

Static and dynamic performance of CFRP cables in longspan cable stayed bridges

Daniel Kumah^a, Liu Ronggui^b, Cornelia Asiedu-Kwakyewaa^c

^aDepartment of Civil Engineering, Jiangsu University, Zhenjiang, 212013, China

^bDepartment of Civil Engineering, Jiangsu University, Zhenjiang, 212013, China

^cDepartment of Civil Engineering, Hohai University, Nanjing, 211100, China

Corresponding Author: Daniel Kumah

Abstract: Carbon fiber-reinforced polymer (CFRP) cables are advantageous over steel cables because of their lightweight, high ultimate tension, and relatively lower elastic modulus. In this research, the static and dynamic behavior of a 1500m central span cable-stayed bridge with CFRP and steel cables is analyzed and compared using a numerical finite element model. The geometric non-linearity was analyzed for the dead load, live load, and temperature load case. The live load includes the pedestrian and primary vehicle load according to BS 5400:2 on the steel deck. The results indicate that the cable tension for CFRP is less than steel cables, however, the vertical displacement of the girder is higher in CFRP than in steel cables. The temperature load effect of the steel cables in the girder is greater than CFRP cables because of the relatively high linear thermal expansion of steel. In the modal analysis, the lateral bending frequency of CFRP is lower than steel but the vertical vibration and torsional frequency mode of the CFRP cable is relatively high. In conclusion, the static and dynamic response indicates that CFRP cables are an optimized substitute for steel stays and can be applied in long span bridges.

Key Word: CFRP Cables; Cable-Stayed Bridge; Geometric Non-linearity; Live Load; Temperature Load; Static and Dynamic analysis.

Date of Submission: 12-11-2020

Date of Acceptance: 29-11-2020

I. Introduction

Cable-stayed bridges have become a preferred alternative over suspension bridges within the past few decades because of their structural stability, aesthetic features, and relatively cheaper construction costs [1, 2]. The main structural components of cable supported bridges are; girder, pylon, and cables. However, several matrix and geometry of the principal structural elements coupled with modern construction methods, and advanced computational models have made it possible for cable-stayed bridges to be used from small pedestrian bridges to medium and long-span bridges [3-5]. In recent times, the long span cable-stayed bridges constructed include the Russky Bridge in Vladivostok, Russia (2012), Sutong-Yangtze River Bridge in Suzhou-Nantong in China (2008), and the Stone Cutters Bridge in China (2009) having 1104m, 1088m, and 1018 m main spans respectively. According to statistics, it is anticipated that even longer spans and more sophisticated cable supported bridges will be constructed [6]. Stay cables are exposed to severe environmental conditions resulting in corrosion affecting the overall reliability and life cycle cost of the bridge [7, 8]. Secondly, the cyclic vehicular loading of the bridge deck initiates fatigue cracks in the cables, which is further accelerated by vibrations caused by wind and rain [9-11]. The self-weight of the steel cables causes an increase in the sag effect decreasing the elastic modulus of the stays [12, 13]. The periodical replacement of the steel cables is expensive and also causes an interruption in the traffic flow. In China, more than twenty bridge cables have been replaced over the past 20 years [14].

CFRP cables are approximately one fifth and the ultimate tensile resistance is approximately twice as compared with steel cables [12, 15]. CFRP cable has excellent fatigue and corrosion with a relatively minimal linear thermal coefficient [14, 16-18]. Relaxation in CFRP cables is minimal because of its excellent creep resistance [14, 15]. However, despite the many desirable features of CFRP cables, it has limited applications which can be attributed to inadequate research [19, 20]. The oldest attempt of the utilization of CFRP cable stays was by Professor Meier who proposed a 8400m center span cable stayed bridge across the strait of Gibraltar in 1987 [21]. Several CFRP cable-stayed bridges have been constructed such as the Herning Pedestrian bridge (1999), Larion footbridge (2002), Jiangsu University footbridge (2005), and the Penobscot Narrows bridge (2006) [22]. A few researchers have studied the static and dynamic characteristics of CFRP cables and its applications in cable-stayed bridges; Xie Gui Hua et al [23] researched on the static and dynamic characteristics of an existing 648m cable stayed bridge. The result indicates that the modified modulus of steel is lower than

CFRP cables and the fundamental frequency is lower in steel as compared to CFRP cables. Similarly, Arin Atabey N et al[24] studied the dynamic properties of CFRP cable using the Bosphorus Suspension bridge as a case study. It was concluded that CFRP cable is more efficient than steel cables in the dynamic analysis. Xie Xu et al [14] and Kuihua Mei et al [1] also simulated a 1400m and 1000m central span stay bridge. It was observed that CFRP cables do not induce vibrations in the dynamic analysis. Feng Bo et al[25] also investigated the fatigue resistance and safety factors of CFRP cables and the results prove that the fatigue performance of CFRP cables increases with an increasing factor of safety than steel cables.

Aside from the many short-comings of steel cables, the self-weight of the cable increases the sagging thereby decreasing the transformed elastic coefficient of the stays. Additionally, the non-linear behavior of the cables contributes to the collapse of the bridges. The geometric non-linear effect includes the bending effect, P-delta, and large rotation analysis effect. However, in the linear theory, the modified elastic coefficient E_q of the cables as a result of sag effect is estimated using the equation (1) where E is the modulus of elasticity of the cable, γ_c is the unit weight of the cable, l is the length of the cable, and σ_l is the applied stress in the cable.

$$E_q = \frac{E}{[1 + \left(\frac{\gamma_c^2 l^2}{12 \sigma_l^3}\right) E]} \quad (1)$$

Thus far, a few studies have been performed to investigate the applications of CFRP cables in stay bridges for relatively shorter spans, however this research is focused on investigating the static and dynamic behavior of 1500m central span cable stayed bridge for CFRP and steel cables under dead load, live load (Pedestrian and primary vehicular load to BS 5400:2) and positive temperature load, thus providing a reference for the utilization of CFRP cables in future spanning stay bridges.

II. Static analysis of 1500 main span CFRP cable-stayed bridge

2.1 Bridge configuration and cable span arrangement

The 1500m center span bridge in Fig.1 has modified fan cable configuration with an overall span of 663+1500+663=2826m. There are 148 cables in the entire bridge with a maximum undeformed cable length of 738m at the main span. The cables are in double plane suspension on the modified H pylon including 4 piers on both sides of the bridge. The reinforced concrete modified H-shaped pylons are 370m high with a ground clearance of 70m in Fig.2. The bridge deck comprises of 14m and 20m segments at the back and main span respectively. The steel box girder has an overall depth of 4.5 m and 29.9m width as shown in Fig.3. The deck comprises of 3-lane dual carriage traffic with two pedestrian or cycle lanes on each side with a 2% surface gradient at the top plate. In Table 1, the sectional and mechanical properties of the structural elements are provided.

