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SEISMIC BEHAVIORS OF MULTI-SPAN CABLE-STAYED BRIDGES WITH HYBRID, RC AND STEEL TOWERS

Ismatullah AMIRI
MSc Student, Department of Civil Engineering, Tokai University, Japan
eng_ismat@yahoo.com

Shunichi NAKAMURA
Professor, Department of Civil Engineering, Tokai University, Japan
snakamu@keyaki.cc.u-tokai.ac.jp

ABSTRACT: Although 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, steel/concrete hybrid and steel tower are 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 and safety of structural members is validated by the limit states design. Second, elastic and plastic analysis is conducted for the three towers using fiber elements. Three different support conditions to connect the girder to the tower are studied: movable, linear and bilinear spring connections. Medium strong and ultra-strong earthquakes of Japanese Seismic Codes for Highway Bridges are adopted. Deformation and sectional force time history is obtained and compared. The restorability of towers is verified in the events of earthquake. In summary, RC and hybrid tower showed 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.

1. Introduction

Multi-span cable stayed bridges are new structures and the Millau Bridge constructed in 2004 is a good example. Its structural form is complicated and the static and seismic characteristics are not fully clarified. Also; there has not been much research about multi-span cable stayed bridges (Virlogeux 2001). Towers play an important role, in particular, for seismic behaviors. This study is conducted to clarify how three types of tower affect the seismic behavior of a multi-span cable stayed bridge. The steel/concrete hybrid tower 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 has not been studies to assess and compare the effect of different types of towers on static and seismic behavior of multi-span cable stayed bridges. In addition, three kinds of seating condition of girder on the tower are studied on seismic behavior of the bridge.

Okamoto and Nakamura (2011) proposed hybrid tower for a multi-span cable stayed bridge and conducted static and seismic analysis and also explained how different girder-tower connections affects seismic response of the structure. It was proved that this kind of 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. The comparative studies in this paper clarify the performance of each types of tower.

The geometry of multi-span cable stayed bridge chosen for this study is similar to Millau Bridge which has 8 spans and 7 towers. First, static analysis is carried out and 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 bilinear springs. Dynamic responses of the towers with different tower-girder connection were compared. The restorability of the towers was verified in the event of earthquake.

2. Analytical model and geometry of bridge

The layout of the multi-span cable stayed bridge with 8 spans (100+6@200+100) and 7 towers is shown (Fig. 1). The girder is an orthotropic girder with 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 plane is assumed. Cross-section of RC, hybrid and steel tower is shown in Fig.4. Three dimensional FEM model of the bridge consisting of fish-bone beam elements is established (Fig. 5). Element discretization of 2000mm for towers and 10000mm for girder is employed. The girder is supported vertically and transversely at the towers but moves longitudinally. Hybrid tower is expected to have high compressive and buckling strength. Because filled concrete increases strength and restrict deformation of steel plates against local buckling. RC tower has high bending stiffness because second moment of area of RC tower is larger and also modulus of elasticity of concrete increases with higher strengths. 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 is chosen for steel plates of hybrid and steel tower. It has yield strength of 355MPa. The compressive strength of concrete is assumed 30MPa for hybrid and 40MPa for RC tower. Reinforcement bars in RC tower is deformed steel, which has yield strength of 490MPa. High strength steel with ultimate tensile strength of 1570MPa is assumed for cables.

Static analysis is carried out for design dead load (D) and design live loads (L) with three types of towers, Live loads are taken from Japanese Specifications for Highway Bridges. Safety of assumed cross-sections of structural members are verified at this stage.

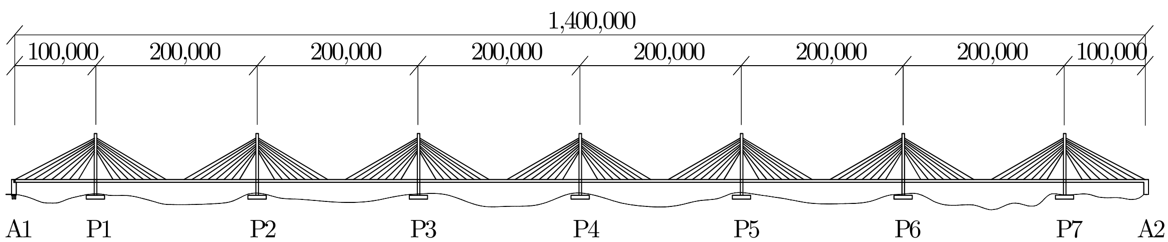


Fig. 1 Layout of bridge (mm)

