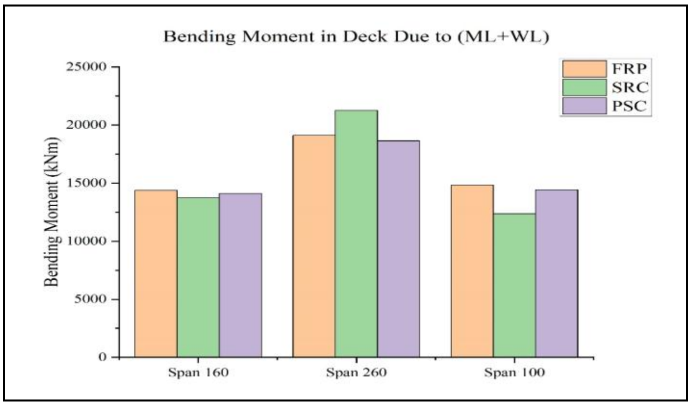

Figure 16. Bending Moment in Deck due to ML+WL

3. CONCLUSIONS:

- The maximum values for all structural entities such as deck and pylon deformation, axial loads in the deck, pylon reaction, cable forces which are considered for the present study, are obtained in FRP, SRC and PSC type of cable stayed bridge. Fibre reinforced polymer deck cable bridge has always lesser values than the maximum. Thus, it can be concluded that FRP deck type of cable stayed bridge is most efficient structure than SRC and PSC cable stayed bridge for large spans.

- The rigidity of steel reinforced concrete deck type cable stayed bridge is more due to their material stiffness and complexity which increases bending moment in deck and pylon and frequency of the structure. However, torsion in FRP deck arrangement is less due to their inherent material properties.

- The torsional stiffness of the FRP deck exhibits better results as compared to the SRC and PSC deck.

- Moving and static wind load which are dominating in cable stayed bridges plays a vital role in designing cable stayed bridge were FRP composites has given better results than SRC composite and traditional concrete.

- As fibre reinforced polymer composite deck have far better results than steel reinforced concrete and precast concrete it can be concluded that FRP is best suited as composite material for cable stayed bridge.

REFERENCES

[1] Adanur, S., Mosallam, A. S., Shinozuka, M. & Gumusel, L. 2011. 'A comparative study on static and dynamic responses of FRP composite and steel suspension bridges.' 30:15, 1265-79.

[2] Cheng, J., Jiang, J.-J., Xiao, R.-C. & Xiang, H.-F. 2002. 'Advanced aerostatic stability analysis of cable-stayed bridges using finite-element method.' *Computers & Structures,* 80:13, 1145-58.

[3] Cho, K., Park, S. Y., Kim, S. T., Cho, J.-R. & Kim, B.-S. 2013. 'Behavioral characteristics of precast FRP-concrete composite deck subjected to combined axial and flexural loads.' *Composites Part B: Engineering,* 44:1, 679-85.

[4] Haifan, X., Jiming, X. & Zhixin, L. 1988. 'Aerodynamic study on a proposed cable-stayed bridge in Shanghai, China.' *Journal of Wind Engineering and Industrial Aerodynamics,* 29:1, 419-27.

[5] Hong, T. & Hastak, M. 2007. 'Simulation study on construction process of FRP bridge deck panels.' *Automation in Construction,* 16:5, 620-31.

[6] Jones, N. P. & Scanlan, R. H. 2001. 'Theory and Full-Bridge Modeling of Wind Response of Cable-Supported Bridges.' 6:6, 365-75.

[7] Khalifa, M. A., Hodhod, O. A. & Zaki, M. A. 1996. 'Analysis and design methodology for an FRP cable-stayed pedestrian bridge.' *Composites Part B: Engineering,* 27:3, 307-17.