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SEISMIC RESPONSE OF CABLE-STAYED BRIDGE STEEL TOWER PROVIDED WITH BRACING SYSTEM

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Abstract. *Cable-Stayed bridges consist of many structural components, which contribute to the overall resistance ability of the system. These structural syntheses give a valuable environment for the nonlinear behavior due to material nonlinearities and geometrical nonlinearities of the relatively large deflection of the structure on the stresses and forces. To improve the bridge seismic performance and to control expected damage, the necessity has arisen to develop more efficient bridge structural systems that can lead to resist the seismic actions. The seismic response of steel structures can be improved by providing bracing elements which can resist the lateral forces affecting the structure. In this paper, the feasibility of providing bracing system as damping elements in cable-stayed bridge steel tower is studied.*

The steel tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered as model of study. The steel tower is taken out of the bridge and modeled as three-dimensional frame structure. The proposed braced model is to provide the tower by X-bracing elements connecting the upper part of the tower. The study based on comparison of the seismic response of the original un-braced tower and that of proposed braced tower. A nonlinear dynamic analysis program based on total Lagrangian formulation using linearized finite displacement theory and fiber model has been developed to be used in this study. The finite element procedure for the nonlinear time history analysis of the steel tower under seismic loadings is set up. Geometric and material nonlinearities are implemented and bending-axial force interaction is considered. The evaluation of the proposed bracing system response was based on displacements at tower top and vertical forces and moments at supports.

The results of this study show that the seismic response of cable-stayed bridge steel tower can be improved by providing bracing elements which will enhance the seismic ductility of the tower. The proposed bracing system, in this study, can reduce the horizontal displacement of the bridge tower and moment at tower base. In addition, shearing and vertical forces at tower base have slight effect.

1 INTRODUCTION

Thousands of highway bridges throughout the world are located in areas of moderate to high seismicity. The seismic resistance of these bridge structures controls their safety and the functional capability of the associated transportation routes in the aftermath of a major earthquake. Among the various structural forms available for the bridges, cable-stayed and suspension bridges have been researched for several past studies on the seismic response of bridges [1,2]. The damages of highway bridges in the 1989 Loma Prieta, 1994 Northridge and 1995 Hyogoken Nanbu earthquakes together with the research triggered as a consequence of the recent earthquakes have led to significant advance in bridge seismic design and retrofitting [3]. The seismic vulnerability of cable-stayed bridges was made dramatically evident by the failure of many of these structures in recent earthquakes. These earthquakes provided a stimulus to investigate the seismic response of highway bridges and emphasized the need to develop new procedures and specifications to assess existing bridges and to improve the seismic design of new bridges.

The seismic resisting system should provide a reliable and uninterrupted load path for transmitting seismically induced forces into the ground and sufficient means of energy dissipation and/or restraint to reliably control seismically induced displacements. All structural elements of the bridge should be capable of achieving anticipated displacements consistent with the requirements of the chosen mechanism of seismic resistance and other structural requirements. One of the traditional seismic coefficient methods is providing the structures with bracing systems.

Braced system is considered as an effective system in enhancing the stiffness and strength of steel structures where it can exhibit high lateral stiffness [4-12]. The capacity of a steel structure can be greatly strengthen under moderate-to-large magnitude earthquakes by increasing the energy absorption of structures and decreasing the demand imposed by earthquake loads. Though, the connections and foundations which need to be strengthened are affected by using braces.

Due to the high efficiency, braced steel frame systems are widely used. Braced steel frame system is effective if the braces in linear stage. The asymmetrical response is developed when at the nonlinear stage starts whereas the lateral stiffness starts to decrees. To resist seismic loads, braced steel frames have many bracing systems, such as concentric bracing system, eccentric bracing system, knee bracing system and mega bracing system.

Bracing is concentric when the center lines of the bracing members intersect. The concentric bracing used in structures include X, Chevron and Knee bracing. X bracing is the most common type of bracing. The diagonal members of X and Chevron bracing go into tension and compression. Connections for X bracing are located at beam to column joints. The frame lateral stiffness is increased resulting in natural frequency increasing and lateral drift decreasing. A larger inertia force in seismic region is attracted due to stiffness increasing. While the axial compression in the braced connected columns is increased with decreasing the bending moments and shear forces in columns. The beams of frames should be strengthened enough to resist the shear vertical forces developed from the concentric braces.