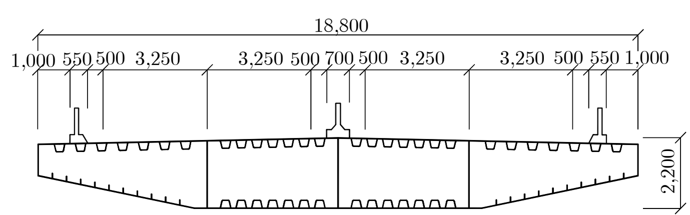


Fig. 2 Girder cross-section (mm)

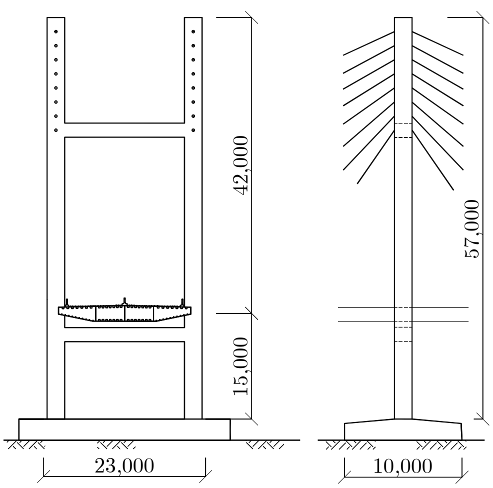


Fig. 3 Tower side view (mm)

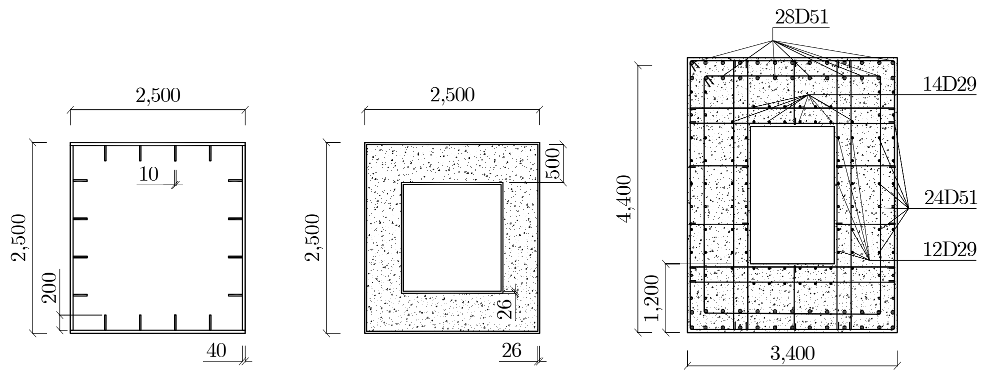


Fig. 4 Cross-section of towers (mm)

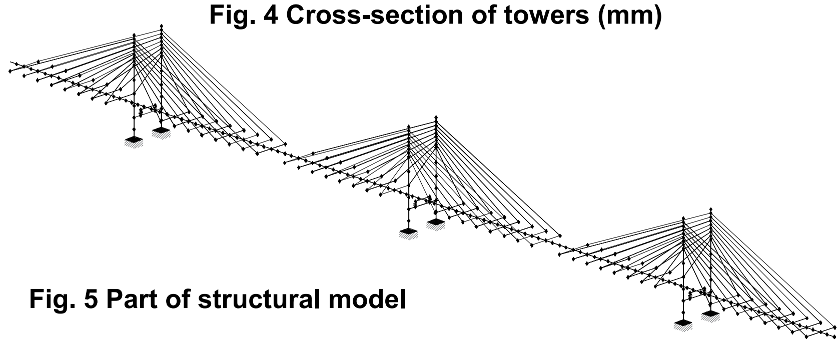


Fig. 5 Part of structural model

3. Seismic analysis

3.1. Bridge model for seismic analysis

Seismic analysis is conducted by accounting the geometrical and 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. 6). For L1-EQ the structural elements should be within their elastic limits and no damage is allowed to the bridge. Plastic behavior is permitted for L2-EQ such that, crossing of emergency vehicles is not interrupted in event of an earthquake.

