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Comparative Study on Multi-Span Cable-Stayed Bridges with Hybrid, RC and Steel Towers

by

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Abstract

Although the multi-span cable stayed bridge is a new and elegant structure, its structural characteristics are not fully understood. The static and seismic behaviors of a multi-span cable stayed bridge with three different types of tower, RC and steel/concrete hybrid and steel tower, were studied. The steel/concrete hybrid tower consists of a sandwich type double steel box section filled with concrete, the RC tower has a rectangular hollow section, and the steel tower has a steel box section. First, static analysis is conducted with different live load patterns. Size and material strength is first assumed, which was validated by the limit states design. Second, elastic and plastic seismic analysis is conducted for the three towers using fiber elements. Three different support conditions to connect the girder to the tower were studied: movable, linear and bilinear spring connections. Medium strong and ultra-strong earthquakes according to the Japanese Seismic Codes for Highway Bridges were adopted. Dynamic responses of deformation and sectional forces were obtained and compared. The restorability of the towers was verified in the events of earthquake. In summary, the RC and hybrid towers showed very good static features and energy dissipating behavior during earthquakes. Bilinear spring is very effective in reducing dynamic response of all the towers, especially for the steel tower.

Keywords: Multi-span cable stayed bridge, RC tower, Hybrid tower, Steel tower, Static analysis, Seismic analysis

1. Introduction

The multi-span cable stayed bridge is a new and attractive structure and the Millau Bridge[1)] constructed in 2004 is a good example. Its structural form is complicated and the static and seismic characteristics are not fully clarified. Towers play an important role, in particular, for seismic behaviors. This study is conducted to clarify how three types of tower, the steel/concrete hybrid tower, the RC tower and the steel tower, affect its seismic behavior. The steel/concrete hybrid tower[2)] is a new structure consisting of a sandwich type double steel box section filled with concrete, the RC tower has a rectangular hollow section and the steel tower has a steel box section. There have been little past studies to assess and compare the effect of different types of towers on static and seismic behavior of multi-span cable stayed bridges.

Okamoto and Nakamura[3)] proposed the hybrid tower for multi-span cable stayed bridges and conducted static and seismic analysis. They also studied how different girder-tower connections affect seismic response. It was proved that the hybrid tower can be applied to multi-span stay systems.

In this study the RC tower and the steel tower are also applied to the bridge and compared with the previous study with the hybrid tower. Comparative study is conducted to clarify structural characteristics of three types of tower in this paper. The model bridge chosen for this study is similar to Millau Bridge and has 8 spans and 7 towers. First, static analysis is carried out with critical live load distribution patterns. Sectional forces and displacements were obtained and compared. The dimension of towers is assumed and verified in this stage. Second, non-linear elasto-plastic seismic analysis is conducted with three types of towers. The girder is free to move longitudinally. The medium strong and ultra-strong earthquake (L1-EQ, L2-EQ) waves according to Japanese Seismic Codes for Highway Bridges were adopted. Three support conditions of the girder at the tower is considered: movable, connection with linear springs and

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bilinear springs. Dynamic response of the towers with three tower-girder connections was compared. Restorability of the towers was verified in the event of earthquake.

2. Analytical model and geometry of bridge

Fig.1 shows the layout of the multi-span cable stayed bridge with 8 spans (100+6@200+100) and 7 towers. The girder is a steel box girder with orthotropic deck and has a width of 18.8 m and height of 2.2 m (Fig.2). The tower is H-shape and has 57m height (Fig.3). Two cable planes are assumed. Cross-sections of RC, hybrid and steel tower are shown in Fig.4. Three dimensional FEM model of the bridge consisting of fish-bone beam elements is used (Fig.5). The tower is divided into 2.0m element and the girder is divided into 1.0m. The girder is supported vertically and transversely at the towers but moves longitudinally. Hybrid tower is expected to increase its compressive and buckling strength because filled concrete increases concrete strength due to confind effect and restricts local buckling. RC tower has higher bending stiffness than other two towers. Stirrups are used to confine and strengthen the cross-section of RC tower against shear force and buckling. Stiffeners are used to support the steel tower against local buckling. In addition to that the global buckling of steel tower is checked not to exceed the safety criteria.

Mild steel with yield strength of 355MPa is chosen for steel plates of hybrid and steel tower. Filled concrete for hybrid tower has compressive strength of 30MPa. For RC tower concrete has compressive strength of 40MPa and reinforcement bars has yield strength of 490MPa.

3. Static analysis

Static analysis was carried out for design dead load (D) and design live loads (L) with three types of towers. Sectional forces and deformations were obtained. The design live loads consist of the uniformly distributed loads p2 of 3.5 kN/m^2 and equivalent to concentrated loads p1 of 10.0 kN/m^2 with a longitudinal width of 10 m.

