Expected Column-Base Vertical Motions Effect on Seismic Analysis of Cable-Stayed Bridges

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1. INTRODUCTION

Serious damages in steel structures are ascribed to the failure of the column bases that was clearly observed in the Hyogoken-Nanbu earthquake 1995 in Japan as the anchor bolts came out or ruptured, the base plates bent out of shape, or the base mortar being crushed. Column base behavior has a strong effect on the overall behavior of the steel frames, hence avoiding failure in the column base connections is most important, so a more attention should be paid to the proper modeling and right construction[1-6].

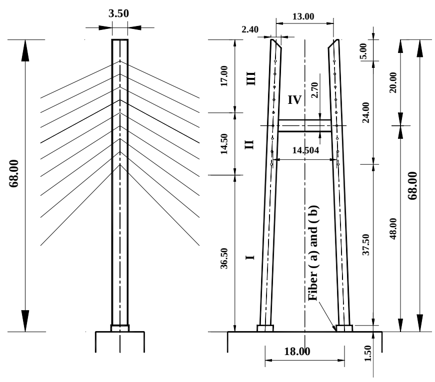
The present study objective is to investigate the seismic response of steel tower of cable-stayed bridges with base plate lift-off and to clarify the different cases of tower damaged performance according to the position of the expected tower base vertical motion. The base connection is idealized by a spring system that considers connection expected vertical motions. A finite element methodology based on theoretical approach and computer simulations for nonlinear dynamic analysis problem including base connection modeling 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 bearing stress demand of anchor bolt is computed.

2. ANALYSIS AND METHODOLOGY

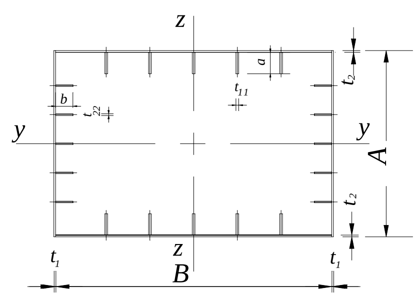
Based on the total incremental equilibrium equations, large displacement 3D beam-column element formulation is carried out. The implicit Newmark's step-by-step integration method is used to directly integrate the equation of motion and then it is solved for the incremental displacement using the Newton 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. In addition, the tower structures damping mechanism is adapted to the viscous damping of Rayleigh's damping type with damping coefficient to the in-plane and out-plane fundamental natural vibration modes equal to 2% for steel material of tower superstructure.

The steel tower of Tappu cable-stayed bridge located in Hokkaido, Japan is considered. The steel tower is taken out of the cable-stayed bridge and modeled as three-dimensional frame structure characterized by a fiber flexural element. The tangent stiffness considers the material nonlinearities through elastic-plastic constitutive model incorporating an unaxial yield surface criteria and kinematic strain hardening flow rule. The steel yield stress and modulus of elasticity are equal to 353 MPa and 200 GPa, respectively; the plastic region strain hardening is 0.01. The geometry of the steel tower and finite element structural model are shown in **Fig. 1**.

Steel towers are usually fixed by multiple bolts to large anchor frame embedded in a concrete pier/footing. The column base connection consists of 24 anchor bolts arranged outside the tower leg flanges, **Fig. 2**. A component spring model for base connections is proposed. This model incorporates vertical deformations from tension bolt elongation, bending of base plate and deterioration of concrete bearing underneath base plates. Each of these springs is characterized by its own deformability curve as an individual component, as shown in **Fig. 3**.



(a)　Tower geometry



(b)　Cross section

Fig. 1 Steel tower of cable-stayed bridge

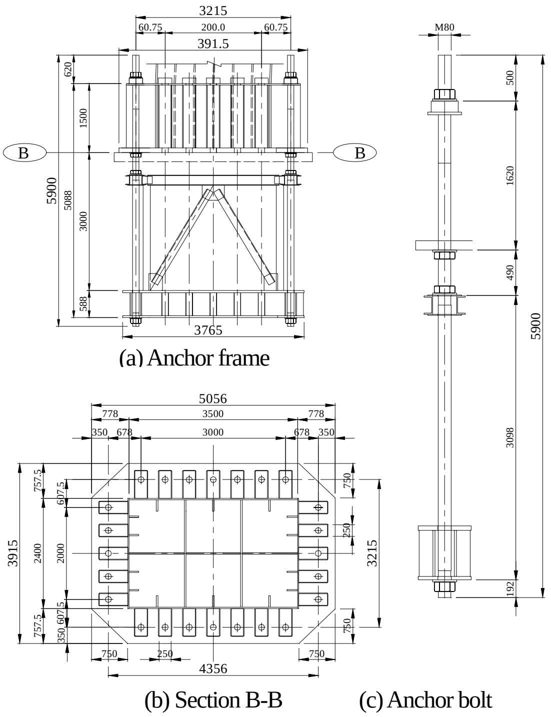


Fig. 2 Details of steel tower base connection (mm)

