Analysis of a long span cable-stayed suspension hybrid bridge considering variable intermediate side span supports

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Abstract. The bridges supported by high strength steel cables are the substitute to attain very lengthy bridge. Usually, cable supported bridge systems known as cable-stayed bridge and suspension bridge are used to achieve longer span bridge. In the cable-stayed bridge system better stiffness is achieved due to inclined stayed cables. In suspension bridge systems longer central span is achieved by provision of stiffened deck. The novelty in structural form, material technology and analysis methods offer further long span cable supported structural system. By combining the cable-stayed bridge and suspension bridge in a bridge, an innovative form of hybrid cable-stayed suspension bridge may offer enhanced behaviour. Mathematical model for innovative form of hybrid cable-stayed suspension bridge is addressed. The geometrical parameters play important role in structural behaviour of the cable-stayed suspension hybrid bridge. Nonlinear static analysis and modal analysis are carried out using SAP2000 software. The effects of intermediate side span support on the static and dynamic behaviour of cable-stayed suspension hybrid bridge are presented in the form of time period of bridge in lateral, longitudinal, vertical directions and pylon bending.

1. Introduction
Now long span bridge need is increasing day by day to facilitate the need of the civilization. Cable stayed bridges and suspension bridges are the systems used to achieve long span bridges. Cable supported bridges use leads to spans between 200m and 2000m. In a cable supported bridge system maximum span is determined by the strength of materials used, stiffness of bridge elements and density of materials used. High strength steel cables are a primary material considered in design and analysis of cable-stayed bridges and suspension bridges, which proves to be superior for efficient tension resistance. In cable supported bridge advantages is the way of the system to use material. The cable supported bridge form plays important role in behaviour. In this article types of cable supported bridges and its structural forms are presented.

2. Suspension bridge
In a suspension bridge a deck is supported by vertical hangers, which are connected to main catenary cables. These main catenary cables are supported at pylons and anchored at anchorage provided at end of the span. Structural form of the suspension bridge system is shown in Figure 1.
The suspension bridge development was started from 18th century. From beginning of the 19th century, suspension bridges have regularly developed in size, and since 1930 the suspension bridge has completely dominated the upper span range. There are several bridges constructed like George Washington Bridge (USA) in 1931 having 1066m mid span, Golden Gate Bridge (USA) with 1280 m main span in USA constructed in 1937, Humber Bridge (England) with mid span 1410m constructed in 1981, Great Belt East Bridge (Denmark) with mid span 1624m constructed in 1997 and Akaski Kaikyo Bridge(Japan) with central span 1991m were constructed in 1998.

3. **Cable-stayed bridge**

   In case of cable-stayed bridge the bridge deck is supported with the help of inclined cable-stays and these cable-stays are connected at the other end at the pylons as shown in Figure 2.

   ![Figure 2 Fan type cable-stayed bridge](image)

   The selection of cable arrangement depends mainly on: (1) Construction material (2) Types of soil in the foundation; (3) main span length; (4) creativity of the structural design.

4. **Cable-stayed suspension hybrid bridge**

   The inclined cables supported directly from pylons are stretched enough to provide required lateral stability to deck. The suspenders supported from the main catenary cables supporting the deck in vertical directional forces. Hence the advantages of both cable-stays and suspension cables could be achieved by adding both the cables in the same bridge system as shown in figure 3. The inclined stays and vertical suspender use in same structure was initiate by Dischinger, Roebling, Gimsing and...
Steinmann etc. Brooklyn bridge in America was rehabilitated after 1920 by introducing the cable-stayes and suspension cables in same structural system.

Some of the other bridge name as Salzar bridge in Portugal, Tancarville bridge in France was also rehabilitated by introducing both the cable-stays and suspenders in same structure. Gimsing 1988, Lin and Chaw 1991, Schlaich 1988 studied the behaviour of cable-stayed and suspension bridge system in a one bridge and elaborated the enhancement in the behaviour of structural system. [1] This also proves that the cable-stayed suspension hybrid bridge is innovative form of cable supported bridge use to achieve improved structural behaviour. From the literature reviewed it can be concluded that the work accomplished in analytical and computational technique was insufficient; the bridge system was not realized until 1997. First cable-stayed suspension hybrid bridge was built in china with main span 288m, in 1997. [2]