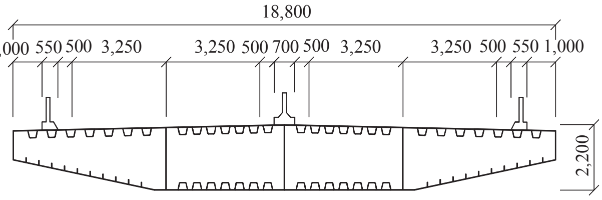


Fig.2 Girder cross-section (mm)

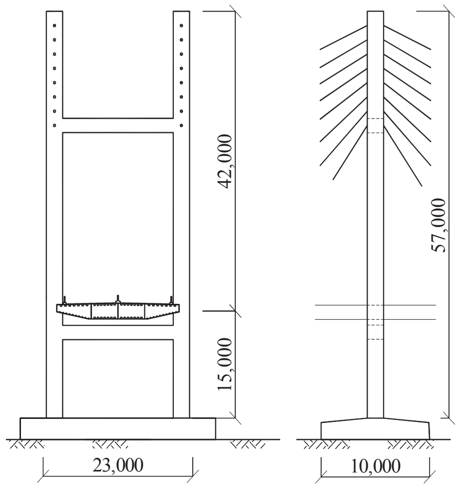


Fig.3 Tower side view (mm)

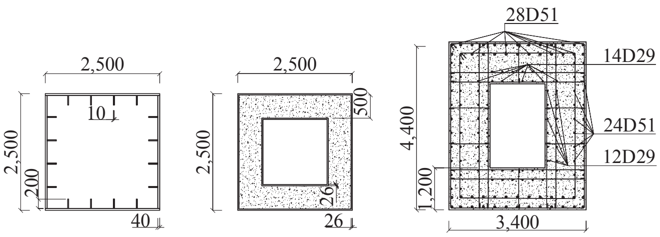


Fig.4 Cross-section of towers (mm)

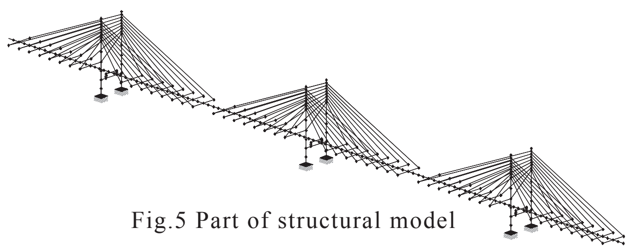


Fig.5 Part of structural model

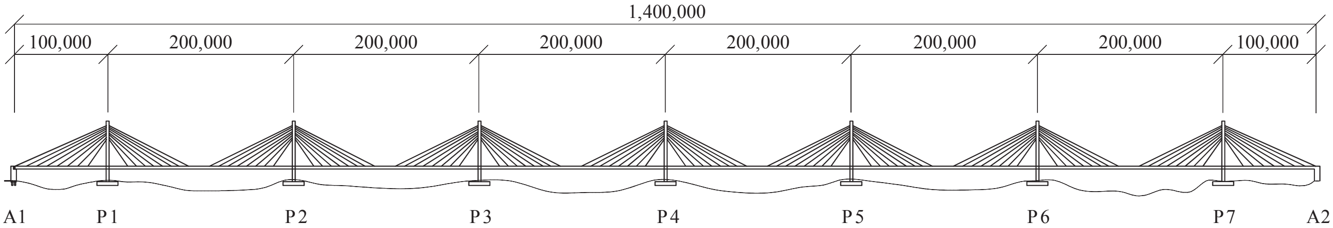


Fig.1 Layout of bridge (mm)

These design live loads are taken from the Japanese specifications for highway bridges[4)]. Three live load cases, LC1, LC2 and LC3 are considered. As shown in Fig.6, in LC1 the live load distributes in full spans, in L2 is that distributes only in the main P1-P2, and in LC3 is that distributes in the alternate spans. LC1 is one of the critical cases for all bridge members especially cables. LC3 with the live loads on the alternate spans produces the larger effects to the towers compared to LC1 and LC2.

The displacement and bending moment of towers are minimized at the dead load stage by installing cable pre-stress forces and counter weights at the side spans. Consequently, deformations and bending moments induced by self-weight of the structure is kept to a minimum level. Fig.7 shows the deformed state of bridge due to D+LC3. In P4 RC tower attained 320 mm displacement three time smaller than steel with 880 mm and twice less compared to hybrid tower with 793 mm because the bending stiffness of RC tower is much larger.

Fig.8 shows the longitudinal bending moment distribution at towers P1-P4 due to D+LC3. Tendency is the same throughout P1-P4 towers. Maximum bending moments of tower P4 are 108MN·m, 56.9MN·m and 46.1MN·m, for RC, hybrid and steel towers, respectively. Bending moment of steel and hybrid towers are nearly twice smaller than that of RC tower.