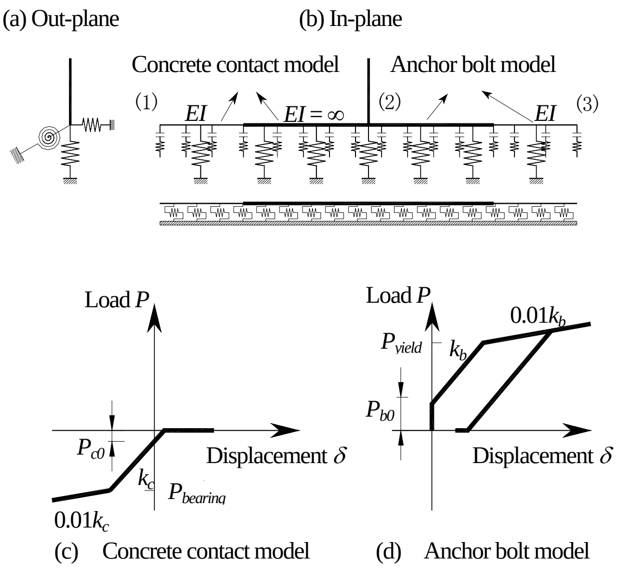


Fig. 3 Base connection components constitutive models

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[7 - 9], are suggested for dynamic response analysis of the steel tower of cable-stayed. 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). 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), as shown in **Fig. 4**.

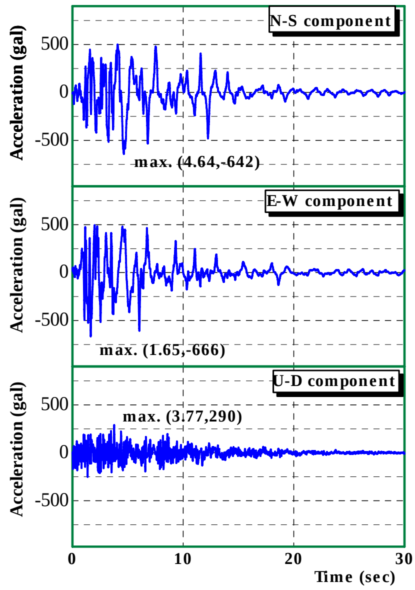


Fig. 4 Ground motion measured at JR Takatori

4. NUMERICAL RESULTS

As base connection structural characteristic change is manifested in the long term due to deterioration of concrete base and steel anchors, the anchor bolt stiffness and pre-tension force could decrease, hence lead to extra vertical motion in the base plate and loosing between the base plate and the concrete. A finite element analysis of steel tower taking into account a more realistic model for the support condition including the expected vertical motion at base plate at the different locations of the tower base as follow:

Case1: unsymmetrical damaged performance.

Case2: symmetrical damaged performance.

Where for unsymmetrical case (case 1), the expected vertical motion assumed to be occurs at one side of the tower leg while for symmetrical case (case 2), the expected vertical motion assumed to be occurs at both sides of the tower legs. A comparison to simplified support condition modeling of fully rigid fixed base connection (original case) which has no vertical motion at the tower base plate is presented. The allowable vertical motion model displays more pronounced difference in tower model seismic response as the base connection rigidity decrease. It can be observed that the tower top displacement response has similar response with slight increase in displacement amplitude in case of unsymmetrical damaged performance in positive direction and it has low displacement in case of symmetrical damaged performance, while after 12 seconds, the tower seismic response is highly damped free vibration response with longer natural vibration, significantly low amplitude and less residual plastic displacement drift as illustrated in **Fig. 5.** The expected vertical motion in case of symmetrical damaged performance leads to a significant reduction in displacement response.