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. 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 or multi-span continuous cable stayed bridge and is studied in this paper.

Three support conditions of the girder at the tower is assumed; movable (MOV), connected with linear springs (LS) and connected with bilinear springs (BLS) as shown in Table 1. The shear modulus 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 follows only elastic modulus K1. BLS follows elastic modulus K1, reaches yield displacement δy=25mm then follows second modulus K2. The shear modulus K1 and K2 are also decided by the sizes of energy dissipating type bearings such as Lead Rubber bearings, High Damping Rubber bearings and so on. The bilinear hysteretic property of BLS produces energy absorbing effect. Structural damping is calculated assuming 0.05 for hybrid column, 0.02 for steel components, 0.1 for concrete columns and 0.05 for cables.

In order to verify the modeling process and confirm accuracy of the seismic calculations each type of tower was modeled with fiber and M-φ element methods separately. Then they are applied to the bridge and push-over analysis carried out. The difference between two methods were around 2%. Also the results of a previous seismic study with the same hybrid tower (Okamoto et al. 2011) [2] was compared with seismic analysis of hybrid tower in this study and the difference was less than 6%. These calculation validates the models of bridge and towers.

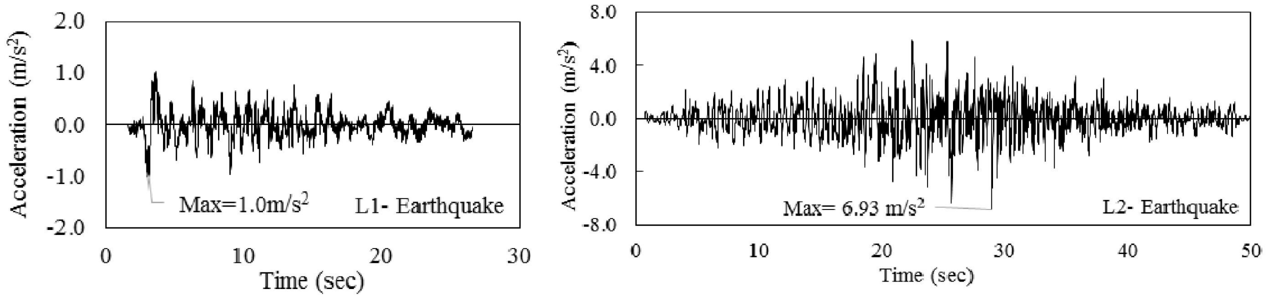
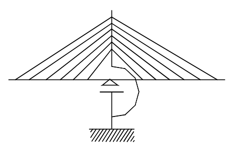
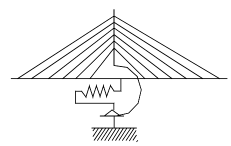
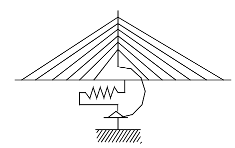
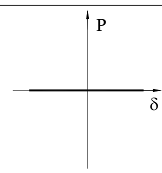
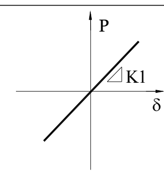
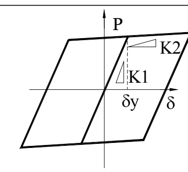


Fig. 6 Seismic waves for L1 and L2 earthquakes

Table 1 Girder and tower connection models

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

3.2. Constitutive law of material

To conduct non-linear analysis, the cross-section of the towers is divided into small fibers. Each fiber conforms to the constitutive law of the material. Fig.7 shows stress-strain curves of concrete, steel plate and reinforcement.

The hysteretic rule of concrete modeled for seismic analysis, by the JSCE (Japan Society of Civil Engineers) 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.(1):

$$\sigma_c = E_0 K\left(\varepsilon_c - \varepsilon_p\right) \geq 0 \tag{1}$$

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

$$K = \exp\left\{-0.73\frac{\varepsilon_{\max}}{\varepsilon_{peak}}\left(1-\exp\left(-1.25\frac{\varepsilon_{\max}}{\varepsilon_{peak}}\right)\right)\right\} \tag{3}$$

$$\varepsilon_p = \varepsilon_{\max} - 2.86\cdot\varepsilon_{peak}\left(1-\exp\left(-0.35\frac{\varepsilon_{\max}}{\varepsilon_{peak}}\right)\right) \tag{4}$$

Where σ_c : concrete stress, E_0 : initial Young 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, 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.