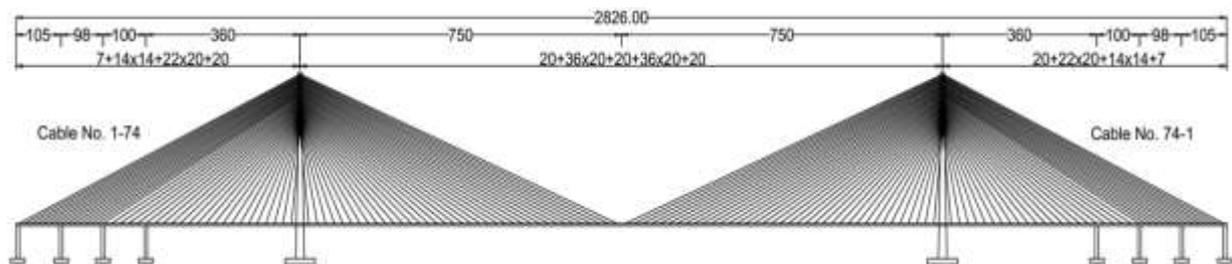


Figure 1: Layout of 1500 main span cable-stayed bridge

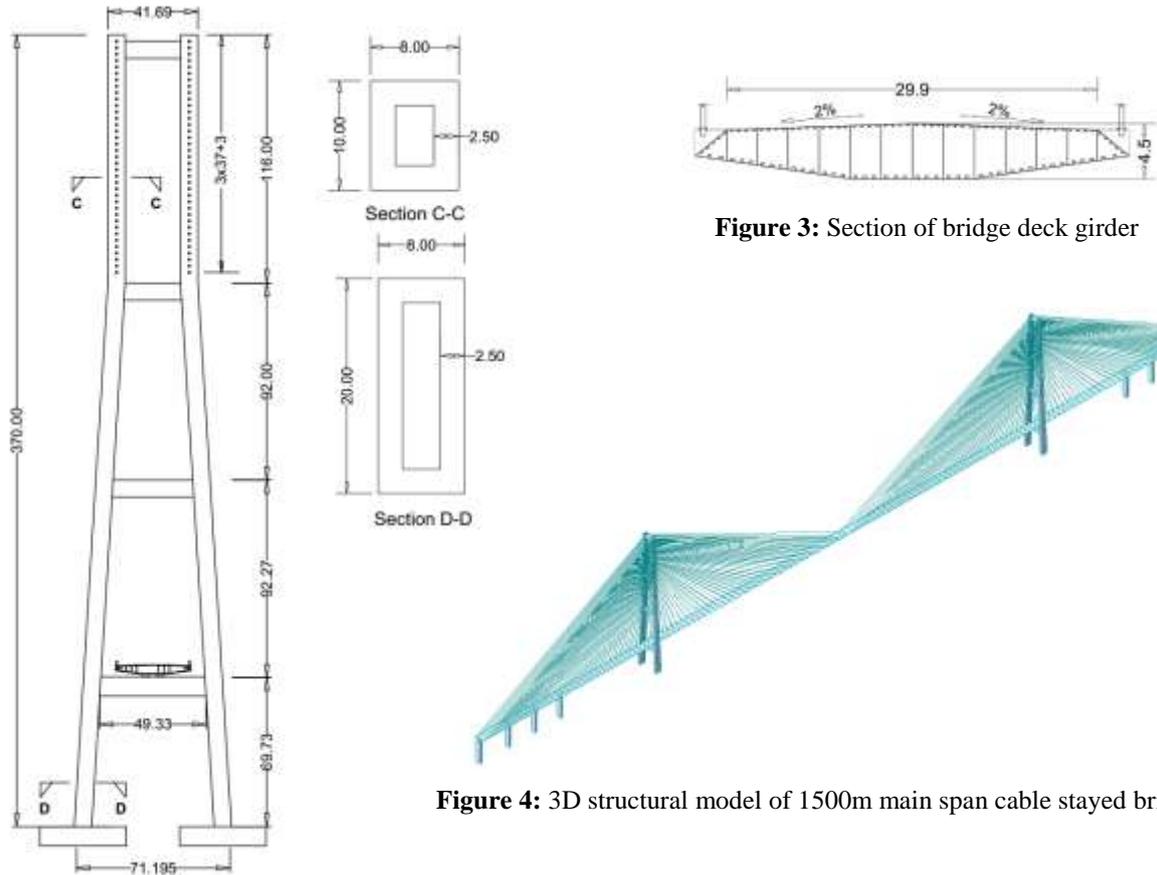


Figure 2: Layout of Tower

Table 1: Structural parameters and mechanical properties of materials

Component	Material	Nominal Area (m ²)	Moment of Area(m ⁴)	Unit weight (KN/m ³)	Elastic modulus (MPa)	Thermal coefficient
Tower	Concrete ($f_{cu}=55MPa$)	65-115	415-4490	25.0	3.5×10^4	1.0×10^{-5}
Main Deck	Steel Girder ($f_y=355MPa$)	2.17	6.80-159	80	2.1×10^5	1.2×10^{-5}
CFRP cable	lead line CFRP cable ($f_t=2550 MPa$)	0.77-1.23	0	16	1.47×10^5	0.7×10^{-6}
Steel Cable	High grade steel tendon ($f_y= 1770MPa$)	0.77-1.23	0	80	2.05×10^5	1.2×10^{-5}

2.2 Static load

Cable-Stayed bridge is a highly redundant system with the load distributed based on the relative stiffness of the load-bearing element. The static load case comprises the dead load, superimposed load, vehicular, pedestrian and the temperature load. The dead weight refers to the materials such as the deck, the pylons, and cables. The superimposed dead load includes road surfacing, services, road kerbs, and footways. The thickness of the road asphalt considered is 40mm.

