STATIC AND SEISMIC BEHAVIORS OF CABLE-STAYED BRIDGES WITH NEW STAY SYSTEMS

Tokai University Student Member ○Fatema Samim
Tokai University Fellow Member Shunichi Nakamura

1. INTRODUCTION

Cable-stayed bridges are structurally rational and can extend the applicable span length. On the other hand, they are relatively flexible and vulnerable to the dynamic loads of traffic. This is one of the reasons why they are not commonly used for railway bridges which require severe deflection restriction.

Two promising solutions have recently come out and applied to the actual bridge: the overlapping stay system and the hybrid cable system. The overlapping stay system has adopted on the New Forth Road Bridge where the girders are suspended with overlapping stays near the span center in addition to the stays spread on other parts (Hussain 2011). As the hybrid cable system, the girders are suspended by the suspension cables at the center part in addition to the stay cables on other parts. This hybrid cable-stayed bridge is a combined system of the cable-stayed bridge and suspension bridge and adopted on the Third Bosporus Bridge. Currently, hybrid cable-stayed suspension bridges are mainly used earth-anchored system; they need huge anchors that mean higher construction cost and difficulty. The hybrid system in this study is self-anchored cable-stayed suspension bridge. However, there are not many studies on their structural characteristics; especially, their behavior under exclusive loads of train is not clarified.

This paper presents static and seismic structural behaviors of these two new cable arrangements. First, static analysis with three-dimensional finite element models are carried out to clarify how the overlapping stays and suspension cable effect on the deflection of the girder and the bending moment of the towers. Three different distributed patterns of live load cases were applied consisting of train and vehicle loads. It is clarified that how much the overlapping stays and hybrid stayed-suspension cable reduces the displacements of the girder and bending moment of the towers. The deflection of the girder with overlapping stays and hybrid stayed-suspension cable due to the train loads are obtained and compared with the conventional cable arrangement. The live load deflection of the new cable arrangements are verified by the allowable value specified for the Shinkansen Train (Japanese Bullet Train) and serviceability limit is discussed. Safety of the girder, the towers and the cables are verified by the allowable stress method for the design loads.

Second, elasto-plastic seismic analysis has been performed for the bridge models with the overlapping cable arrangements, hybrid stayed-suspension cable arrangement and the conventional cable arrangement due to the two ground motion seismic waves: the medium-strong earthquake (L1-EQ) and the ultra-strong earthquakes (L2-EQ). It is clarified whether the new systems with overlapping cable arrangements and hybrid stayed-suspension cable arrangement can improve the seismic performance by comparing with the conventional system. The energy hysteretic behaviors of the bridge systems are also discussed for the L1-EQ and the L2-EQ.

2. BRIDGE MODEL

The long span cable-stayed bridge with a main span length of 800 m is studied in this paper (Fig.1). Four bridge models with four different stay cable arrangements are considered: Model-I with conventional cable arrangement, Model-II with no clearance at the span-center of the right and left cables, Model-III with overlapping stay cables near the span-center and Hybrid Cable-Stayed-Suspension Model with suspension cable at the main span.

The girder is a steel box girder with width of 26.2 m and height of 3.5 m with orthotropic deck (Fig.2). The bridge has two main tower and two side piers. The span length is 128+192+800+192+128m. The main tower is 210 m high and designed as an A-shaped (Fig.3). The cross-section is a steel box section with 7m length and 5m width with 40mm thick steel plates (material SM490Y), as shown in Fig.4. The side piers are located at 128m from the bridge end. All four models have the same dimension of towers and girder, but different number of cables. Cables have multi-fan stay systems in two planes with the maximum cable length of about 540 m for Model-III. A semi-parallel wire strand consisting of 7mm diameter galvanized wires were assumed. Five different numbers of strands were used for the models: the maximum wire number of 499 is used as an anchor cable in all three models and as a suspension cable in hybrid model; and the minimum number of wires of 199 is used in model-III. The number of stays in both Model-I and Model-II is the same 160 stays, but in Model-III are 184 stay cables and in hybrid Model 166 stays plus two suspension cables and hangers.