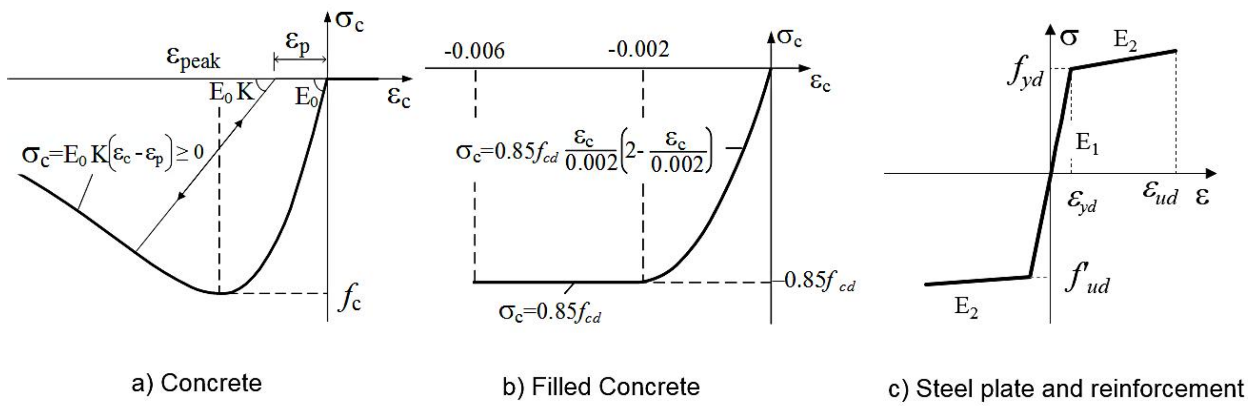


Fig. 7 Stress-strain curves of material

3.3. Responses due to two design earthquakes

Seismic analysis executed with three types of towers. Time interval of analysis is 0.01 seconds. The displacement and bending moment time history obtained for the three types of tower in combination with three types of girder-tower connection. Maximum responses occur between 20 to 50 seconds. Results of tower P4 is discussed in this section.

Fig.8 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 are shown in Fig.9. LS and BLS connections are very effective in reducing the longitudinal displacement. The dynamic displacement is smallest with BLS, followed by LS and further increased with MOV.

Fig.10 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 three times less displacement of girder with 265mm, LS and MOV connections obtained 416mm and 846mm respectively. Dynamic displacement at Fig.9 and Fig.10 follows the same trend because the displacement of tower reflects to the girder by means of stay cables.

Fig.11 shows bending moment at the base of tower P4 with MOV connection due to L2 earthquake. Bending moment of RC tower is 286MN·m, more than three times of steel tower with 79MN·m and more than twice of hybrid tower with 113MN·m. This is because bending stiffness of RC tower is much more and MOV connection does not absorb seismic energy. Girder-tower connection also affects the intensity of bending moments in towers. Fig.12 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, 30%, 46% and 51% reduction is obtained respectively for RC, hybrid and steel towers.

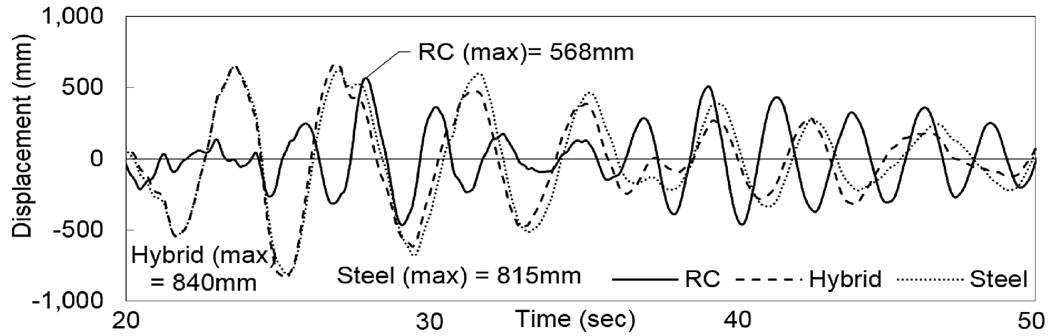


Fig. 8 Longitudinal displacement at the top of tower P4 due to L2-EQ (MOV)