Table 1 shows displacement at the top and bending moment at the base of tower P4 for three types of tower. Longitudinal displacement at the top and bending moment at the base of tower P4 are zero when dead load is applied. They increase at D+LC1 and further increase at D+LC3. In all load cases displacement of RC tower is smallest, followed by hybrid tower and that of steel tower further large. On the other hand, bending moment of RC is largest and that of steel tower is smallest. Fig.9 shows bending moment of girder with three types of tower. Bending moment of RC tower is smaller by 22-67% than steel tower and that of hybrid tower is smaller by 4-16%. Table 1 and Fig.9 clelarly indicate that the flexial rigidity of the tower significantly affects the static behaviours of the structure.

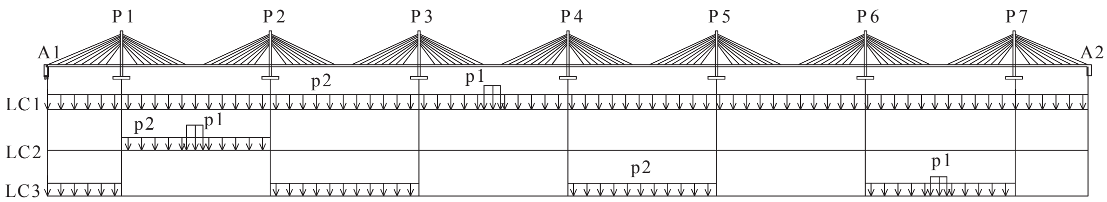


Fig.6 Live load cases

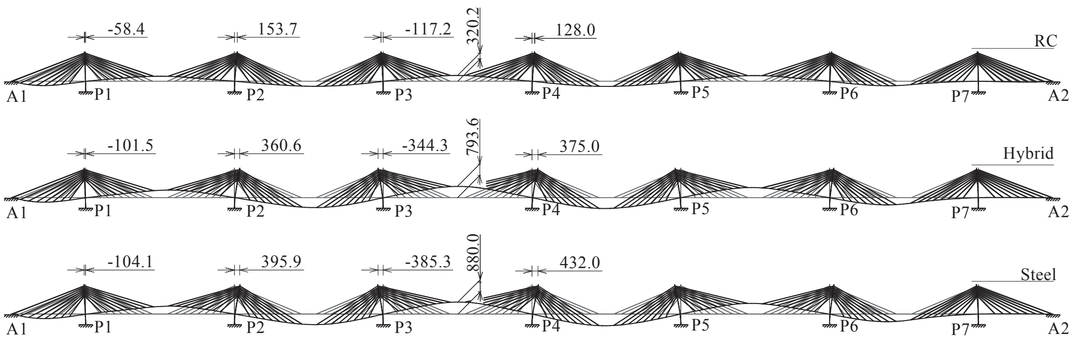


Fig.7 Displacement of bridge elements with RC, hybrid and steel tower due to D+LC3 (mm)

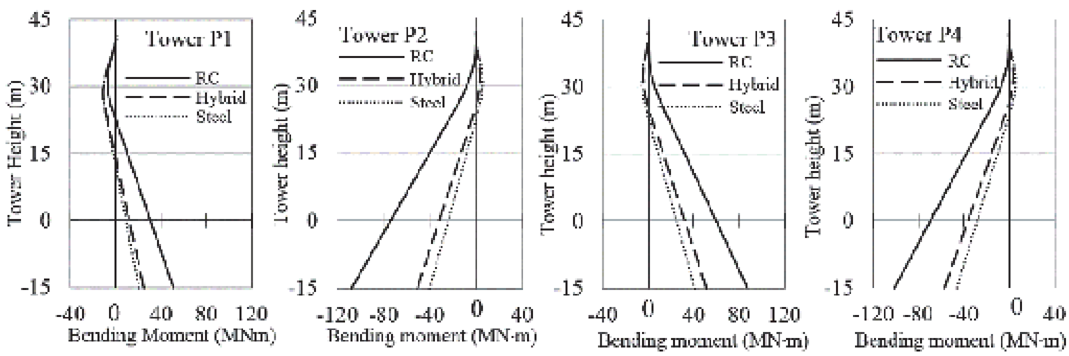


Fig.8 Bending moment of three types of tower due to D+LC3

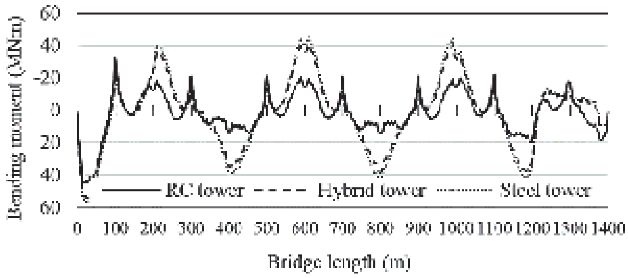


Fig.9 Bending moment of girder due to D+LC3

Table 1 Longitudinal Displacement and bending moment of tower P4

Tower type	Longitudinal displacement at tower top (mm)			Bending moment at tower base (MN·m)		
	D	D+LC1	D+LC3	D	D+LC1	D+LC3
RC	0	26	128	0	20	101
Hybrid	0	61	375	0	9	57
Steel	0	69	432	0	7	46

4. Safety verification

As the size and material strength of the structural elements is first assumed, it must be verified by the obtained sectional forces due to dead and live loads. Safety verification is carried out by the limit states design method considering the critical D+LC3 case. The ultimate design bending moment and axial compressive force are calculated and checked if they are within the design ultimate strength of the cross-sections considering the safety factors. Eq.(1) is basically used to perform the safety verification considering the buckling effect of the towers.