The present study objective is to investigate the seismic response of steel tower of cable-stayed bridges provided with X-bracing system at tower top in order to enhance the seismic behavior of the tower. A finite element methodology based on theoretical approach and computer simulations for nonlinear dynamic analysis problem is presented. A representative problem of a cable-stayed bridge tower subjected to strong ground motion of Hyogoken-Nanbu earthquake is analyzed. In addition, the maximum displacements at tower top and the vertical forces and moments at tower bases are computed.

2 FINITE ELEMENT OUTLINE

2.1 Finite element model of tower structure

The steel tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered. Figure 1 shows a general view of the cable-stayed bridge elevation. The steel tower is taken out of the bridge and modeled as three-dimensional frame structure. A fiber flexural element is developed for characterization of the tower structure, in which the element incorporates both geometric and material nonlinearities. The stress-strain relationship of the beam element is modeled as bilinear type with kinematic strain hardening rule. The yield stress and the modulus of elasticity are equal to 355 MPa (SM490Y) and 200GPa, respectively. The plastic region strain hardening is 0.01.

The tower has nine cables in each side; the dead load of the stiffening girder is considered to be equivalent to the vertical component of the pretension force of the cables and acted vertically at the joint of cables. The inertia forces acting on the steel tower from the stiffening girders is neglected. For the numerical analysis, the geometry and the structural properties of the tower is shown in figure 2. The tower has rectangular hollow steel section with internal stiffeners, which has different dimensions along tower height and its horizontal beam; the geometrical properties of the tower are summarized in table 1. A spectral damping scheme of Rayleigh's damping is used to form damping matrix as a linear combination of mass and stiffness matrices, which effectively captures the tower structures damping and is also computationally efficient. The damping ratio corresponding to the frequencies of the fundamental in-plane and out-plane modes of tower free vibration is set to 2%. The natural periods for different modes in three global directions obtained from the linear analysis are shown in table 2.

C. S. Dim.		Outer dimension				Stiffener dimension			
		A	*B*	t_1	t_2	*A*	*b*	t_{11}	t_{22}
Tower parts	I	240	350	2.2	3.2	25	22	3.6	3.0
	II	240	350	2.2	3.2	22	20	3.2	2.8
	III	240	350	2.2	2.8	20	20	2.8	2.2
	IV	270	350	2.2	2.6	31	22	3.5	2.4

Table 1: Cross section dimensions the tower (cm)