The British Standard BS 5400:2 design manual for roads and highway bridges[26]provides typeHA (normal) and HB (abnormal) loading to be used as vehicle load. TheKEL (Knife-edge load) is 120KN for every notional lane. Appropriate lane factors of $\beta=1.0$ and $\beta=0.6$ are applied to the UDL+KEL to modify the loads to account for lateral bunching along the traffic lanes. From equation (2), the applied HA UDLload ω is 17.9KN/mplacedat any unoccupied region along the deck but spaced at 25m away from the HB vehicle. The 45 units HB vehicle is used with 6m axle spacing. The HB vehicle is positioned at the center span of the bridge in one notional lane for the worst load effect.

$$\omega = 36 \left(\frac{1}{L}\right)^{0.1} \text{ KN/m} \tag{2}$$

The temperature load reaction of the bridge elements is influenced based on the thermal resistance, the cross-sectional dimensions, and the environmental conditions [27]. CFRP cables has a lower linear coefficient of expansion than steel cables however, there is alack of adequate research on the performance of CFRP cables in higher or lower temperatures because of itscomplexinternal bond forces [28]. There is a high linear static relationship between the temperature effects on the pylons which induce additional cable forces [29].Therefore, the positive temperature change of 20°C is applied to the Girder and Pylon and 15°C is applied to the cables.

2.3 Static analysis results.

The completed stage cable tension is derived using the unknown load factor and influence matrix method. The cable tension is calculated using the cable force tuning function with displacement constraints of the deck and pylon for the dead and superimposed dead load. The chart in Fig.5shows the final stage forces of Steel and CFRP cable.

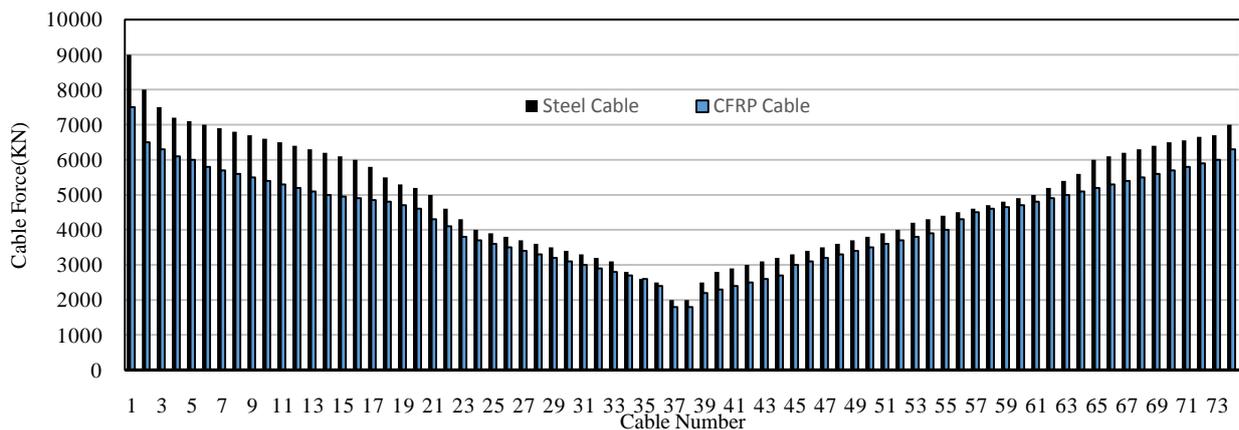


Figure 5: Final stage cable force for CFRP and steel stays

The ultimate tension force of CFRP and steel stay cables are 6700KN and 7500KN respectively accounting for approximately 10.667% increment. This increase is attributed to the high tensile strength and low density of CFRP over steel cables. The girder moment, axial force, and deflection of the main girder is analyzed for the dead load, live load (Pedestrian Load, Full HA-UDL, HA-KEL, and HB vehicle loading at mid-span), and the cable pretension is applied as uniform and concentrated forces. The geometric non-linear analysis of the cables including sag effects, P-Δ, and large displacement analysis was checked.

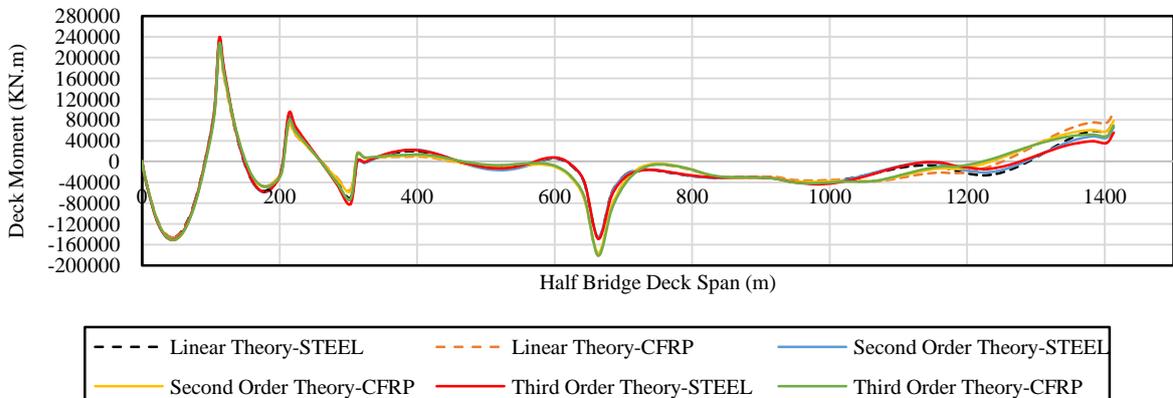


Figure 6: Bending moment diagram for CFRP and steel cable

Fig.6 indicates that the utmostdeck bending moment for CFRP and steel cables is 102.13x103 KN.m and 110.75x103 KN.m respectively corresponding to about a 7.79% increase in the girder moment for steel cables usingthe large displacement theory. Similarly, the maximum axial force in the girder for the P-Δ analysis from Fig. 7 for CFRP and steel cables is 181.70x103 KN.m and 194.45x103KN.m respectively attributingto about 6.65% increase in the girder axial force for Steel cables.