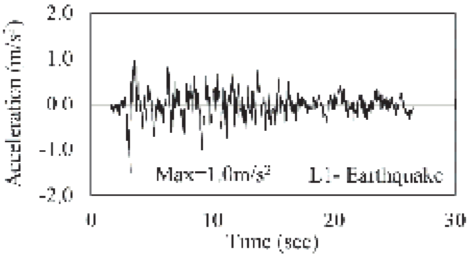
$$\gamma_i \frac{S_d}{R_d} \leq 1.0 \qquad (1)$$

Where, γ_i: structure factor (=1.1), S_d: design response, R_d: design resistance.

For combination of bending moment and axial force, the M-N interaction curve is first obtained for three types of towers. It is then confirmed that the obtained M and N are within this curve.

For shear force, it is resisted by concrete and stirrups in RC tower. It is resisted by filled concrete plus steel web plates in hybrid tower. It is resisted by steel web plates in steel tower.

Safety index of towers are obtained as 0.92, 0.90 and 0.85 for hybrid, RC and steel towers respectively indicating the assumed section is properly chosen.



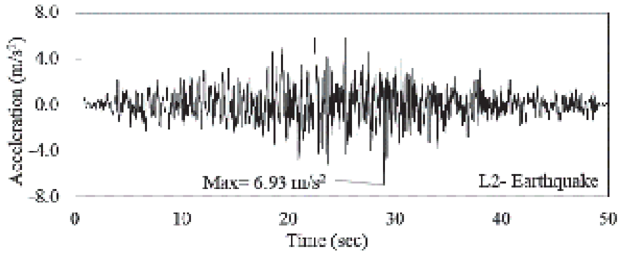


Fig.10 Seismic waves for L1 and L2 earthquakes

5. Seismic analysis

Seismic analysis is conducted by accounting the material non-linearity. The medium strong and ultra-strong earthquake waves (L1-EQ, L2-EQ) according to Japanese Seismic Code for Highway Bridges are adopted (Fig.10). For L1-EQ the structural elements should be within their elastic limits and no damage is allowed to the bridge. Plastic behavior and minor damage is permitted for L2-EQ but emergency vehicles can be run after the occurrence of earthquake. Hard and good ground condition is assumed. Grounds are shaken by earthquakes in three directions: longitudinal, transverse and vertical directions. The longitudinal response is particularly interesting on multi-span continuous cable stayed bridges and is studied in this paper.

Three support conditions of the girder on the cross beams of the tower are assumed; movable (MOV), connected with linear springs (LS) and connected with bilinear springs (BLS) as shown in Table 2. The spring constant of LS, K1, is decided by the size of elastic rubber bearing. These springs only controls the longitudinal displacement of girder and are fixed in other directions. The LS behaves elastically. BLS follows the initial spring constant K1 and, when reaches yield displacement δy=25mm, then follows the second spring constant K2. The spring constants K1 and K2 are decided by the sizes of energy dissipating type bearings such as Lead Rubber bearings and High Damping Rubber bearings. The bilinear hysteretic property of BLS produces energy absorbing effect. Structural damping is assumed 0.05 for hybrid column, 0.02 for steel components, 0.1 for concrete columns and 0.05 for cables.

Table 2 Girder and tower connection models

	Movable (MOV)	Linear Spring (LS)	Bilinear Spring (BLS)
Spring model			
P-δ	P, δ	P, K1, δ	P, K2, K1, δy, δ
K1	-	11,000 kN/m	33,000 kN/m
K2	-	-	4,950 kN/m