Mode order	Period (sec.)	Mode type
1	2.072	H
2	0.934	L
3	0.773	T
4	0.156	V

Table 2: Principal vibration modes for tower model

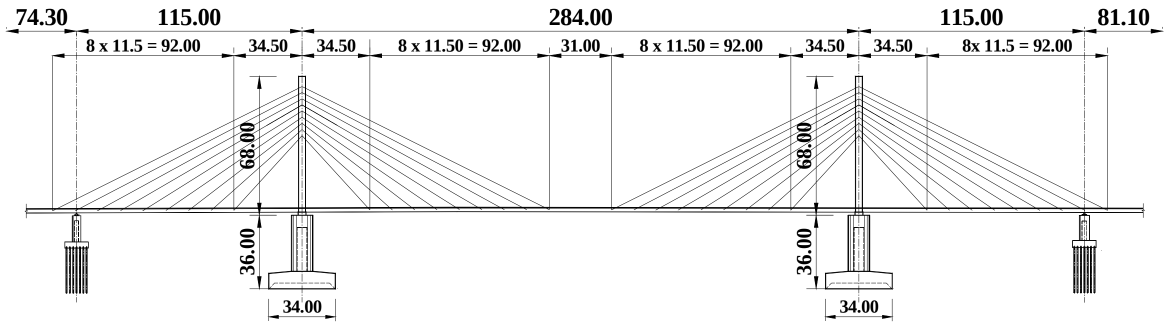
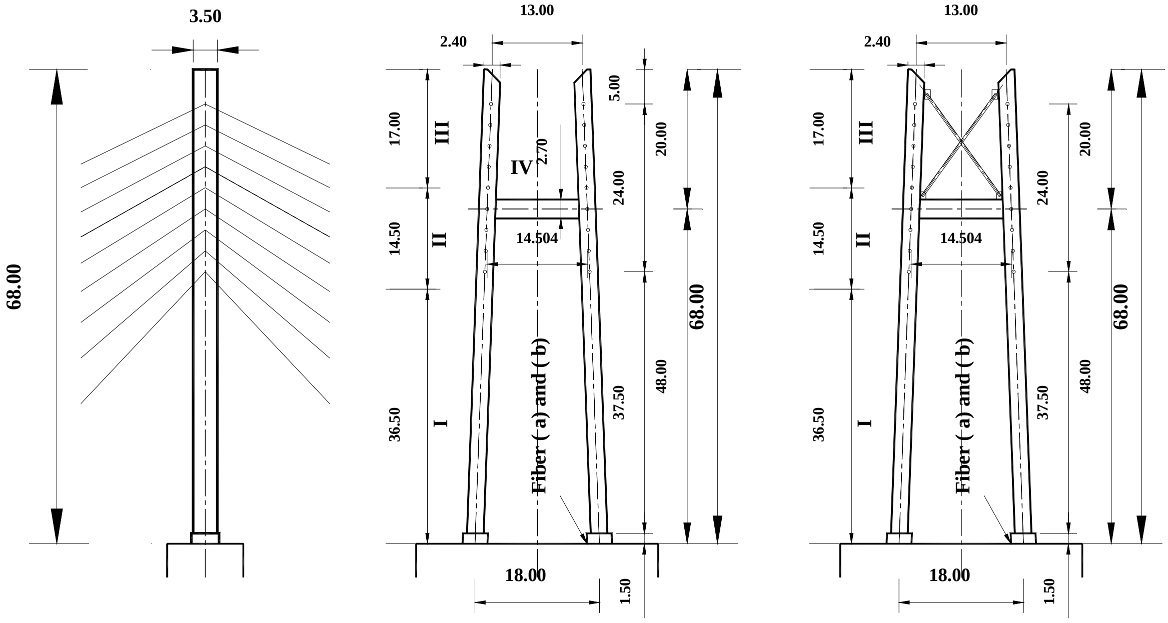
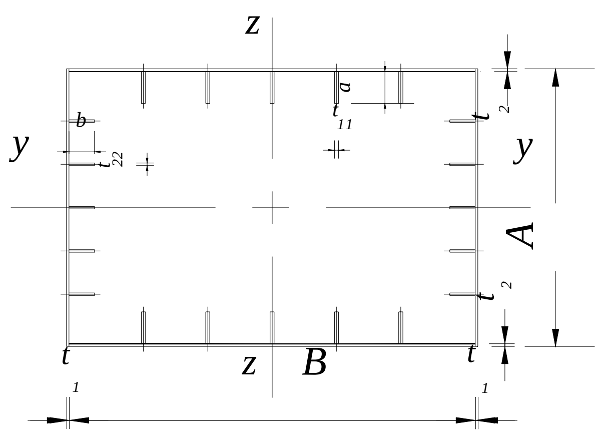


Figure 1: General view of the cable-stayed bridge (m)



(a) Tower geometry (Un-braced and braced tower)



(b) Cross section

Figure 2: Steel tower of cable-stayed bridge

2.2 Nonlinear equilibrium equation solution technique

Based on the total incremental equilibrium equations, finite displacement three-dimensional beam-column element formulation is carried out. The tangent stiffness matrix and nodal point force vectors considering both geometrical and material nonlinearities can be determined by using the fiber model in which the bending-axial force interaction is automatically considered. The initial state of residual stresses effects on both tangent stiffness and force vector is considered. The implicit Newmark step-by-step integration method is used to directly integrate the equation of motion. Since it has been experienced that the Newmark method is the most suitable for nonlinear analysis; it has the lowest period elongation and has no amplitude decay. In addition, the stability concern is not a problem with the variable ratio of time increment to natural period. The equation of motion is solved for the incremental displacement using the Newton Raphson iteration method where the stiffness matrix is updated at each increment to consider the geometrical and material nonlinearities and to speed the convergence rate. As the incremental displacement is determined, the response acceleration and velocity components of the tower can be determined. In addition, attenuation of the steel tower structure is adopted the Rayleigh’s viscous damping with damping coefficient equal to 2% to the in-plane and out-plane fundamental natural vibration modes.