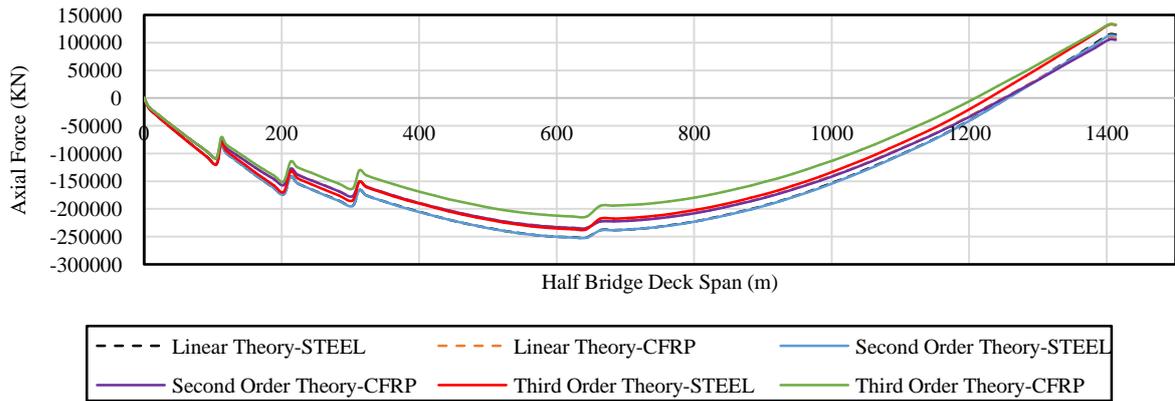


Figure 7: Deck axial force for CFRP and steel cable

In addition, from Fig.8, the maximum girder deflection at mid-span for CFRP and Steel Cables in the P-Δ effect is 2.35m and 1.95 m respectively which accounts for about 20.51% decrease in the Girder mid-span deflection using steel. There is a large mid-span deflection in CFRP cable and this increase can be attributed to the relatively lower elasticity coefficient of CFRP cables.

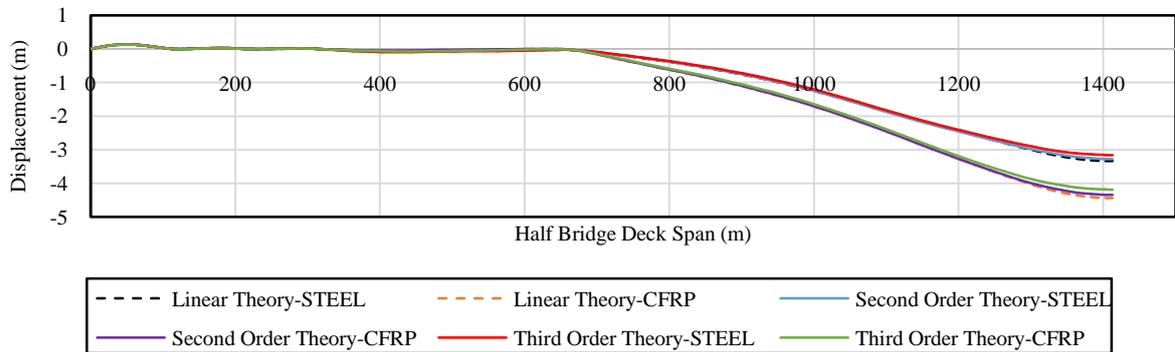


Figure 8: Deck deflection for CFRP and steel cables

Furthermore, from Fig. 9, the maximum pylon axial force at the base for CFRP and steel cables for the P-Δ analysis is 644.959×10^3 KN and 660.602×10^3 KN respectively which accounts for approximately 2.37% increase in the pylon axial force Steel cables. In addition, the maximum pylon bending moment at the support from Fig.10 for CFRP and steel cables for the large displacement analysis is 991.78×10^3 KN.m and 857.77×10^3 KN.m respectively which accounts for about a 15.62% decrease for Steel cables. Finally, the maximum pylon deflection at the top from Fig.11 for CFRP and Steel Cables for the large displacement analysis is 0.576m and 0.510 m respectively which also accounts for about a 12.94% decrease in the pylon deflection for Steel cables compared to CFRP cables.