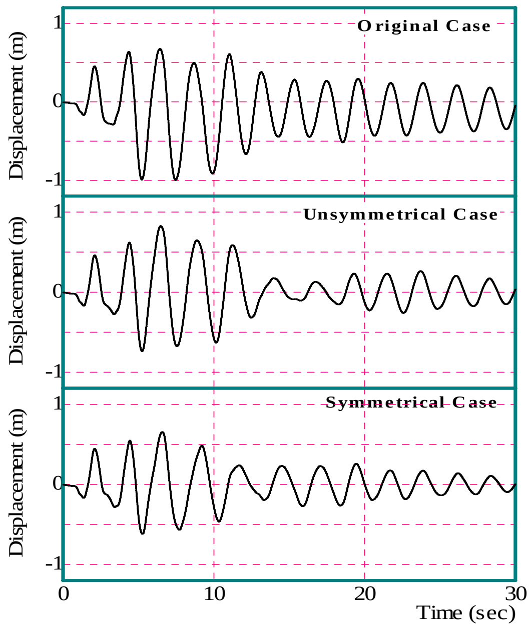


Fig. 5 Displacement time history at tower top

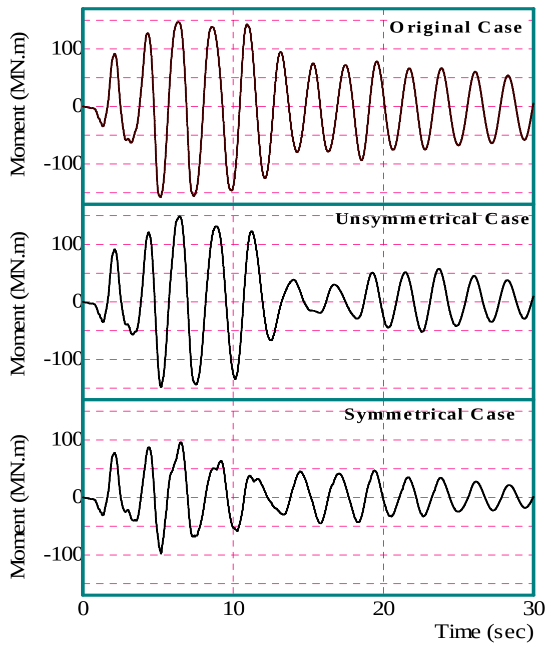


Fig. 6 Moment time history at tower base

The base including the vertical motion provides pronounced reduction in the moment responses compared to the original tower response; moreover the presence of vertical motion at both sides of column bases (symmetrical Case) displays more effectiveness in reaction force reduction and moment than its presence at one side (unsymmetrical Case) as shown in **Fig. 6**. The bridge towers affected by the base plate vertical motions show a little plastic behavior with significantly low amplitude of yield moment (*My*) at the tower base compared with original towers, which show plastic response with yield moment equal to 130 MN·m. The reduction in case of unsymmetrical damaged performance is slightly while it is more significantly in case of symmetrical damaged performance which still within the elastic range.