Inelasticity of the flexure element is accounted for by the division of the cross section into a number of fiber zones with uniaxial plasticity defining the normal stress-strain relationship for each zone, the element stress resultants are determined by integration of the fiber zone stresses over the cross section of the element. By tracking the center of the yield region, the evolution of the yield surface is monitored, and a stress update algorithm is implemented to allow accurate integration of the stress-strain constitutive law for strain increments, including full load reversals.

To ensure path dependence of the solution, the implementation of the plasticity model for the implicit Newton Raphson equilibrium iterations employs a stress integration whereby the element stresses are updated from the last fully converged equilibrium state. The transformation between element local and global coordinates is accomplished through a vector translation of element forces and displacements based on the direction cosines of the current updated element coordinate system.

3 SELECTED GROUND MOTIONS

In the dynamic response analysis, the ground motion that was recorded during Hyogoken-Nanbu earthquake 1995 with the largest intensity of ground acceleration is used as an input ground motion to assure the seismic safety of bridges. The horizontal and the vertical accelerations recorded at the station of JR Takatori observatory, as presented in figure 3, are suggested for dynamic response analysis of the steel tower of cable-stayed bridge at type II of soil condition, because it is considered to be capable of exciting of this tower well into its nonlinear range. The selected ground motion has maximum acceleration of its components equal to 642 gal (N-S), 666 gal (E-W) and 290 gal (U-D). From Fourier spectrum analysis, the predominant frequencies for N-S and E-W components are 0.83 and 0.81 Hz, respectively, which are relatively low, and that for the U-D component is 7.96Hz, which includes high frequency components and indicates the vertical motion time lag to horizontal motions. The earthquake force of E-W wave is put into the bridge axis direction (out-plane), and N-S wave to the right angle to the bridge axis (in-plane).

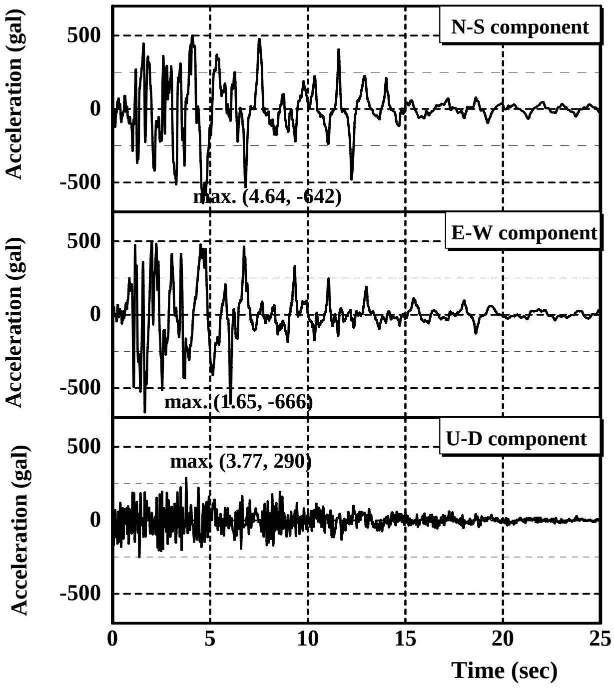


Figure 3: Strong ground motion measured at JR Takatori

4 RESULTS AND DISCUSSION

Seismic response analysis using the time history inputs is required to meet the goals of performance based design. Seismic response behavior of the cable-stayed bridge tower provided with bracing system under a great input ground motion is presented, and compared to the response of un-braced tower.

A finite element analysis of steel tower and provided with suggested bracing system was carried out. A seismic response analysis comparison to un-braced steel tower (original case) is presented. The resulting seismic characteristics of the braced tower model are different from the un-braced tower due to control of the upper part from side sway. The providing tower with bracing system displays more pronounced difference in tower model seismic response as the lateral displacements controlled.

It is noticeable that the results of seismic response vary with different structural system for the same input earthquake motion. The acceleration response for the braced system shows lower acceleration response than the un-braaced system along all the time history. The acceleration response is significantly affected by the tower lateral stiffness. It is interesting to see that the braced and the un-braced systems show similar acceleration responses along the time history with higher amplification of input excitation in the high frequency bridge axis direction as can be illustrated in figure 4.