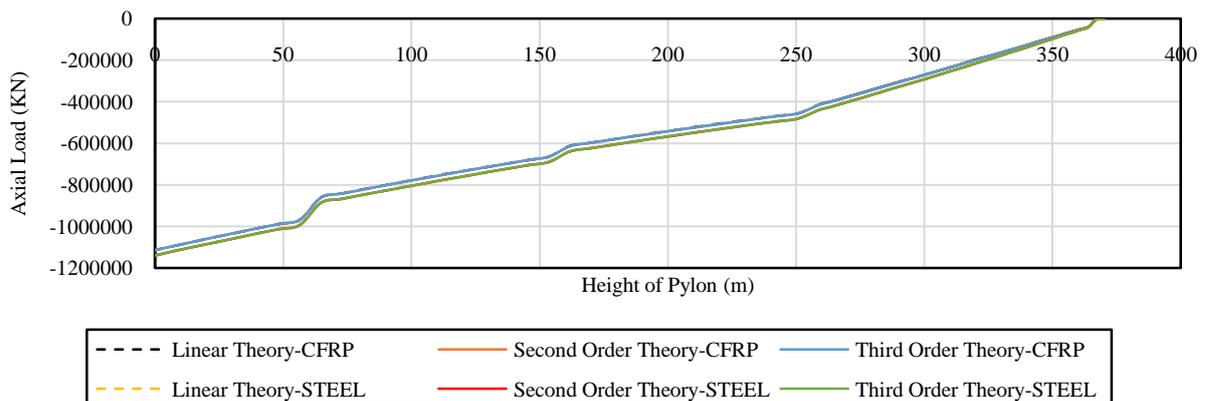


Figure 9: Pylon axial force for CFRP and steel cables

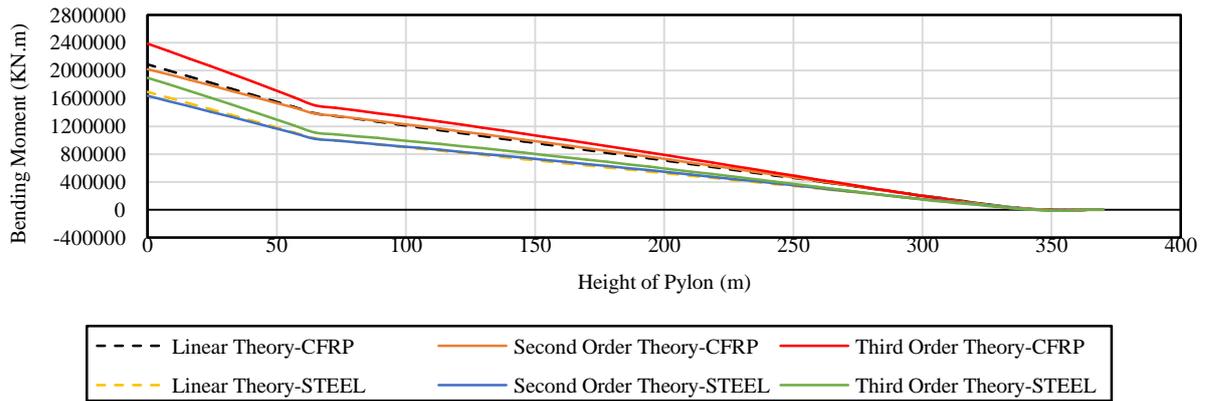


Figure 10: Pylon bending moment for CFRP and steel cables

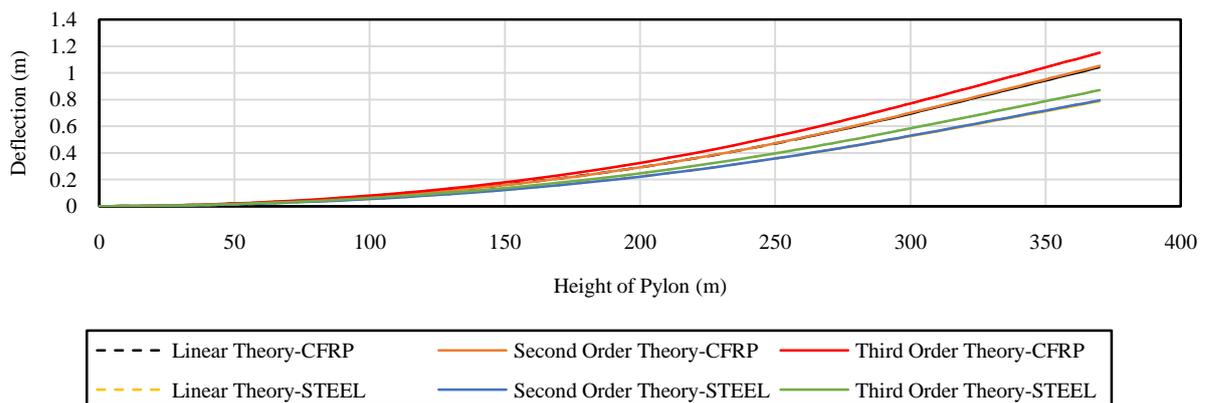


Figure 11: Pylon deflection for CFRP and steel cables

2.4 Temperature load effect

The temperature load effect cannot be disregarded for a highly indeterminate structure such as cable-stayed bridges. Temperature load affects the internal forces producing expansion and contraction of the structural members based on the temperature gradient of the material. CFRP cable has a smaller linear coefficient of expansion hence the change in deformation is small as compared with steel cables. The cable forces for CFRP increase by 0.33% while the Steel cables decrease by 0.21 % with increasing temperature. The girder deflection increases by 7.37% in steel cables while decreasing in CFRP cables.

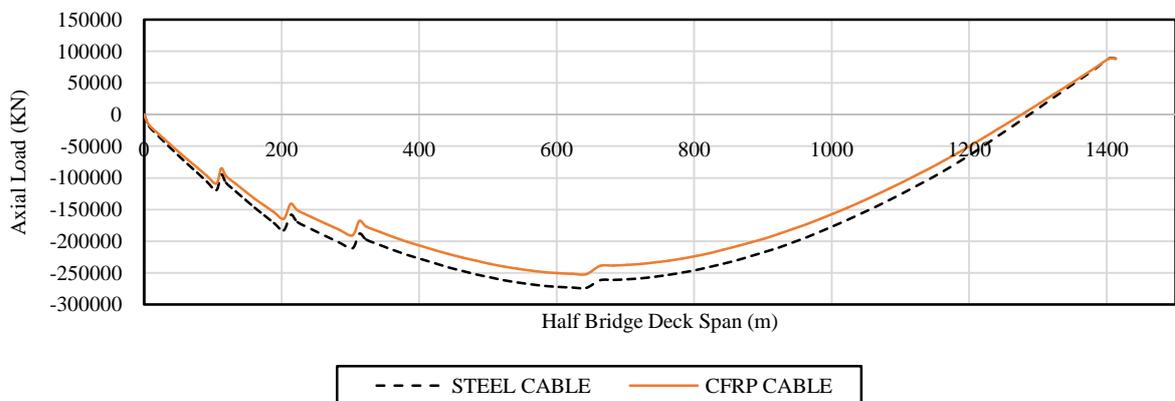


Figure 12: Deck axial force for CFRP and steel cables under positive temperature

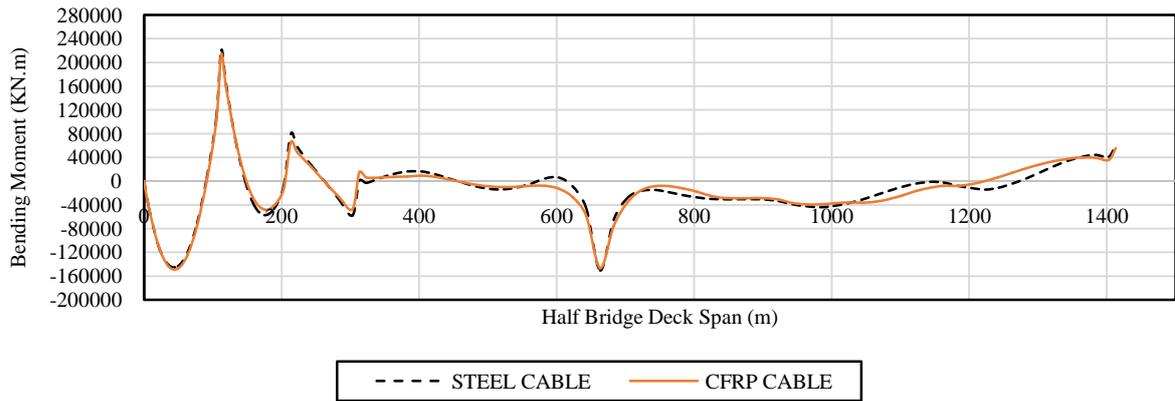


Figure 13: Deck bending moment for CFRP and steel cables under positive temperature