4.1 Behavior of cable-stayed suspension hybrid bridge:
The system of bridge achieved by joining both the system of cable supported bridge like suspension bridge system and cable-stayed bridge system following compensation could be achieve:
1. To achieve very long span in bridge system the hybrid cable-stayed suspension becomes an attractive alternative bridge systems.
2. The load from the suspenders is transfer to the main catenary cable in suspension bridges. Here in combined cable-stayed suspension bridge system deck is also supported by cable-stays thus the tensional forces in the main catenary cables are greatly decreased compared to the suspension bridge with the same span length.
3. During erection of bridge cantilevers are shortened effectively thus wind stability of the bridge therefore improved during construction.
4. The combined bridge system can reduced the overall cost of the project as cost of main catenary cables and massive anchorages are reduced efficiently with respect to same span of suspension bridge.
5. The centre span enhancement causes elimination of difficulty to construct them in water, and therefore makes it possible to build even in the soft soil strata.
6. The portion of bridge supported by cable-stayes is also shortened, results reduction in the axial forces in the deck, length of stays and height of tower.
7. This combined bridge system results in saving the materials in deck and makes it economical, different materials can be employed in the suspension and cable-stayed portions.
8. The light weight steel box girder can be employed for suspension bridge portion and prestressed concrete girder can be used for the cable-stayed bridge portion.

4.2 Analysis of cable-stayed suspension hybrid bridge
The Cable-stayed suspension hybrid bridges designed for conventional loads, these structures very flexible in nature and are very sensitive to wind and seismic loads. Analysis of Short to medium span bridges are carried out with methods for determining quasi-static wind or seismic effects, whereas long or super-long span bridges necessarily exhibit a marked dynamic behaviour. The dynamic behaviour of a bridge is reliant upon the structural as well as dynamic characteristics like mass of the elements, stiffness of structure, frequency of structure, geometrical shape and damping of bridge. These characteristics are often related to form and main span of the bridge. In 2005 aerodynamic behaviour of 1400 m main span cable-stayed suspension hybrid bridges was presented by Zhang et. al. Authors studied and presented three-dimensional nonlinear aerodynamic stability analysis for cable-stayed-suspension hybrid bridge. The design parameters like the cable sag, length of suspension portion, cable plane arrangement, subsidiary piers in side spans, the deck form, etc. also considered for the aerodynamic stability of the bridge are analytically investigated.[3]

The flutter stability analysis of cable-stayed suspension hybrid bridges is studied by Zhang et. al. in 2006. In this article taking into consideration the geometrical nonlinearity of bridge structures, three dimensional nonlinear flutter stability analysis of 1400m span hybrid cable-stayed suspension bridge carried out. The discussion on method, its procedure and the effects of nonlinear wind structure
interaction carried out. [2] The investigation on mechanics performance of cable-stayed bridge, suspension bridge and cable-stayed suspension hybrid bridges is carried out by Zhang et. al. in 2007. The mechanics performance of 1400 m main span Cable-stayed suspension hybrid bridge. From the study author found and investigated that compared to cable-stayed bridge and suspension bridge, hybrid cable-stayed suspension bridge has greater structural stiffness less internal forces and good wind stability. [4]

### 4.3 Mathematical modeling of cable-stayed suspension hybrid bridge

The cable-stayed suspension hybrid bridge diagram is represented in figure 4. The bridge geometrical parameters like side span $l_1$ and one central main span $l_2$ shown in the figure.

![Figure 4: Hybrid cable-stayed suspension bridge configuration](image)

#### 4.4 The equation of motion for cable-stayed suspension hybrid bridge

The forced flexural vibration of hybrid cable-stayed bridge system is obtained by the following relation neglecting the longitudinal deformations, and the damping of the system:

$$M \ddot{u}(t) + C \dot{u}(t) + K u(t) = R_i(t) + R_s(x,t)$$  \hspace{1cm} (1)

Where, $M$ is the mass, $C$ is damping and $K$ is stiffness matrices. $R_i(t)$ is the notation for applied dynamic load vectors. In this system for seismic analysis, seismic load is presented by $R(t)$. In this equation Vectors $\ddot{u}$ is the absolute acceleration $\dot{u}$ is absolute velocity and $u$ is absolute displacement.