The displacement response of the tower structure is calculated, the braced system gives much lower displacements in the right angle bridge axis direction, figure 5. This effect is characterized by three cycles of large displacement amplitude related to the large pulse in the input ground motion, decaying rapidly after the peak excursions due to the large plastic deformation caused by the high intensity. Unfavorable residual deformation in the tower structure after earthquake is attained. The bracing system can control the residual deformation. The providing tower with bracing system can affect the tower top displacement global response, where its contribution in the maximum displacement reaches about 30 % of that of the un-braced tower.

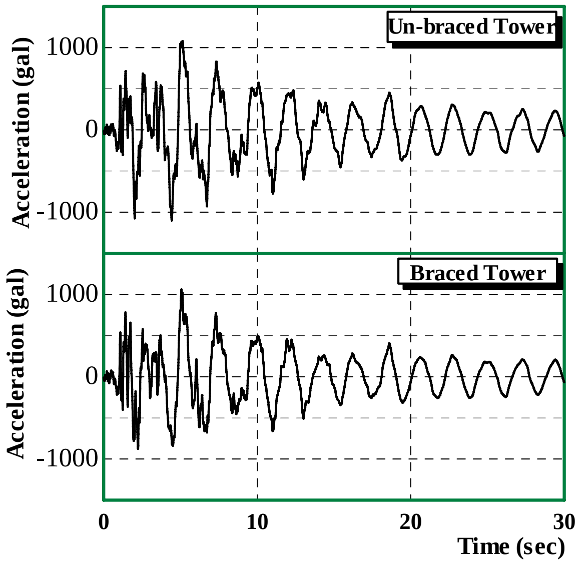


Figure 4: Acceleration time history at tower top

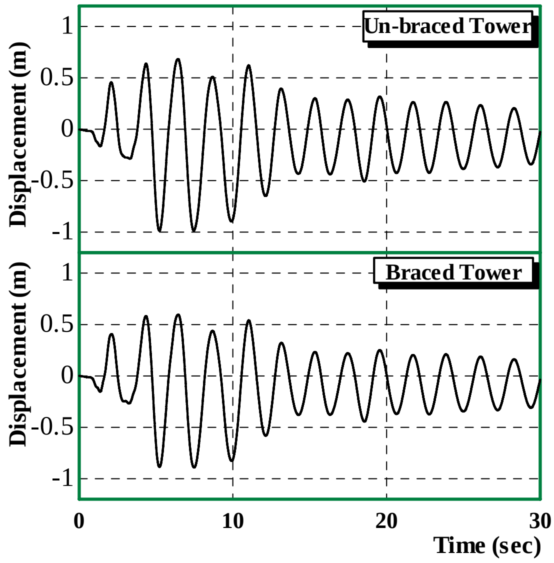


Figure 5: Displacement time history at tower top

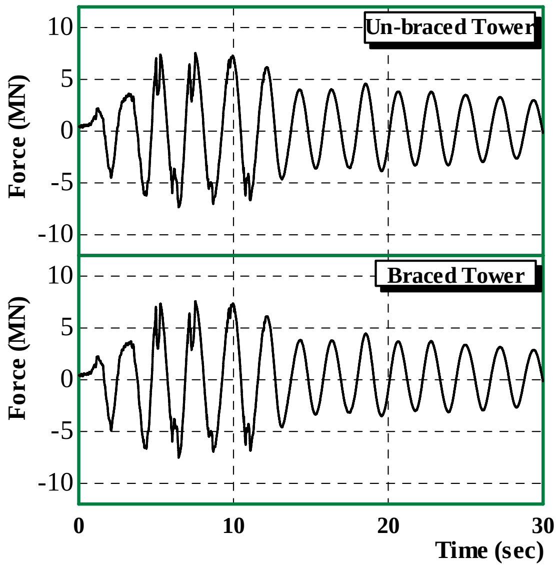


Figure 6: Shear force time history at tower base

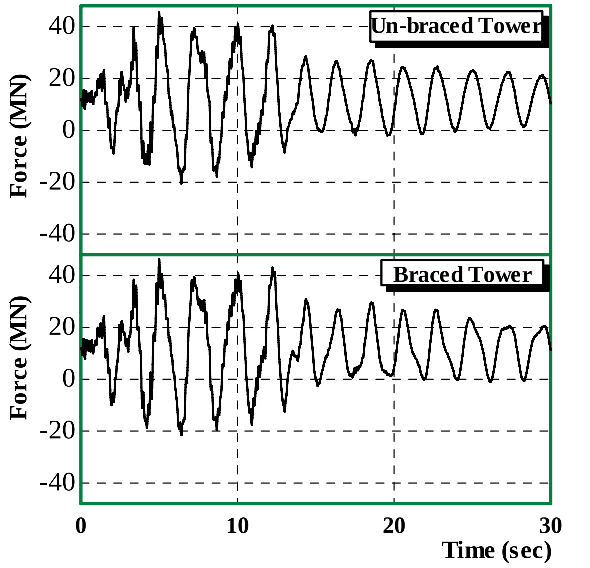


Figure 7: Vertical force time history at tower base

The negative effect of bracing system is increasing the shearing force at supports of structures. Hence, the shearing force is important to be examined at tower base after providing the bracing system. The shear force time history at tower base is shown in figure 6. Providing the tower with bracing system gives negligible increasing in the shearing force magnitude. The increasing of the shearing force can be calculated by 0.5 % only which considered has no obvious effect. By comparing the vertical reaction force time history at the tower base for the two different tower models, it is found that the tower provided with bracing system displays slight increase in the reaction force responses