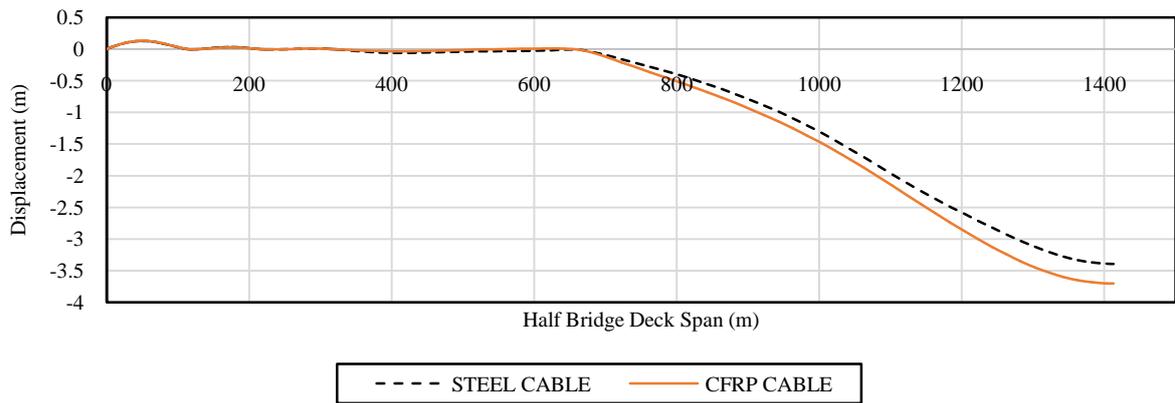


Figure 14: Deck deflection for CFRP and steel cables under positive temperature

Finally comparing the results from Fig.14, the deflection of the deck for the CFRP and Steel Cables is 17.39% and 7.02% corresponding to the reduced bending moment at the pylon support.

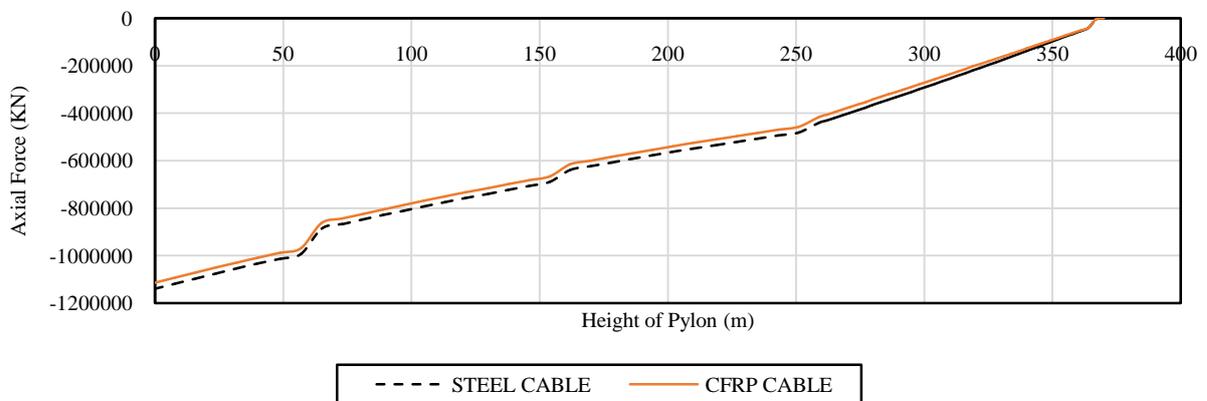


Figure 15: Pylon axial force for CFRP and steel cables under positive temperature

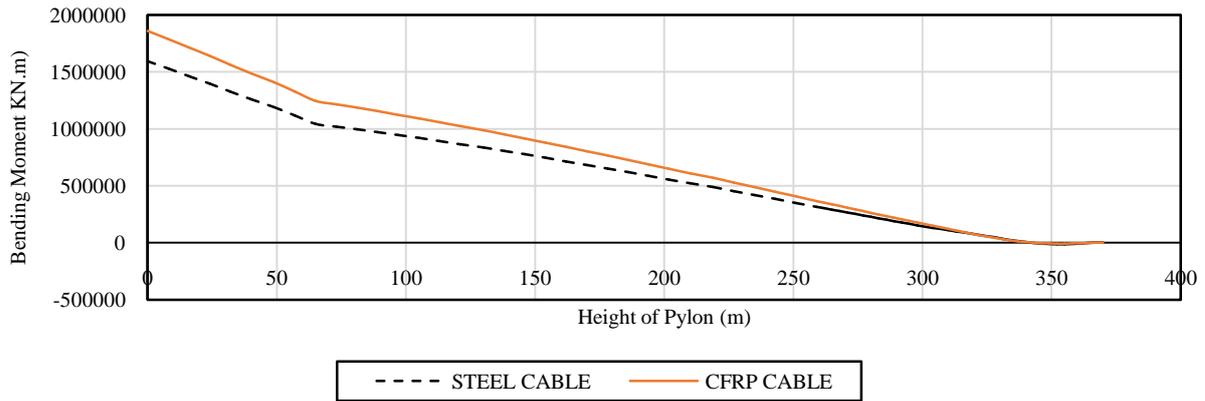


Figure 16: Pylon bending moment for CFRP and steel cables under positive temperature

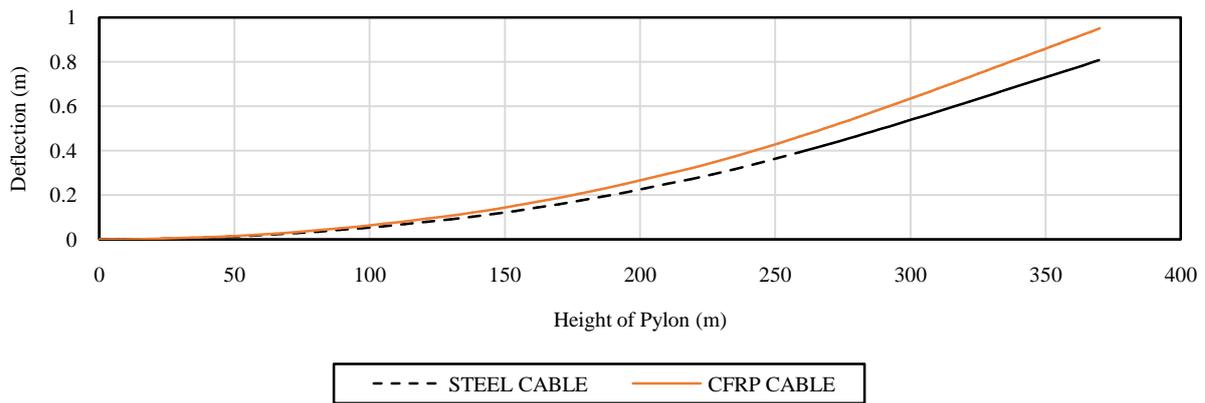


Figure 17: Pylon deflection for CFRP and steel cables under positive temperature

III. Dynamic analysis of 1500 main span CFRP cable-stayed bridge

Dynamic modal characteristics of stay cables is crucial to the overall behavior and safety of cable bridge[27]. Some major dynamic forces include aerodynamic, seismic, and pedestrian-induced vibrations [28, 29]. With increasing cable length, the frequency resonates with the entire bridge and thereby inducing resonance in the bridge[30]. The factors affecting the dynamic response of cable supported bridges is the soil condition, seismic wave, material geometric non-linearity, structural deformation, boundary conditions, structural vibration control mechanisms, and multiple support excitation [31-35].