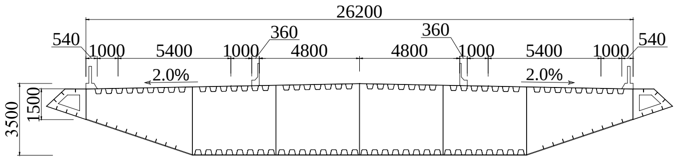

Fig.2 Girder cross-section (mm)

Keywords: Cable-stayed Bridge, overlapping stay-cables, serviceability limit, seismic analysis
Contact address: 4-1-1 Kitakaname, Hiratsuka, Japan, Tel:+81-463-58-1211 Email: snakamu@keyaki.cc.u-tokai.ac.jp

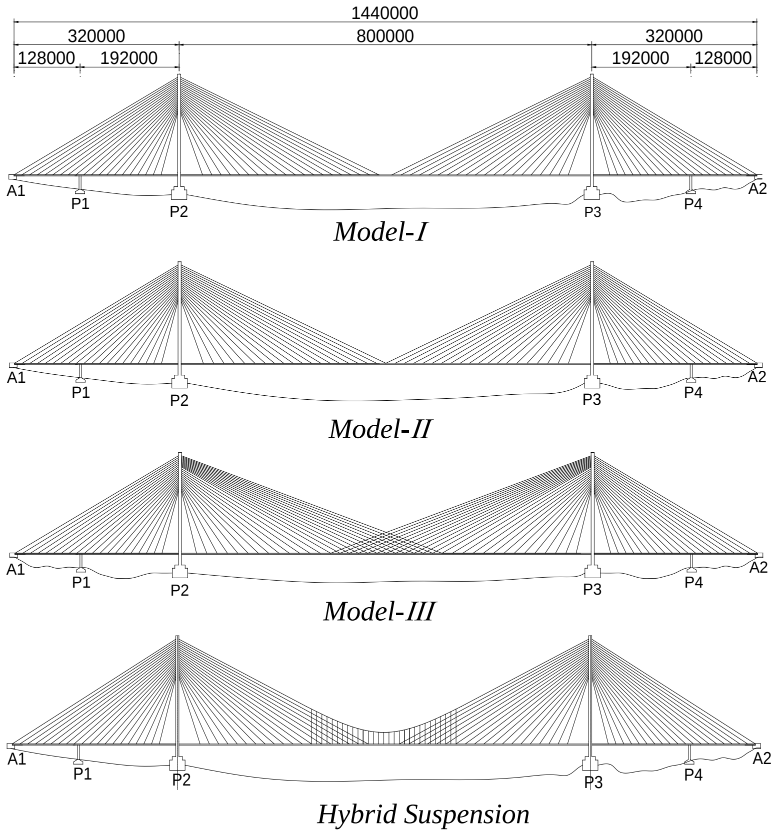

Fig.1 Side view of the three bridge models (mm)

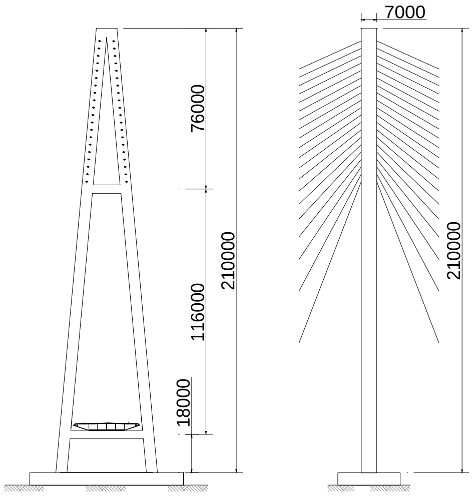

Fig.3 Main tower (mm)

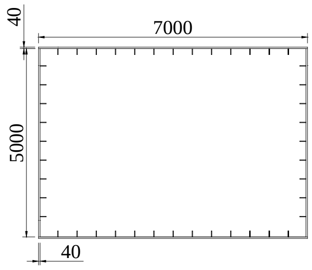

Fig.4 Tower cross-section

The finite element model is used in the static analysis, where the girder is supported vertically at the towers and piers but it is free to move longitudinally.