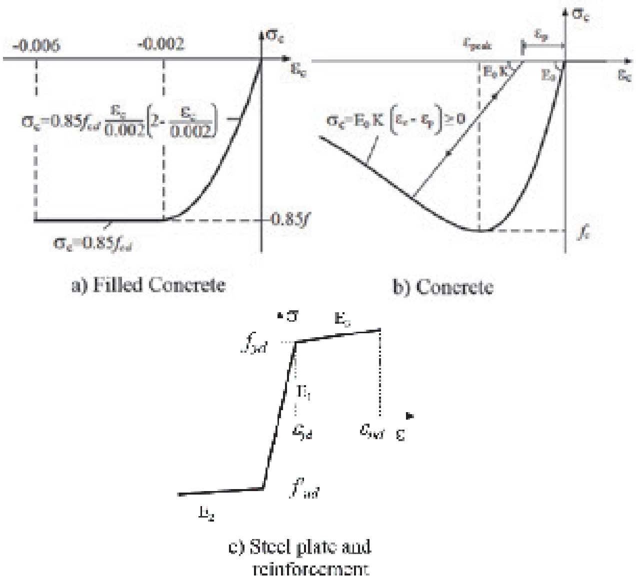


Fig.10 Stress-strain curves of material

To carry on seismic analysis cross-section of towers is divided into small fiber elements. Each fiber element conforms to the constitutive law of concrete, steel reinforcement or steel plate. Fig.11 shows stress-strain curves of concrete, steel plate and reinforcement.

The constituitive law of concrete modeled for seismic analysis, by the JSCE Specification[4)] is adopted. Tensile capacity of concrete is neglected. Residual plastic strain and stiffness degradation on loading and reloading path of stress hysteresis is also considered. Stress-strain curve of concrete is defined by eq.(2):

$$\sigma_c = E_0 K(\varepsilon_c - \varepsilon_p) \geq 0 \tag{2}$$

$$E_0 = \frac{2f_{cd}}{\varepsilon_{peak}} \tag{3}$$

$$K = exp\left\{-0.73\frac{\varepsilon_{max}}{\varepsilon_{peak}}\left(1 - exp\left(-1.25\frac{\varepsilon_{max}}{\varepsilon_{peak}}\right)\right)\right\} \tag{4}$$

$$\varepsilon_p = \varepsilon_{max} - 2.86 \cdot \varepsilon_{peak}\left\{1 - exp\left(-0.35\frac{\varepsilon_{max}}{\varepsilon_{peak}}\right)\right\} \tag{5}$$

Where σ_c : concrete stress, E_0 : initial elastic modulus of concrete, ε_c: concrete strain, ε_p: plastic strain, K: residual rate of elastic stiffness, ε_{peak}: peak strain corresponding to compressive strength (generally assumed 0.002), ε_{max}: maximum strain and ε_p: plastic strain.

Stress-strain curve of filled concrete of hybrid tower has good ductility due to confined effect. Steel plates of steel tower and reinforcements in RC tower have modulus of elasticity E_1=200GPa at first and then follows E_2=2GPa beyond yeild point. High strength steel with ultimate tensile strength of 1570MPa is assumed for stay cables.

In order to verify the models and confirm accuracy of the seismic calculations each type of tower was modeled with fiber and M-φ element methods as well. Then they were applied to the bridge and push-over analysis was carried out. The difference between the fibre element model and M-φ model was around 2%. In addition, the results of a previous seismic study with the same hybrid tower (Okamoto and Nakamura[3)]) was compared with seismic analysis of hybrid tower in this study and the difference was nearly equal. These calculations validate the models of bridge and towers.

Dynamic seismic analysis was executed with three types of towers. Time interval of analysis is 0.01 seconds. Dynamic responses of the displacement and bending moment were obtained for the three types of tower with three types of girder-tower connection. Maximum acceleration occurs between 20 to 50 seconds. Results of tower P4 is mainly discussed in this section.

Fig.12 illustrates the longitudinal displacement at the top of tower P4 due to L2-EQ for three types of tower with MOV connection. Displacement of RC tower is 567mm which is smaller than those of hybrid and steel towers with 843mm. Longitudinal displacement at the top of hybrid tower with different girder-tower connections is shown in Fig.13. LS and BLS connections are effective in reducing the longitudinal displacement. The dynamic displacement is smallest with BLS, followed by LS but largest with MOV.

Fig.14 shows how three types of girder-tower connections affect longitudinal displacements at the midpoint of girder when L2-EQ hits the model. The response of girder is similar to that of tower. BLS connection provides significantly smaller displacement of girder with 265mm, compared with the displacements of the LS and MOV connections of 416mm and 846mm, respectively. Dynamic displacement at Fig.13 and Fig.14 follows the same trend because the displacement of tower reflects to the girder by means of stay cables.

Fig.15 shows bending moment at the base of tower P4 with MOV connection due to L2 earthquake. Bending moment of RC tower is 286MN·m, which is more than three times of steel tower with 79MN·m and more than twice of hybrid tower with 113MN·m.