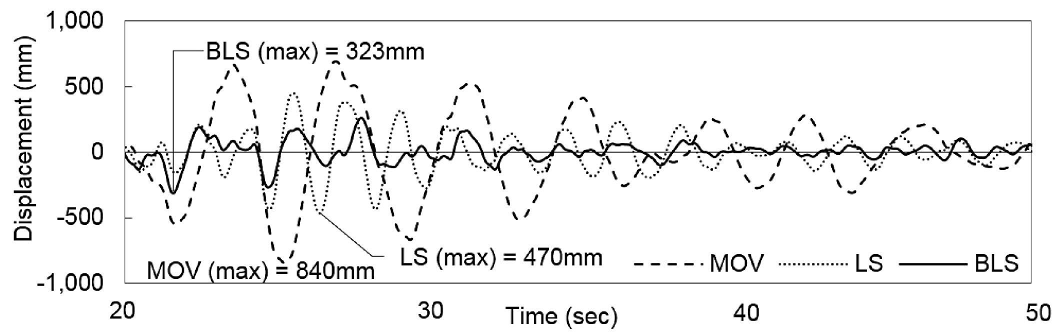


Fig. 9 Longitudinal displacement at the top of tower P4 due to L2-EQ (Hybrid)

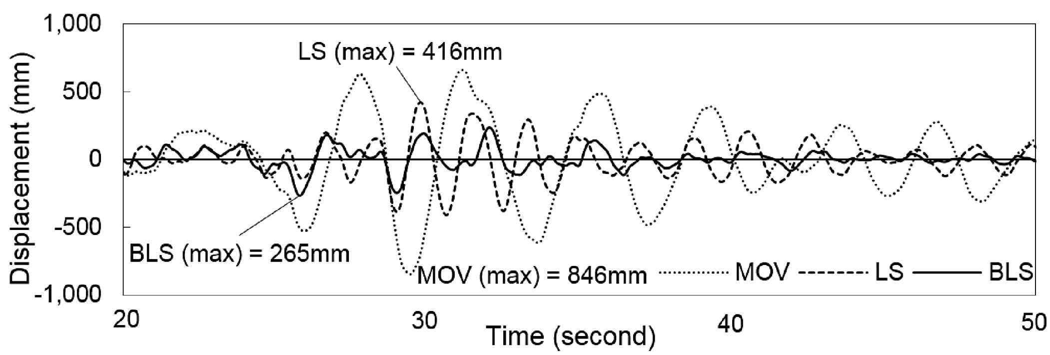


Fig.10 Longitudinal displacement at the midpoint of girder due to L2-EQ. (Hybrid)

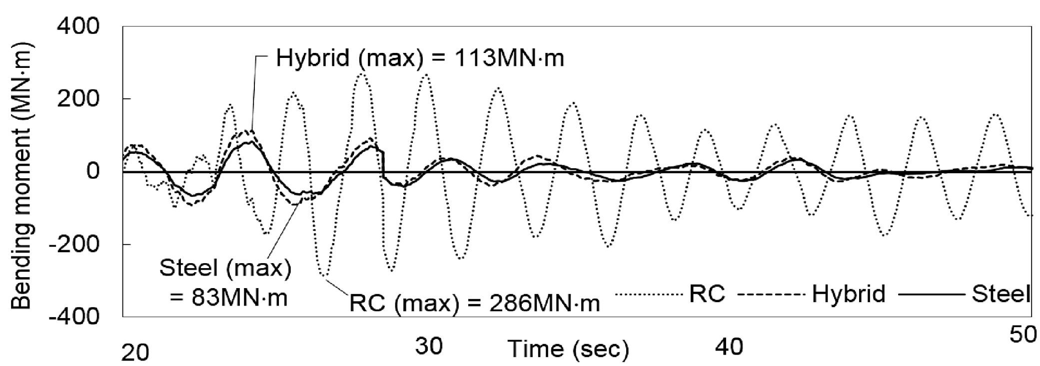


Fig. 11 Longitudinal bending moment at the base of tower P4 due to L2-EQ. (MOV)