$R_s(x,t)$ is the prestressing forces due to the influence of stayers and hangers on the bridge deck.

$$R_s(x,t) = q_c(x,y,t) + q_s(x,y,t) + q_{CH}(x,y,t)$$  \hspace{1cm} (2)

Where,

$q_c(x,y,t)$ is the considered stayers tensions,

$q_s(x,y,t)$ is the considered stayers tensions,

$q_{CH}(x,y,t)$ is the the considered horizontal component of stayers tensions.

For bridge system by ignoring for instant the effect of seismic force of the deck and the effect of the horizontal components of the stayers, the mathematical equation for a free vibration mode of bridge takes the following form:

$$M \ddot{u}(t) + C \dot{u}(t) + K u(t) = -q_c - q_s$$  \hspace{1cm} (3)

From the above mathematical model it is presented that in the free vibration of bridge system, motion of the bridge are affected by the mass matrix $M$, damping matrix $C$, stiffness matrix of the bridge $K$, along with the influence of the tension forces in stayers in cable-stayed portion and vertical suspenders in suspension portion.

### 5. Bridge configuration data:

Bridge modeling and analysis of 1400m main span earth anchored cable-stayed suspension hybrid bridge is carried out in SAP 2000 V14 software. The considered geometrical parameter intermediate side span supports influence is studied to establish the behavior of the bridge in current manuscript.
5.1 Bridge Configuration:
Central span length in considered bridge = 1400 m, side span = 700m, pylon height=258.98m
Suspension portion to main span ration in hybrid cable-stayed suspension bridge=0.5
In order to improve the vertical bending stiffness of cable supported bridges, several subsidiary piers can be used in side spans [2]. To investigate the effect of the subsidiary piers in side spans, different cases considered as shown in Table 1.

| No. of subsidiary piers considered | 0  | 1  | 2  | 3  |
|-----------------------------------|----|----|----|----|
| Locations of subsidiary piers: (Ls = Length of side span) | Ls | ½ Ls | 1/3 Ls | ¼ Ls |

The cable-stayed suspension hybrid bridge is analyse considering following sectional properties of structural elements as shown in the following Table 2.

| Members          | E  (Mpa) | A (m²) | Jₜ (m⁴) | Iₚ (m⁴) | Iₚz (m⁴) | M (Kg/m) | Jₜm (Kg.m²/m) |
|------------------|---------|--------|---------|---------|---------|---------|-------------|
| Girder           | 2.1x10⁵ | 1.2481 | 5.034   | 1.9842  | 137.754 | 18386.5 | 1.852x10⁶   |
| Stay cable       | 2.0x10⁵ | 0.0154 | 0.0     | 0.0     | 0.0     | 120.12  | 0.0         |
| Hanger cable     | 2.0x10⁵ | 0.0065 | 0.0     | 0.0     | 0.0     | 50.2    | 0.0         |
| Main Cable CS    | 2.0x10⁵ | 0.3167 | 0.0     | 0.0     | 0.0     | 2660    | 0.0         |
| Main Cable SS    | 2.0x10⁵ | 0.3578 | 0.0     | 0.0     | 0.0     | 2980    | 0.0         |
| Tower C          | 3.3 x10⁴ | 30     | 350     | 320     | 220     | 78000   | 5.7x10⁵     |
| Tower TB         | 3.3 x10⁴ | 10     | 150     | 70      | 70      | 26000   | 4.7x10⁵     |

Where, E is Modulus of Elasticity of considered materials; 
A is Cross section area of bridge elements; 
M is Mass of elements per unit length; Jₜ is the torsional Constat; 
Iₚ is the Lateral Bending moment of inertia; 
Iₚz is the Vertical Bending moment of inertia; 
Jₜm is the mass moment of inertia per unit length.

5.2 Modeling of different members of the bridge in Sap2000
The assignment of different structural elements is as follows.
Deck of bridge is model as a frame element with cross sectional properties as mentioned in the below Table 2. Pylon and pylon beam are modeled as a frame section. All the cables of the bridge are model as a tension only resistant cable element having cross sectional properties as presented in Table 2.