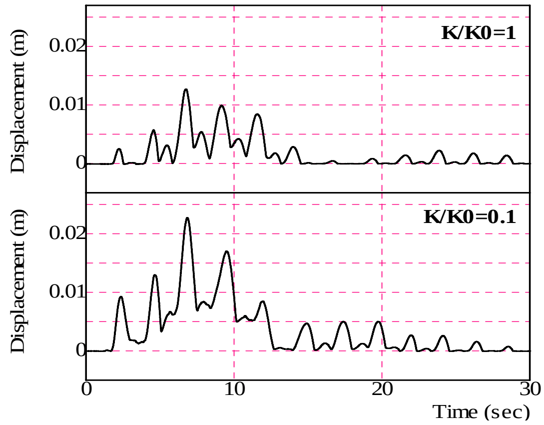


Fig. 7 Base plate deformation time history

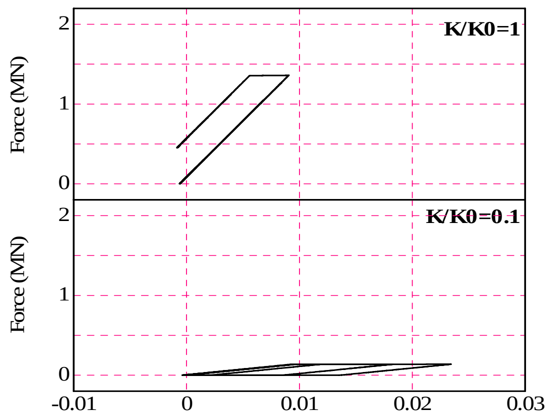


Fig. 8 Anchor bolt load deflection relationship

The base plates are designed thick to transfer primarily compression forces into concrete block and are restrained by stiffener. The case of symmetrical damaged performance has been considered to study the base plate deformation and the input energy absorbed by the tower to stand upon the required understanding of the real behavior of the base plate and anchor bolts before and after the tower affecting by the base vertical motions. The compression part of the base plate designed for resistance of the concrete in crushing under the flexible base plate. The base plate deformation time history at plate middle, **Fig.7**, is significantly affected by the relative decrease in anchor bolts where K is the vertical stiffness of the anchor bolt and K_0 is its initial stiffness, which significantly affects vertical motion. It can be observed that decreasing of vertical stiffness anchor bolt by 10% leads to nonlinear increase of maximum base plate vertical deformation from 1.268 cm to 2.27 cm (about 80 % increasing). Then the presence of vertical motion at tower base plates and reduction of the anchor bolt stiffness reduces forces and displacement while increase significantly the base plate deformation; hence it is need to know the anchor bolt bearing force. The anchor bolt force as a function of time is shown in **Fig.8**. The reduction in anchor bolt stiffness leads to increasing its flexibility as a result increasing the flexibility of the whole tower. Therefore, it is important to know the total force transferred to the tower.

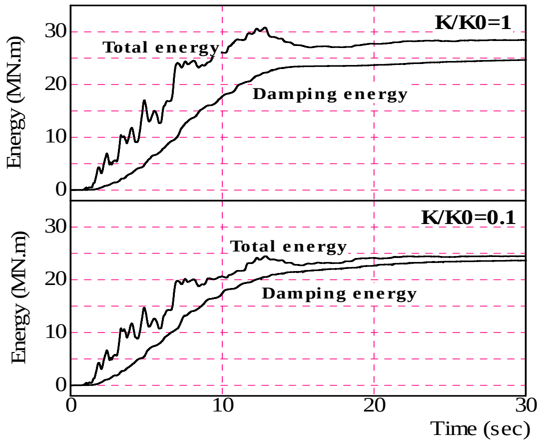


Fig. 9 Energy time history of the whole tower

The input energy is defined as the total energy related to inertia forces induced by the ground motion. it is appeared ,as shown in **Fig. 9 ,** that the inclusion of these vertical motions at tower base has great effects on the tower response that is to change the tower stiffness to be more flexible, resulting in an increase the ability of tower structural system to reflect a portion of earthquake input energy. It is appeared the effect of the vertical motion to increase the amount of damping and dissipation energy because of the hysteretic properties of the inelastic deformation for the anchor bolts. The results obtained show effective vertical motion. Moreover, the vertical motion significantly increases the deformation of base plate which should be strongly considered in design. This can be attributed that the anchor bolts play apart in dissipating energy; hence the reduction in its stiffness as well as increasing its flexibility could make it works as dissipation energy device and that lets the tower structural system gets its full damping quickly.

5. CONCLUSIONS

Numerical parametric study of the steel tower cable-stayed bridge has been conducted to investigate the dynamic behavior considering expected vertical motion at tower base connection. A finite element program based on the fiber model theory for the nonlinear dynamic analysis of steel tower under static and dynamic loadings of great earthquake ground motion is developed, considering material nonlinearity. The nonlinear finite element dynamic analysis demonstrates how base plate vertical motion influence tower seismic response for the different cases of damaged performance position. From this study, the conclusions can be drawn as follow:

1) The base including the vertical motion provides pronounced reduction in the displacement and moment responses compared to the original tower response; moreover the presence of vertical motion for the tower symmetrical damaged performance column bases displays more effectiveness in displacement reduction and moment than its presence as tower unsymmetrical damaged performance.
2) The reduction in anchor bolt stiffness leads to increasing its flexibility as a result increasing the flexibility of the whole tower, resulting in an increase the ability of tower structural system to reflect a portion of earthquake input energy and increase the amount of damping and dissipation energy because of the hysteretic properties of the inelastic deformation for the anchor bolts.
3) The anchor bolts play apart in dissipating energy and the reduction in its stiffness as well as increasing its flexibility could make it works as dissipation energy device and that lets the tower structural system gets its full damping quickly.

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