The modal analysis included the fundamental frequency and mode shape of the cable-stayed bridge. Fig.18 and Table no. 2 shows the vibrational modes of the 1500m center span steel and CFRP cable supported bridge for the first 25 modes. The analysis results indicate that the first lateral bending, vertical bending, longitudinal drift, and torsion mode for CFRP cable-stayed bridge occurs at 0.048779 Hz, 0.151056 Hz, 0.176784 Hz, and 0.442715 Hz respectively. Similarly, for steel cable-stayed bridge, the first lateral bending, vertical bending, longitudinal drift, and torsion mode occurs at 0.046365 Hz, 0.133429 Hz, 0.163851 Hz, and 0.431886 Hz respectively. Comparing both results, the vertical bending of the CFRP cables surpasses steel cables resulting from the decreasing equivalent elastic modulus with span increment and sagging. Because of the CFRP cable lightweight and bending, the torsional characteristics is superior to steel cables.

Table2: Modal characteristic of CFRP and steel cable stayed bridge

Cable Stayed Bridge-CFRP		Cable Stayed Bridge-STEEL		Modal Characteristics
Order	Frequency (Hz)	Order	Frequency (Hz)	
1	0.048779	1	0.046365	Girder lateral bending
3	0.151056	3	0.163851	Girder vertical bending
4	0.176784	4	0.190322	Girder longitudinal drift + pylon vertical bending
5	0.227228	5	0.222764	Girder + pylon symmetric lateral bending
15	0.442715	15	0.431886	Girder and pylon torsion

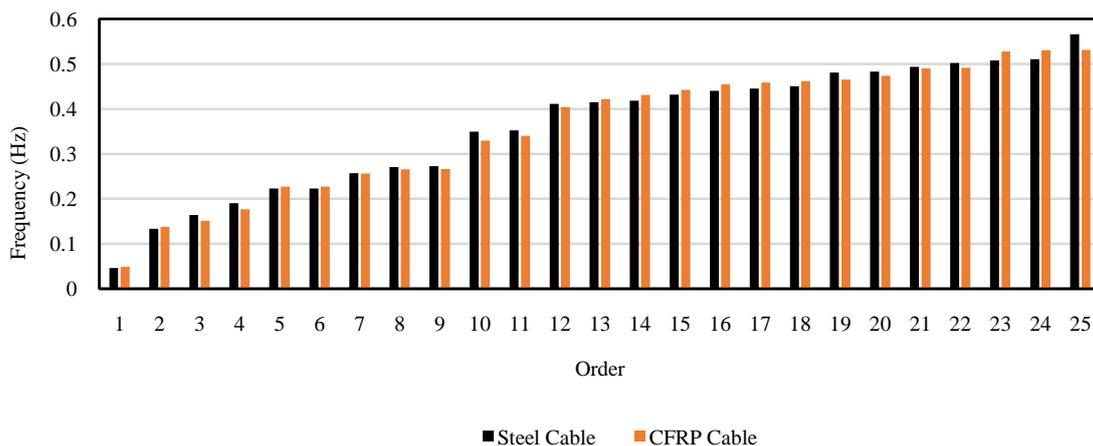


Figure 18: First 25 order frequencies for CFRP and steel cables

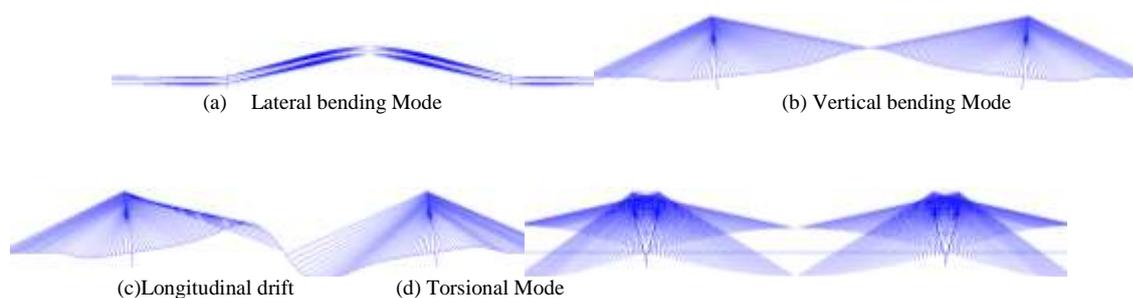


Figure 19: Vibration Mode shape of cable stayed bridge

IV. Conclusion

A finite element 1500m central span cable-stayed bridge model was modelled to explore the static and dynamic response of CFRP and steel stay cables. The influence of the nonlinear geometric characteristics of the cable-stayed bridge was investigated for the static analysis and the modal analysis was performed for the dynamic analysis. The following was observed from this research;

1. Maximum tension force of CFRP cables is lesser than steel cables for the same bridge configuration. This results from the higher unit weight and pronounced cable sag of steel.
2. The steel cables induces a maximum bending moment of the deck than steel for the live load interaction at the serviceability limit state.
3. The deck mid-span deflection for CFRP cables is higher than steel cables and this can be attributed to the greater elastic modulus of steel to CFRP. Similarly, the lateral deformation of the tower is lower in steel cables than in CFRP cables.
4. The temperature effect is higher in steel cables than in CFRP cables largely because of the lower linear coefficient of thermal expansion of CFRP cables.
5. The natural frequencies of steel cables are synonymous with CFRP cables, however, the higher damping ratio of CFRP cables enables the dissipation of lower vibration modes better than steel cables. In addition, the lateral and torsional frequency is high in CFRP than steel cables but the vertical bending frequency of steel is higher than CFRP cables.
6. The modal response of the bridge is not greatly affected by the live and temperature load effect hence it has a minimum consequence on the dynamic behavior of the cable-stayed bridge.

In conclusion, the results prove that the static and dynamic performance of CFRP cables in a 1500m center span cable stayed bridge for the dead load, live load (pedestrian and vehicle load-BS5400:2), and positive temperature load case is structurally optimized and can be utilized or replace the conventional steel stays in long span stay bridges using reliable anchorage together with adequate safety factors and further research.