compared to the un-braced tower response (original case), as shown in figure 7. The increase of the vertical reaction force in both negative and positive directions may be reaches around 0.2 % which can be considered has no effect. It can be concluded that the bracing system provided to the tower structure has no effect on the reaction forces at tower base.

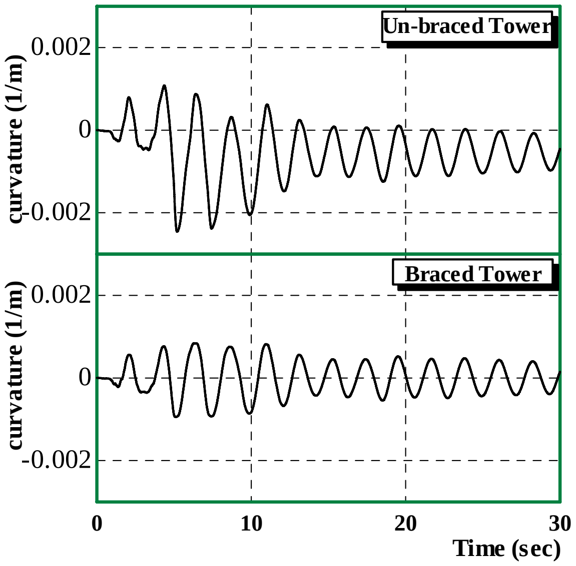


Figure 8: Curvature time history at tower base

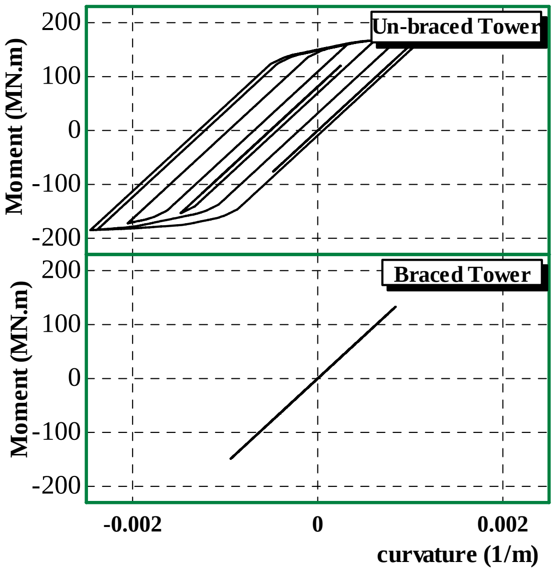


Figure 9: Moment & curvature relationship at tower base

Figure 8 shows the curvature time history which represent the residual curvature at tower base in case of original un-braced tower. It is can be shown the great effect of suggested bracing system which can control this residual curvature after earthquake end. Form the moment curvature relation for the original un-braced tower, figure 9; it can clarify the effect of the near fault acceleration pulse on the tower structural response that tends to be characterized by progressive yielding in one direction starts from tome 5 seconds in the negative direction. The asymmetric accumulation of inelastic deformation in one direction becomes increasingly important as the duration of the ground motion is increased. For the mass proportional damping, it can be observed that the asymmetry strength and moment curvature diagram shift due to fluctuating axial force effect. This asymmetric completely disappears in case of using bracing system. That means using of the bracing system can overcome the effect of near fault acceleration pulse in the input wave and makes equalization of the hysteric response. On the other hand, the axial force-moment interaction which leads to irregular shape due to presence of vertical motion can be balance by the suggested bracing system.