3. STATIC BEHAVIOR UNDER DESIGN LOADS

Static analysis was conducted with four bridge models with different stay cables arrangement and the sectional forces and deformations were obtained. The girder is supported vertically and transversally on the cross beam of the tower but moves longitudinally. Considering the geometrically nonlinear effect, the static performances of four models were analyzed for the design loads. The design loads consist of dead loads (D) and design live loads (L) for vehicles and trains. The vehicle design live load is assumed uniformly-distributed loads p1=3.0 kN/m^2, which is a simplified value for long span bridges based on the Japanese specifications for highway bridges (Japanese Road Association 2012). The train design live load is uniformly-distributed loads p2=25.6 kN/m^2/train which is for Shinkansen 700 series, one of the heaviest trains in Japan. The total length of this train is 400m consisting of 16 cars with each car 25m long. As an axial load is 160 kN/wheel, the distributed live load of each car is “load × No. of wheels/length = (160 × 4)/25 = 25.6 KN/m” according to the Japanese Railway Specifications (Railway Technical Research Institute 2010).

Three live load cases L1, L2 and L3 are considered. First, the bridge subjected to vehicle loads in full spans and train loads in 400m length at the center of mid-span. Second, both vehicle and train loads are considered only at mid-span and in the third case one side span is loaded (Fig.5). Third, it is clarified that the mid-span loading is the critical loading case. The maximum girder deflection and bending moment of the tower occurred for the combination of D+L2.

Fig.6 shows the girder deflection of Model III due to D+L, which is the maximum in the case of D+L2. So, it clearly indicates that the mid-span live load loading is critical. Fig.7 shows the tower displacement of the four models with four different stay arrangements for D+L2, showing that the displacement is smaller in the Model-III and hybrid model. It is observed that the overlapping of stay cables and hybrid-stayed-suspension cable have significant effect on reducing of the bridge deflection.

It is noted that the allowable stress method is used for the safety check of girder, towers and cables. Sizes of the box section and plate thickness of the girder and the towers were determined by the maximum sectional forces. The same girder and tower

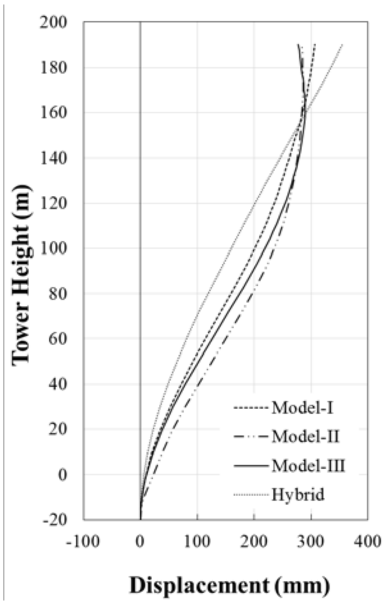

Fig.7 Tower displacements (D+L2)

sections are applied in the whole model. Different size and number of cables are used for four models depending on the tensile forces due to the design loads. It is checked that all the stays are in tension under the design loads.