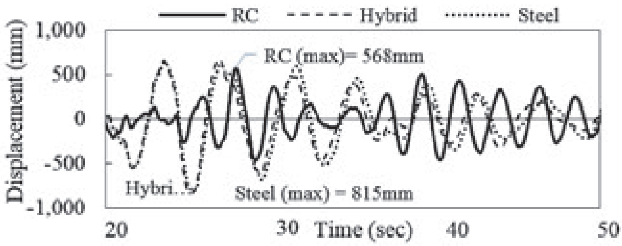


Fig.12 Longitudinal displacement at the top of tower P4 due to L2-EQ (MOV)

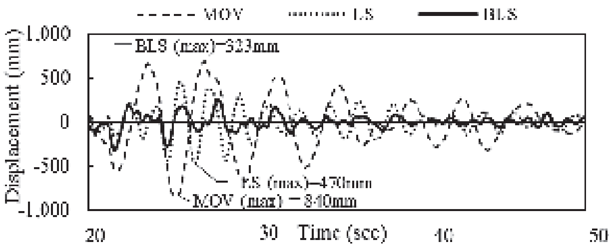


Fig.13 Longitudinal displacement at the top of tower P4 due to L2-EQ (Hybrid)

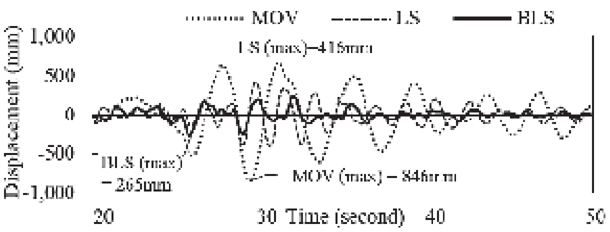


Fig.14 Longitudinal displacement at the midpoint of girder due to L2-EQ. (Hybrid)

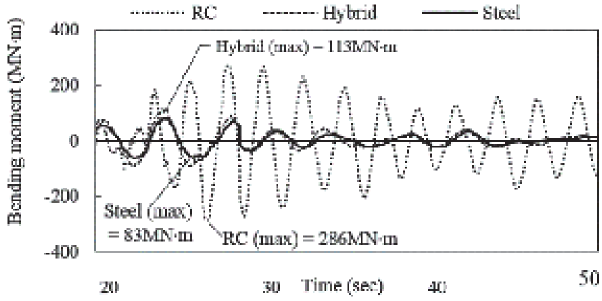


Fig.15 Longitudinal bending moment at the base of tower P4 due to L2-EQ. (MOV)

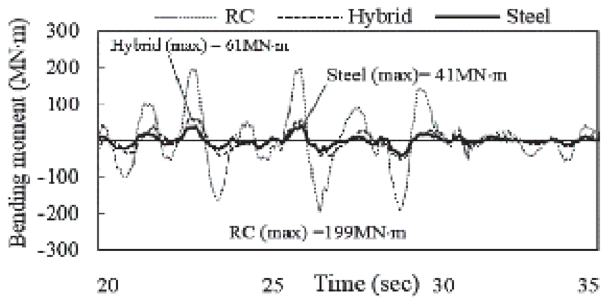


Fig.16 Longitudinal bending moment at the base of tower P4 due to L2-EQ. (BLS)

Fig.16 shows bending moment at the base of tower P4 with BLS connection. Remarkable reduction in bending moment of steel and hybrid tower is observed. Compared to MOV connection, bending moment is smaller by 30%, 46% and 51% for RC, hybrid and steel towers, respectively.

The moment-curvature hysteresis at the base of tower P4 with MOV connection is shown in Fig.17. Hysteresis of RC tower is largest and non-linear. Hybrid and steel towers showed little energy dissipating property because the structures remain elastic. No energy absorption is expected from MOV connection.

Fig.18 shows bending moment-curvature hysteresis of RC tower. Hysteresis cycles are large with MOV and LS. On the other hands, moment-curvature hysteres is linear with BLS connection. This figure indicates that seismic energy is absorbed is by RC and Hybrid pier itself and is absorbed by the BLS bearing.

Fig.19 illustrates the maximum responses of three types of tower with three kinds of girder-tower connection due to L1-EQ and L2-EQ. Displacements and bending moments caused by L1-EQ are much smaller than those caused by L2-EQ.

As for dsplacements due to L2-EQ, it is largest with MOV spring and smallest with BLS and the LS is in between. RC tower is smaller than steel and hybrid towers with MOV connection, while the three towers are nearly the same with BLS. BLS is very effective in controlling the displacements of towers, especially with steel tower.

As for bending moments due to L2-EQ, RC is much larger than steel and hybrid towers. The bending moent of RC tower with MOV connection is significantly reduced with BLS connection. BLS is also effective in controlling the bending moments of towers.

These dynamic responses can be understood by energy interaction mechanism. Seismic energy is absorbed by the tower itself and the spring connection. RC tower has good hysteretic behavior with favorable energy absorption capacity. BLS has also good energy absorption capacity wheras LS and MOV do not contribute.

MOV, LS and BLS connections affect natural frequency of bridge. As shown in Fig.20, MOV connection produces the smallest natural frequency followed by LS and further increases with BLS. Natural frequency of bridge with RC tower is nearly twice of hybrid and steel tower with MOV connection. BLS increases natural frequency of bridge by twice compared to MOV in all three types of towers.