5 CONCLUSIONS

The feasibility of providing bracing system in cable-stayed bridge steel tower is studied. The steel tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered as model of study. The steel tower is taken out of the bridge and modeled as three-dimensional frame structure. The proposed braced model is to provide the tower by X-bracing elements connecting the upper part of the tower. The study based on comparison of the seismic response of the original un-braced tower and that of proposed braced tower. A nonlinear dynamic analysis program based on total Lagrangian formulation using linearized finite displacement theory and fiber model has been developed to be used in this study. The finite element procedure for the nonlinear time history analysis of the steel tower under seismic loadings is set up. The results of this study show that the seismic response of cable-stayed bridge steel tower can be improved by providing bracing elements which will enhance the seismic ductility of the tower. The proposed bracing system, in this study, can reduce the horizontal displacement of the bridge tower. In addition, the vertical force and bending moments at tower support give more reduced values compared to those of un-braced tower.

From this study, the following conclusions can be drawn as follow:

- Providing the tower with proposed X-bracing system can affect the tower top displacement response, where its contribution in the maximum displacement reaches about 30 % of that of the un-braced tower.
- The proposed X-bracing system provides slight increase in the reaction forces while the moment reduced compared to the un-braced original tower response, moreover the curvature at tower base give symmetrical response.
- The proposed X-bracing system leads to no residual curvature at tower column.

REFERENCES

[1] T. Hayashikawa, and S. E. Abdel Raheem, Nonlinear dynamic behavior of steel tower of cable-stayed bridges with passive energy dissipation system, *Journal of Structural Engineering, JSCE*, Vol. 48A, pp. 863-874, 2002.

[2] M. OMAR, Seismic Performance of Cable-Stayed Bridge Steel Towers, *PhD thesis, Graduate School of Engineering, Hokkaido University*, 2008.

[3] Committee of Earthquake Engineering, The 1995 Hyogoken-Nanbu Earthquake, Investigation into Damage to Civil Engineering Structures, *Japan Society of Civil Engineers*, June, 1996.

[4] M. OMAR: Seismic Response of Braced Steel Frames with Shape Memory Alloy and Mega Bracing Systems, WASET, *International Journal of Civil, Architectural Science and Engineering* Vol:8 No:2, 2014.

[5] M. OMAR and T. HAYASHIKAWA, Improvement of Nonlinear Response of Plan-Irregular Multi-Storey Steel Buildings under Three-Dimensional Earthquake Motion Using Bracing System, *Journal of Steel Construction, JSSC,* Vol.22, 2014.

[6] R. Sabelli, S. Mahin, C. Chang. Seismic demands on steel braced frame buildings with buckling-restrained braces, *Engineering Structures*, 25(5):655-66, 2003.

[7] M. Nakashima, K. Inoue, M. Tada, Classification of damage to steel buildings observed in the 1995 Hyogoken-Nanbu Earthquake, *Engineering Structures*,20(4-6):271-81, 1998.

[8] FEMA. Recommended seismic design provisions for new moment frame buildings, *Federal emergency management agency report* No. 350. 2000.

[9] J. Osteraa, H. Krawinkler, The Mexico earthquake of September 19, 1985 behavior of steel buildings. *Earthquake Spectra,* 5(1):51-88, 1989.

[10] H. Kim, S. Goel, Seismic evaluation and upgrading of braced frame structures for potential local failures, UMCEE 92-24, *Dept. of civil engineering and environmental engineering, Univ. of Michigan, Ann Arbor,*Oct. p. 290, 1992.

[11] R. Tremblay, P. Timler, M. Bruneau, A. Filiatrault, Performance of steel structures during the 1994 Northridge earthquake, *Canadian Journal of Civil Engineering*, 22:338-60, 1995.

[12] R. Trembla, M. Bruneau, M. Nakashima, HGL Prion, A. Filiatrault, R. DeVall, Seismic design of steel buildings: lessons from the 1995 Hyogo-ken Nanbu earthquake, *Canadian Journal of Civil Engineering*, 23: 727-56, 1996.