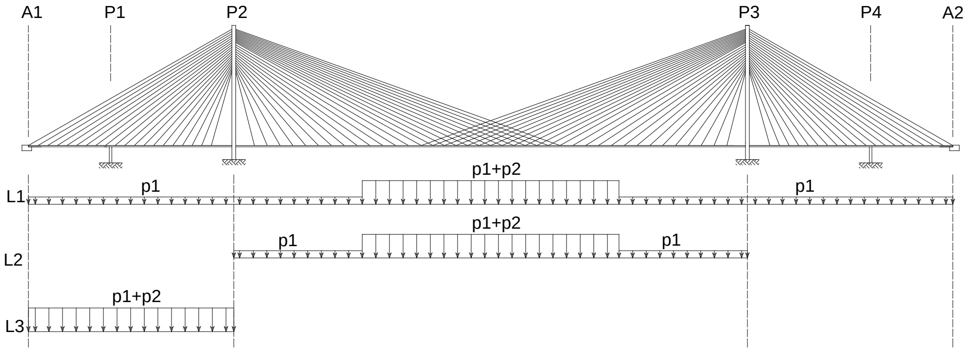

Fig.5 Live load cases

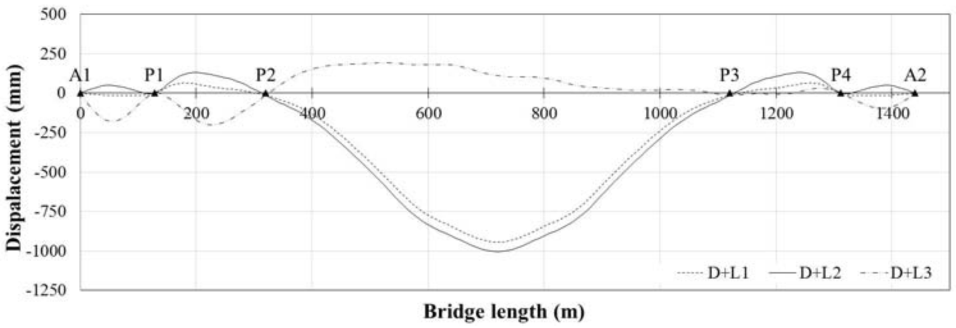

Fig.6 Displacement of the girder under D+L for Model-III

4. SERVICEABILITY OF THE BRIDGE DUE TO TRAIN LOAD

The deflection of the main girder of four models due to the train loads are shown in Fig.8. It shows that the vertical deflections of the steel girder in mid-span is smaller in Hybrid-suspension and Model-III, followed by Model-II and Model-I. The allowable deflection of the steel girder for Railway Bridge is 400mm and allowable deflection angle is 2.5mrad according to the Japanese Railway Bridge Specifications. Only Model-III with 398mm deflection and Hybrid-suspension with 395mm deflection satisfy the allowable deflection value for the steel girder and all the models satisfy the allowable deflection angle. The deflection of Model-I and Model-II are 440mm and 437mm respectively. Therefore, the overlapping of stay cables at the center of mid-span can increase the girder stiffness and decrease the girder deflection.

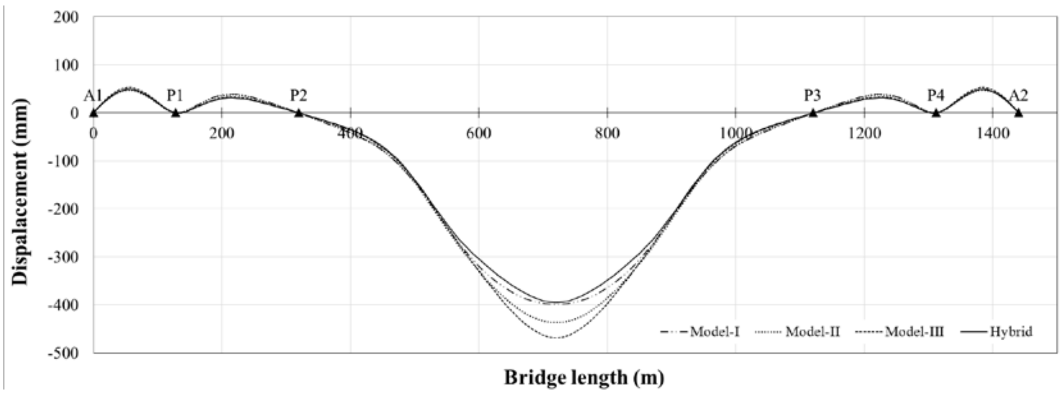

Fig.8 Deflection of the girders under train load

5. SEISMIC ANALYSIS

Seismic analysis was conducted for the ultra-strong earthquake wave, Level-2 earthquake (L2-EQ). Hard and good ground condition is assumed. L2-EQ has two different types: Type-I and Type-II. Type-I is the plate boundary earthquake and Type-II is the inland earthquake. Type-II, L2-EQ design earthquake waves is used in this study (Fig.9). The support condition is free to move longitudinally for all three models (Fig.10).

Dynamic analysis also shows different behavior regarding the longitudinal displacements of the towers and girder between four models with different stay arrangements. The largest displacements can be obtained for the Model-II with maximum value about 1.7m at the tower position due to larger spacing of stay cables compare to Model-I and the smallest value is for Model- III about 1.2m. therefore, can be concluded that the Model- III is the best case with overlapping stay cables and Model- II is the worst case with maximum displacement and Model- I and hybrid are in between with displacement about 1.4m (Fig.11).