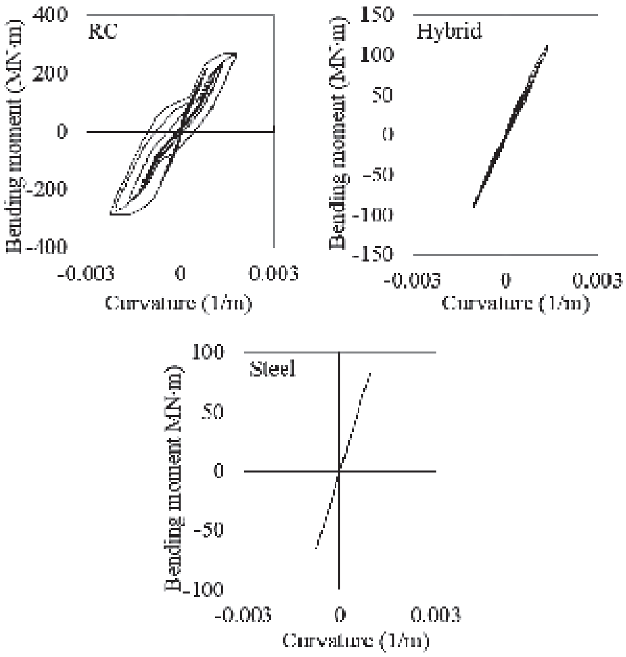


Fig.17 Moment-curvature hysteresis at the base of tower P4 due to L2 (MOV)

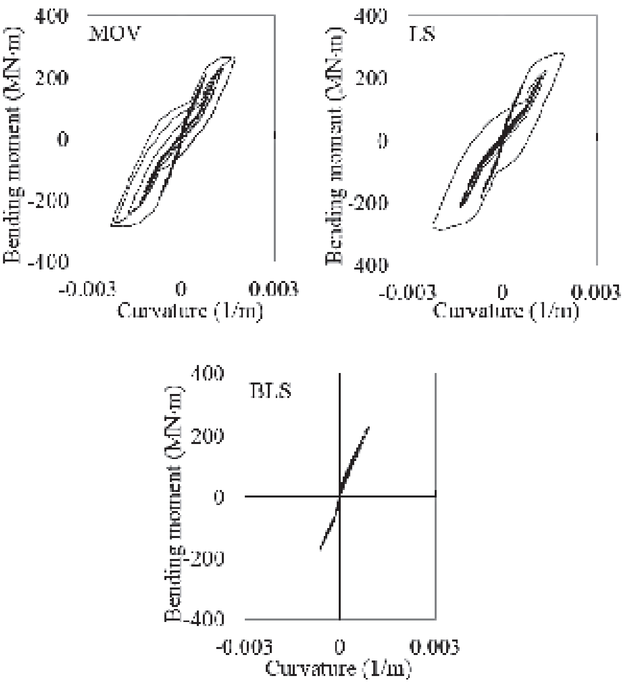


Fig.18 Moment-curvature hysteresis at the base of tower P4 due to L2-EQ. (RC)

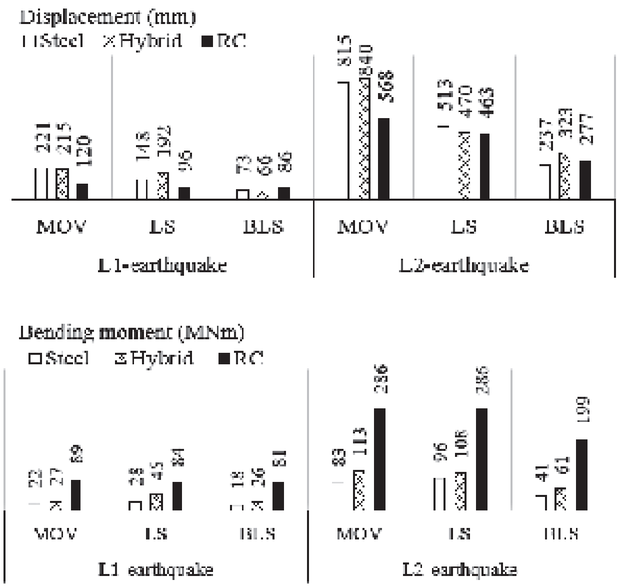


Fig.19 Comprison of displacements and bending moment

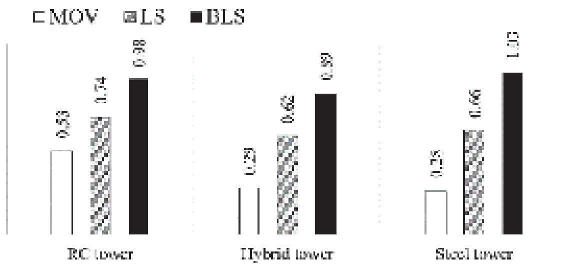


Fig.20 Natural frequency of bridges (Hz)

6. Restorability verification

It is important to asess the post-earthquake restorable capacity of the structure. The restorability of structure is assessed by seismic performance levels according to moment-curvature curve of structural members, as shown in Fig.21. In seismic performance level-1 (SPL-1), no damage is allowed to the bridge and vehicles can pass after technical observation of bridge. In seismic performance level-2 (SPL-2), minor damage is allowed to the bridge and light vehicles can pass with minor repair work. In seismic performance level 3 (SPL-3), severe local damage may be allowed, but emergency vehicles can go without repair work.