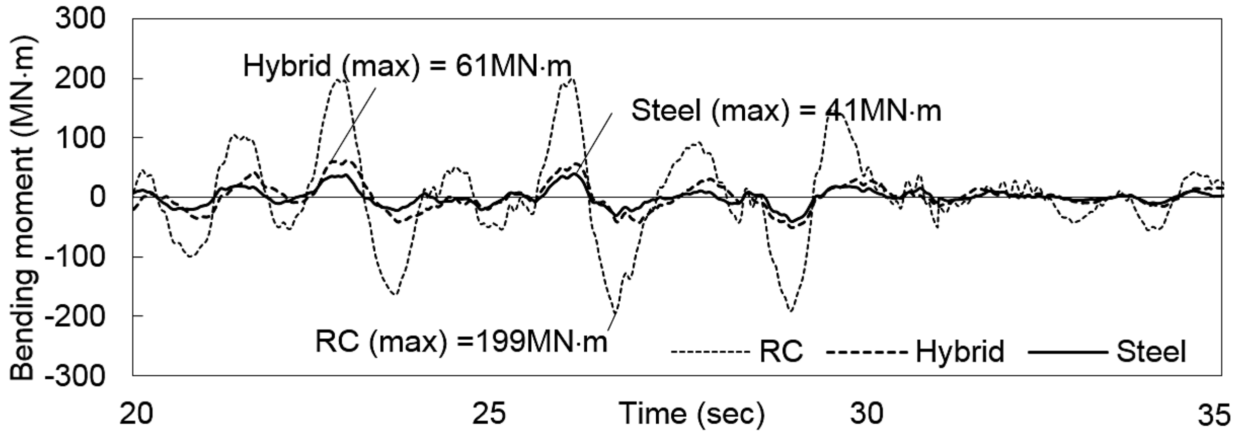


Fig.12 Longitudinal bending moment at the base of tower P4 due to L2-EQ. (BLS)

The moment-curvature hysteresis at the base of tower P4 with MOV connection is shown in Fig.13. Hysteresis of RC tower is largest and non-linear. Hybrid and steel towers showed little energy dissipating property with elastic behavior.

Fig.14 shows bending moment-curvature hysteresis of RC tower. Hysteresis cycles are large with MOV but the curvatures are within the ultimate values (Table 2). Moment-curvature hysteresis are elastic with BLS connection. The LS connection is good in reducing hysteresis cycles but not the intensity of bending moment.

Fig.15 illustrates maximum responses of three types of tower in combination with three kinds of girder-tower connection due to L1-EQ and L2-EQ. responses are small with L1-EQ. Steel tower attained the least bending moment and the largest displacement. Dynamic displacement and bending moment with MOV spring was maximum compared to BLS. Responses with BLS was minimum and the behavior of LS was in between. This is because the hysteretic property of BLS absorbs energy. BLS was very effective in controlling the dynamic responses of towers, especially with steel tower. Displacement at the top of steel tower due to L1-EQ with MOV (221mm) and L2-EQ with BLS (237mm) is almost the same. L2-EQ is nearly 7-times larger than L1-EQ, however displacement of towers due to L2-EQ is 4.7 times larger for RC, 3.9 times larger for hybrid and 3.7 times larger for steel compared to L1-EQ when MOV connection is used. Also, displacement at the top of the tower due to L2-EQ is 3.5 times larger with LS and 1.5 times larger with BLS compared to L1-EQ for all towers.