References

- [1] Kuihua, M., et al., *Static and Dynamic Mechanical Properties of Long-Span Cable-Stayed Bridges Using CFRP Cables*. Advances in Civil Engineering, 2017. 2017: p. 11.
- [2] Pedro, J. and A. Reis, *Composite cable-stayed bridges: state of the art*. 2015. 1-26.
- [3] Granata, M.F., et al., *Construction sequence analysis of long-span cable-stayed bridges*. Engineering Structures, 2018. 174: p. 267-281.
- [4] Lozano-Galant, J.A., et al., *Analysis of the construction process of cable-stayed bridges built on temporary supports*. Engineering Structures, 2012. 40: p. 95-106.
- [5] Sham, S.H.R. and T.A. Wyatt, *Construction aerodynamics of cable-stayed bridges for record spans: Stonecutters Bridge*. Structures, 2016. 8: p. 94-110.
- [6] Karoumi, R., *Response of cable-stayed and suspension bridges to moving vehicles : Analysis methods and practical modeling techniques*. 1998.
- [7] Wang, C.S., et al., *Life-cycle cost based maintenance and rehabilitation strategies for cable supported bridges*. Advanced Steel Construction, 2015. 11: p. 395-410.
- [8] Das, R., et al., *Progressive Collapse of a Cable Stayed Bridge*. Procedia Engineering, 2016. 144: p. 132-139.
- [9] Xie, G.-h., et al., *Experimental study on fatigue performance of adhesively bonded anchorage system for CFRP tendons*. Composites Part B: Engineering, 2018. 150: p. 47-59.
- [10] Mei, K., Y. Li, and Z. Lu, *Application study on the first cable-stayed bridge with CFRP cables in China*. Journal of Traffic and Transportation Engineering (English Edition), 2015. 2(4): p. 242-248.
- [11] Li, C.X., X.S. Tang, and G.B. Xiang, *Fatigue crack growth of cable steel wires in a suspension bridge: Multiscaling and mesoscopic fracture mechanics*. Theoretical and Applied Fracture Mechanics, 2010. 53(2): p. 113-126.
- [12] Meier, U., *Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?* Arabian Journal for Science and Engineering, 2012. 37(2): p. 399-411.
- [13] Niels J, G. and C.T. Georgakis, *Cable Supported Bridges, Concept and Design*. Third Edition ed. 2012, United Kingdom: John Wiley & Sons Limited.
- [14] Xie, X., X. Li, and Y. Shen, *Static and Dynamic Characteristics of a Long-Span Cable-Stayed Bridge with CFRP Cables*. Materials (Basel, Switzerland), 2014. 7(6): p. 4854-4877.
- [15] Liu, Y., B. Zwingsmann, and M. Schlaich, *Carbon Fiber Reinforced Polymer for Cable Structures—A Review*. Polymers, 2015. 7(10): p. 1501.
- [16] Masuelli, M.A., *Introduction of fibre-Reinforced Polymers and Composites; Concepts; Properties and Processes*. 2013, Rijeka, Croatia: INTECH Open Access Publisher.
- [17] Derkowski, W., *Opportunities and Risks Arising from the Properties of FRP Materials Used for Structural Strengthening*. Procedia Engineering, 2015. 108: p. 371-379.
- [18] Wang, X. and Z. Wu, *Integrated high-performance thousand-metre scale cable-stayed bridge with hybrid FRP cables*. Composites Part B: Engineering, 2010. 41(2): p. 166-175.
- [19] Ren, L., Z. Fang, and K. Wang, *Design and behavior of super-long span cable-stayed bridge with CFRP cables and UHPC members*. Composites Part B: Engineering, 2019. 164: p. 72-81.
- [20] Xiong, W., et al., *Study of super long span cable-stayed bridges with CFRP components*. Engineering Structures, 2011. 33(2): p. 330-343.
- [21] Meier, U., *Proposal for a Carbon Fibre Reinforced Composite Bridge across the Strait of Gibraltar at its Narrowest Site*. Proceedings of the Institution of Mechanical Engineers, Part B: Management and engineering manufacture, 1987. 201(2): p. 73-78.
- [22] Jay Rohleder, W., et al., *Carbon Fiber-Reinforced Polymer Strand Application on Cable-Stayed Bridge, Penobscot Narrows, Maine*. Vol. 2050. 2008. 169-176.
- [23] Xie, G.-h., et al., *Experimental and numerical investigation on the static and dynamic behaviors of cable-stayed bridges with CFRP cables*. Composites Part B: Engineering, 2017. 111: p. 235-242.
- [24] Arin Atabey, N., et al., *Dynamic Analysis of a Suspension Bridge Using CFRP Composite Material*. 2013.
- [25] Feng, B., X. Wang, and Z. Wu, *Fatigue life assessment of FRP cable for long-span cable-stayed bridge*. Composite Structures, 2019. 210: p. 159-166.
- [26] *BS 5400: Steel, Concrete and Composite Bridges-Part 2: Specification for loads*. 2006.
- [27] Wei, L., H. Cheng, and J. Li, *Modal Analysis of a Cable-stayed Bridge*. Procedia Engineering, 2012. 31: p. 481-486.
- [28] Larsen, A. and G.L. Larose, *Dynamic wind effects on suspension and cable-stayed bridges*. Journal of Sound and Vibration, 2015. 334: p. 2-28.
- [29] Frýba, L. and J.-D. Yau, *Suspended bridges subjected to moving loads and support motions due to earthquake*. Journal of Sound and Vibration, 2009. 319(1): p. 218-227.
- [30] Cai, H. and A.J. Aref, *On the design and optimization of hybrid carbon fiber reinforced polymer-steel cable system for cable-stayed bridges*. Composites Part B: Engineering, 2015. 68: p. 146-152.
- [31] Zhong, J., J.-S. Jeon, and W.-X. Ren, *Risk assessment for a long-span cable-stayed bridge subjected to multiple support excitations*. Engineering Structures, 2018. 176: p. 220-230.
- [32] Eftymiou, E. and A. Camara, *Effect of spatial variability of earthquakes on cable-stayed bridges*. Procedia Engineering, 2017. 199: p. 2949-2954.
- [33] Zhou, L., X. Wang, and A. Ye, *Shake table test on transverse steel damper seismic system for long span cable-stayed bridges*. Engineering Structures, 2019. 179: p. 106-119.
- [34] Martínez-Rodrigo, M.D. and A. Filiatrault, *A case study on the application of passive control and seismic isolation techniques to cable-stayed bridges: A comparative investigation through non-linear dynamic analyses*. Engineering Structures, 2015. 99: p. 232-252.
- [35] Han, Q., et al., *Nonlinear seismic response of a base isolated single pylon cable-stayed bridge*. Engineering Structures, 2018. 175: p. 806-821.