In the same way, the bending moment at the base of tower is larger in the two other models than Model-III and Hybrid-Suspension. The maximum bending moment of Model-III is 176.4MN.m, and Hybrid-Suspension is 163.4MN.m, which is smaller than the maximum bending moment of Model-I (179.3MN.m) and Model-II (199.3MN.m). Therefore, it is clearly shows that the overlapping stays and Hybrid-Suspension cable have effective impact on longitudinal displacement of the bridge as well.

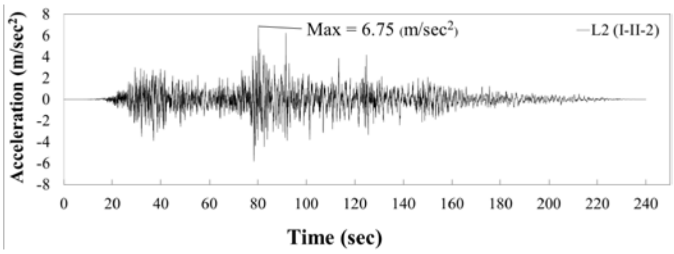

Fig.9 Design earthquake wave (L2-Earthquake Type-II)

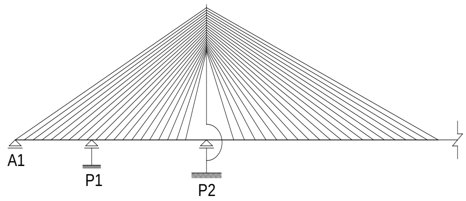

Fig.10 Longitudinal support of girder

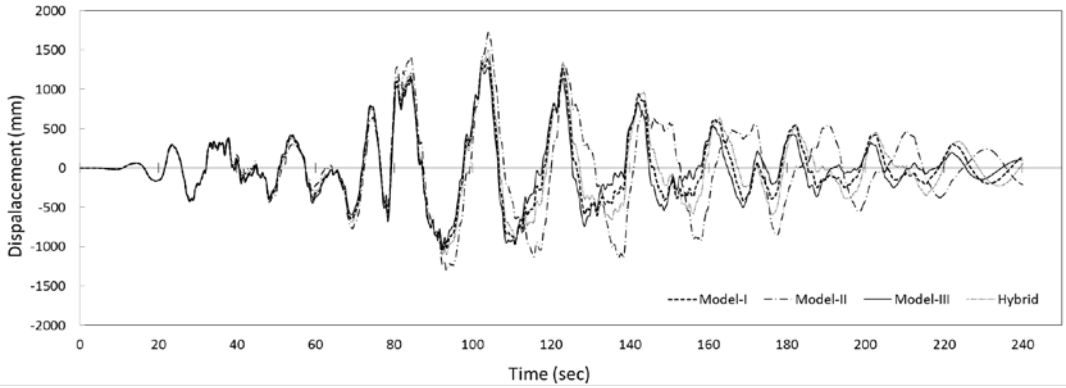

Fig.11 Girder longitudinal displacements at the tower position (P2)

8. CONCLUSIONS

Static and seismic behaviors of cable-stayed bridges with new stay systems were studied, overlapping and hybrid. Main conclusion is summarized below,

First, static analysis is carried out with three different distributed patterns of live load consisting of train and vehicle loads. The live load distributed in the mid-span gives larger deflection for all three models. It was found that overlapping stays and hybrid stayed-suspension cable can significantly reduce the displacements of the girder and bending moment of the towers. The deflection of the girder with overlapping stays due to the train loads decreases by 9.5% and the hybrid stayed-suspension cable decreases by 10% in comparison with the conventional cable arrangement. The deflection of the new cable arrangements are within the allowable value specified for the Shinkansen Train, confirming that serviceability limit is satisfied. Second, seismic response of the four models of cable-stayed bridges is investigated for the ultra-large seismic waves. It was found that the displacement at the top of tower and bending moment at tower base is smaller for model-III with overlapping stay cables and Hybrid-Suspension with stayed-suspension cable.

In conclusion, the cable-stayed bridges with overlapping stays and hybrid model provide smaller girder deflection and deflection angle and also show better performance against seismic forces, which validates the superiority of this structure.

REFERENCES

Hussain N., Carter M., Kite S. and Minto B.: Forth replacement crossing – Concept design, IABSE Symposium in London, 2011.

Japan Road Association: Specifications for highway bridges, 2012.

Railway Technical Research Institute: Specification for Railway Structures, Steel and Composite Structures, 2010.