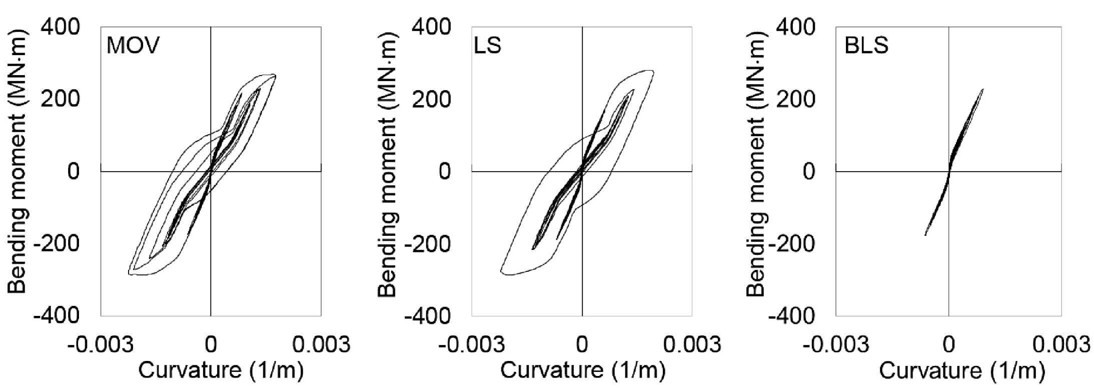


Fig.13 Moment-curvature hysteresis at the base of tower P4 due to L2-EQ. (RC)

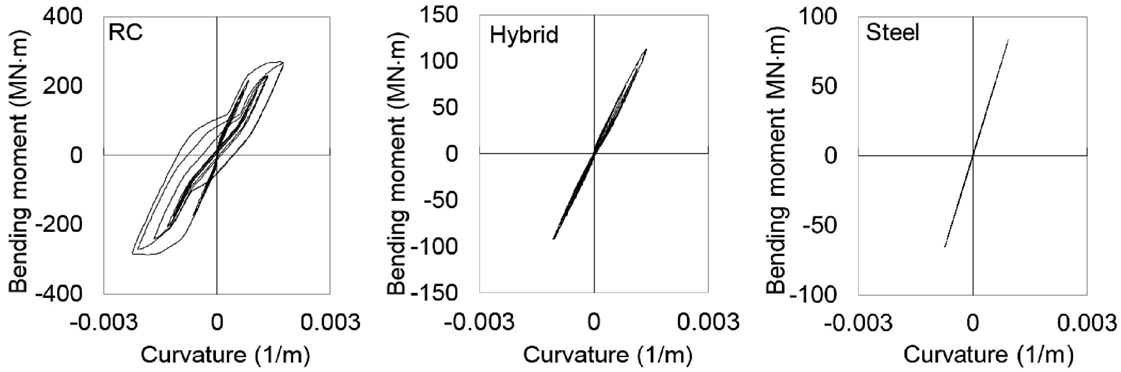


Fig.14 Moment-curvature hysteresis at the base of tower P4 due to L2

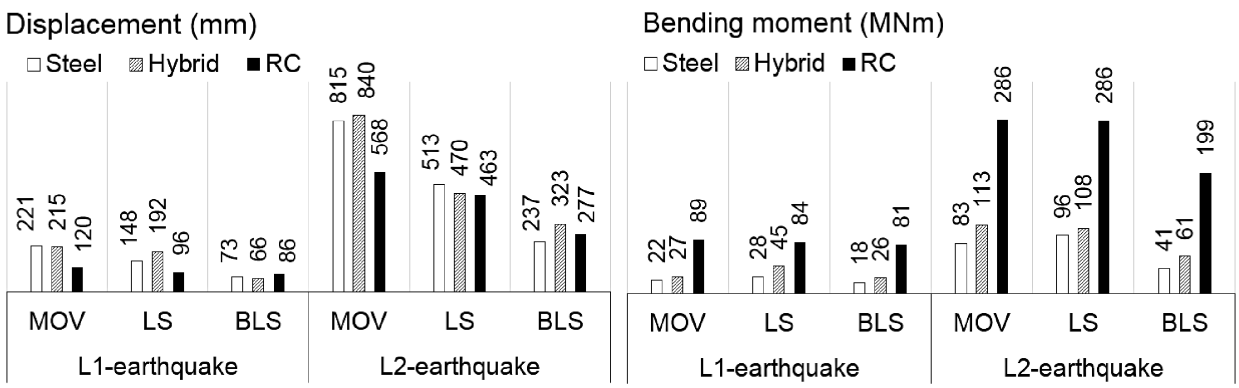


Fig.15 Peak dynamic displacement and bending moment of tower P4 due to L1 and L2 earthquakes

MOV, LS and BLS connections affects natural frequency and period of bridge. As seen in Fig.16, MOV connection produces the smallest natural frequency followed by LS and further increased with BLS. Natural frequency of bridge with RC tower is nearly twice of hybrid and steel tower in MOV connection case. BLS increases natural frequency of bridge by twice compared to MOV in all three types of towers.