5.3 Load Assignments to Structural Elements of Bridge
Structural elements of bridge are assigned with load cases which are shown in below Table 3.

| Type of the load | Value of Assigned Load | Element Assigned |
|------------------|------------------------|-----------------|
| Dead Load        | 97.980 kN/m            | Deck            |
| SIDL             | 50.0 kN/m              | Deck            |
| Live Load        | 34.650 kN/m            | Deck            |
5.4 Load cases considered for analysis of bridge:

(1) Static nonlinear analysis
(2) Modal analysis

Table 4: Configuration of cable-stayed suspension hybrid bridge with number of subsidiary piers

| Subsidiary piers and distance between supports | Geometrical Configuration of cable-stayed suspension hybrid bridge with number of subsidiary piers in side span and distance between two piers |
|-----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
| 0 @ 700m                                      | ![Configuration Diagram](image)                                                                                                    |
| 1 @ 350m                                      | ![Configuration Diagram](image)                                                                                                    |
| 2 @ 233 m                                     | ![Configuration Diagram](image)                                                                                                    |
| 3 @ 175 m                                     | ![Configuration Diagram](image)                                                                                                    |

5.5 Results and Discussion

The analysis of 1400m main span and 700m side span cable-stayed suspension hybrid bridge with suspension to main span ratio of 0.5 is carried out to understand the nonlinear static and dynamic behavior considering 0, 1, 2 and 3 number of ISSS as shown in Figure 4. Figure 5 and Figure 6 given below present the time period in lateral and longitudinal bending mode respectively with 0, 1, 2 and 3 numbers of ISSS.

![Figure 5](image) Lateral mode shapes time period of 1400m main span and 700m side span cable-stayed suspension hybrid bridge (Sus. to span=0.5) with various ISSS

![Figure 6](image) Longitudinal mode shapes time period of 1400m main span and 700m side span cable-stayed suspension hybrid bridge (Sus. to span=0.5) with various ISSS

Figure 7 given below present the time period of vertical mode of 1400m main span and 700m side span cable-stayed suspension hybrid bridge (Sus. to span=0.5) with various ISSS in lateral and longitudinal bending mode with 0, 1, 2 and 3 numbers of ISSS. Figure 8 given below present the time period of pylon mode of 1400m main span and 700m side span cable-stayed suspension hybrid bridge (Sus. to span=0.5) with various ISSS in lateral and longitudinal bending mode with 0, 1, 2 and 3 numbers of ISSS.
Behaviour of cable-stayed suspension hybrid bridge with suspension to main span ratio=0.5 is studied with different numbers of ISSS. Dynamic analysis is carried out for cable-stayed suspension hybrid bridge with different number of ISSS. From the analysis, following points are observed:

1. It is found from dynamic analysis of cable-stayed suspension hybrid bridge bridges that increasing numbers of ISSS, the time period of bridge is reduced effectively.
2. Time period in lateral, vertical and longitudinal direction is reduce 1.00%, 3.65% and 2.11% respectively by providing only one intermediate side span supports.
3. Time period in lateral, vertical and longitudinal direction is reduce 1.59%, 4.01% and 2.3% respectively by providing three number of intermediate side span supports.
4. Reduction in pylon bending time period is observed as 1.06 % and 4.98% respectively by providing one and three number of intermediate side span supports.

From the above results it is found that maximum enhancement in behaviour is found in vertical direction of deck and in pylons by provision of ISSS, thus vertical bending stiffness of the bridge can be efficiently enhance by provision of ISSS.

6 Conclusion

The current article addressed theme concerned related to the development of cable-stayed bridge, suspension bridges and cable-stayed suspension hybrid bridge. It is found from the available literature that, combine system provides better stiffness and suspension bridge systems provides longer span. Mathematical model of hybrid cable-stayed suspension bridge is also addressed in the article. It is found from the review carried out that there is wide scope for the analysis of cable-stayed suspension hybrid bridge considering non dimensionless geometrical parameters. The analysis of 1400m main span and 700m side span cable-stayed suspension hybrid bridge with suspension to main span ratio of 0.5 is carried out to understand the nonlinear static and dynamic behavior considering 0, 1, 2 and 3 number of ISSS. From the considered geometrical parameters it is found that intermediate side span support plays important role in the vertical bending behaviour of cable-stayed suspension hybrid bridge. The vertical bending behaviour of bridge is enhanced effectively and reduced time period of bridge by 3.65% by provision of only one intermediate side span supports.

7 References

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