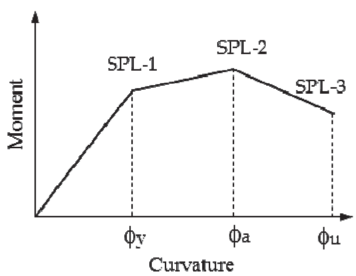


Fig.21 Seismic performance levels

Table 3 Check of restoration (MOV)

Tower type	Design earthquake	Design curvature ϕ_d (1/m)	Curvature induced ϕ_{rd} (1/m)	Structure factor γ_i	Seismic performance level	$\gamma_i(\phi_d/\phi_{rd})$	Verification
RC tower	L1-EQ	0.0002	0.0010	1.00	1	0.24	OK
	L2-EQ	0.0023	0.0024	1.00	3	0.92	OK
Hybrid tower	L1-EQ	0.0003	0.0018	1.00	1	0.15	OK
	L2-EQ	0.0014	0.0129	1.00	3	0.11	OK
Steel tower	L1-EQ	0.0003	0.0015	1.00	1	0.17	OK
	L2-EQ	0.0009	0.0075	1.00	3	0.12	OK

Eq.(6) is used to perform restorability verification.

$$\gamma_i \frac{\emptyset_{sd}}{\emptyset_{rd}} \leq 1.0 \qquad (6)$$

Here; γ_i: structure factor (=1.1), $\emptyset_{sd}$: design response curvature and $\emptyset_{rd}$: design resistant curvature.

Table 3 shows the restoration of three types of tower with MOV connection. L1-EQ is checked with seismic performance level-1. Performance level-2,3 is used for L2-EQ. All towers are verified for L1-EQ and L2-EQ. The restoration index of RC tower with L2-EQ is very large (0.92) and critical compared to those of hybrid and steel towers.

7. Discussions and conclusion

Multi-span cable stayed bridge is a new and attractive bridge. It possesses excellent aesthetics and technical advantages. This study is conducted to clarify static and seismic behavior of a multi-span cable stayed bridge with three types of towers. In designing a multi-span cable stayed bridge the choice of tower is important because it affects the displacements and sectional forces of the tower and the girder. The tower also affects the seismic behaviors of the whole bridge. It is therefor important to clarify advantages and disadvantages of each type of tower.

RC and steel towers are widely used in the construction of multi-span cable stayed bridges. Hybrid tower is a new structure and has many advantages such as: (1) filled concrete increases strength due to confined effect of concrete and restricts deformations, (2) steel plates increase resistance against local buckling, (3) construction process is easier because steel plate works as formwork of the concrete and (4) it has superb static and seismic behavior.

Three types of connection of girder at the tower is studied: Movable (MOV), connection with linear spring (LS) and connection with (BLS). MOV connection acts like a roller bearing and allows free longitudinal movement and rotation of the girder. LS acts as a rubber bearing and restricts horizontal displacement of girder. BLS works as a lead-rubber bearing, which it first behaves linearly and, after reaches its yield point, conforms to bilinear relation.

In conclusion, all three types of tower are feasible for a multi-span cable stayed bridge from static and seismic aspects. In static analysis, RC tower had triple less displacement and several times larger bending moment compared with steel and hybrid towers. Steel tower had the largest displacement but the least bending moment. In seismic analysis, bilinear spring (BLS) connection is very effective in reducing the dynamic response of all the towers. The response of steel tower is particularly reduced with BLS.

Finally, RC and hybrid tower showed very good static features and energy dissipating behavior during earthquake. Bilinear spring is very effective in reducing dynamic response of all the towers especially the steel tower.

References

1) Virlogeux, M.: Bridges with multi-span cable-stayed spans, Structural Engineering International, Journal of IABSE, Vol.11, No.1 (2001), pp. 61-81
2) Nakamura, S.: New Structural Forms of Steel Concrete Composite Bridges, Structural Engineering International, Journal of IABSE, Vol.10, No.1 (2000), pp. 45-50
3) Okamoto, Y., Nakamura S.: Static and seismic studies on steel/concrete hybrid towers for multi-span cable-stayed bridges, Elsevier, Journal of Constructional Steel Research, Vol.67, No.2 (2011), pp. 203-210
4) Japan Road Association: Specifications for highway bridges, I. General, IV. Seismic Design, (2002).
5) Japanese Association of Civil Engineers: Guidelines for performance verification of steel–concrete hybrid structures (2006).