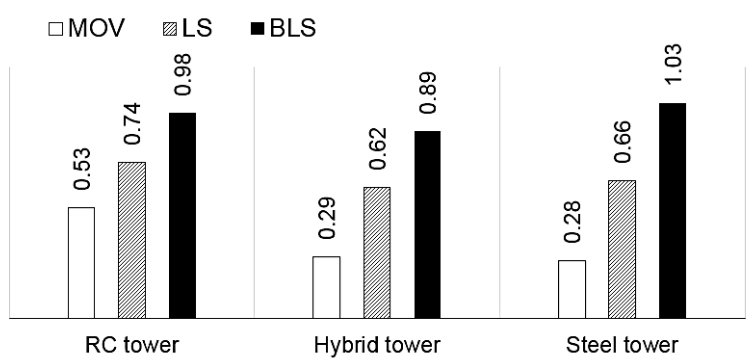


Fig.16 Natural frequency of bridge with three types of tower (Hz)

3.4. Restorability verification

In addition to safe operation during earthquake, the post-earthquake restoration of the structure is also important. In L1-EQ the restorability of structure is assessed by seismic performance levels according to moment-curvature curve of structural members. Eq.(6) is used to perform restorability verification.

$$\gamma_i \frac{\phi_{sd}}{\phi_{rd}} \leq 1.0 \tag{1}$$

Here; γ_i: Structure factor (=1.1), ϕ_{sd}: Design response curvature, ϕ_{rd}: Design resistant curvature. Fig.17 shows the seismic performance levels. In seismic performance levels-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 during repair work. In seismic performance level 3 (SPL-3), severe local damage may be allowed, but emergency vehicles can go without repair work.

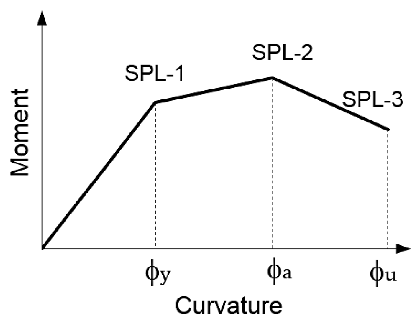


Fig.17 Seismic performance levels

Table 2 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.

Table 2 Check of restoration (MOV)

Tower type	Design earthquake	Design curvature ϕ_d (1/m)	Curvature 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

4. Discussions and conclusion

Multi-span cable stayed bridge is a new and popular bridge of this time. It possesses excellent aesthetics and technical advantages. This study is conducted to clarify seismic behaviors of three types of towers for a multi-span cable stayed bridge. In process of designing a multi-span cable stayed bridge the choice of tower marks an important step. This is due to the fact that horizontal displacement at the top of tower could impose adverse effects to the operational service of bridge. Moreover; the seismic motions are transmitted to the upper superstructure by means of towers. Hence; clarifying the advantages and disadvantages of each type of tower carries high importance and this paper deals with it. The RC and steel towers are widely used in the construction of multi-span cable stayed bridges.

Hybrid tower has many advantages, (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 plates works as formwork of the concrete. (4) It has superb static and seismic behavior.

Over and above that, three type of connection of girder at the tower is studied. Movable (MOV), connection with linear spring (LS) and connection with (BLS). Utilization of these connection does only affects the static behavior of the bridge. MOV connection acts like a roller bearing and allows free longitudinal translation and rotation of the girder. LS acts as rubber bearing and restricts horizontal displacement of girder with a linear law. BLS shows lead-rubber bearing, first it acts linearly, reaches its yield point and continuous with bilinear law.

As a conclusion; all three types of tower; the steel/concrete hybrid tower, the RC tower and the steel tower are proved feasible for a multi-span cable stayed bridge from static and seismic aspects. In static analysis; RC tower showed triple less displacement and several times larger bending moment in contrast to other towers. Steel tower had the largest displacement but the least bending moment. In addition, the seismic properties are described with three types of girder-tower connection. The bilinear spring (BLS) connection is very effective in reducing the dynamic response of all the towers. The minimal dynamic response of bridge is achieved at steel tower with BLS assemblage.

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

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