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Behavior of a concrete filled steel box column with considering detachment under seismic load

S. Zenzai*, S. Shimizu, Y. Chikahiro

Department of Civil Engineering, Shinshu University, Wakasato 4-Chome, Nagano 380-8553, Japan

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ABSTRACT

Various numerical studies have been conducted on the dynamic behavior of concrete-filled steel columns. However, the detachment caused by the tensile stress between the steel plates and the concrete is rarely considered. This paper describes the results of dynamic numerical analysis conducted on a concrete-filled steel box column used as a pier of a motorway viaduct under seismic load, with detachment considered as a contact problem. The results obtained indicate that detachment causes large residual displacement and reduces the peak load of the column. Further, the influence of the detachment on column behavior is shown to depend on the depth of the concrete.

1. Introduction

A steel box column used as a pier of a motorway viaduct is often filled with concrete at its base. Initially, the concrete was expected to prevent damage from collision by vehicles, and was assumed to have no effect on the strength and structural behavior of the columns.

However, following damage investigation of the Kobe earthquake in 1995 [1], it was discovered that the filled-in concrete effectively improves the seismic-proof behavior of the column and can carry a part of loading. Accordingly, many studies have been conducted on both the static and the dynamic behavior of steel box columns under seismic load [2–19]. These studies include experimental investigation of the behavior under cyclic and/or seismic load [2–6] and numerical analysis of concrete-filled steel columns [7–14].

In general, when a column filled with concrete is subjected to bending due to a seismic load, detachment of the steel column from the filled-in concrete arises. When this occurs, the filled-in concrete can no longer carry the load; thus, detachment may reduce the strength of the column. Such detachment can be considered easily in experimental studies. On the other hand, detachment is difficult to introduce into numerical studies. Consequently, numerical studies such as [7–9] do not consider detachment, whereas studies such as [10–14] do consider detachment. However, the studies that do consider detachment are conducted based on static load rather than dynamic load.

Shimizu and Iwamoto [15] and Watanabe and Shimizu [16] also conducted numerical studies on the seismic behavior of steel box columns, in which the effect of detachment under static load is considered. Shimizu and Watanabe [17] and Shimizu [18] further conducted unidirectional dynamic analysis under seismic load, whereas Zenzai and Shimizu [19] discuss the effects of seismic load in two or three directions on column behavior.

In this study, we conducted numerical analysis considering the detachment of the steel-concrete interface under practically observed seismic motion involving all three components. Thus, this paper elucidates in detail the influence of detachment on the behavior of a concrete-filled steel box column under seismic load. More specifically, it discusses the results of dynamic analysis conducted under seismic load of a concrete-filled steel box column considering detachment between the steel plates and the filled-in concrete.

2. Detachment

The detachment of the interface between the steel plates and the filled-in concrete is caused by tensile stress. Once detachment occurs, the column undergoes repeated contact and separation events between the steel and the concrete under seismic load. In this paper, the detachment phenomenon in the column is represented as a "contact problem." Modeling of the detachment at the steel-concrete interface is illustrated in Fig. 1. In the initial state (Fig. 1**(a)**), the steel plate is in contact with the concrete, and they act in concert. When the interface is subjected to tensile stress, detachment arises, and the steel plate separates from the concrete with a gap g_0, as shown in Fig. 1**(b)**. Subsequently, any application of tensile stress changes the compressive stress under seismic load, and the steel plate begins to approach the concrete with a displacement u, as shown in Fig. 1**(c)**. That is, the distance g_0 in Fig. 1**(b)** becomes g at this stage. The gap g is required to satisfy the

* Corresponding author.
E-mail address: 16st403c@shinshu-u.ac.jp (S. Zenzai).

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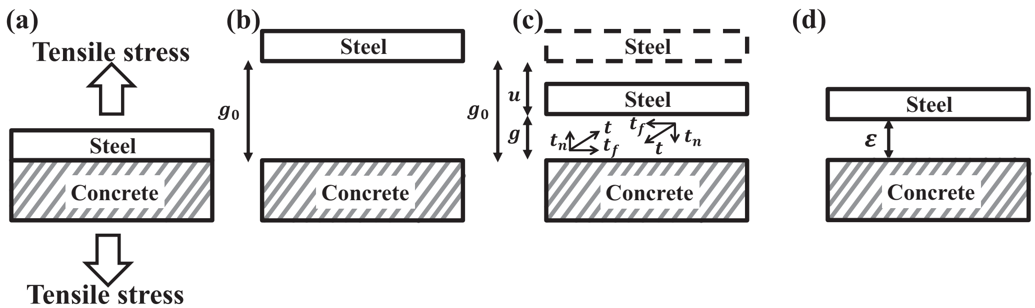

Fig. 1. Contacting and detachment.

following relational expression:

$$g = g_0 - u \geqq 0 \tag{1}$$

This equation means that the steel plate does not penetrate the concrete. When the steel plate and the concrete are in contact again, i.e., $g = 0$ in Eq. (1), a contact force t arises, as shown in Fig. 1**(c)**. In general, contact force t consists of a vector normal to the interface t_n and of friction t_f. However, for simplification, in this paper, friction t_f is ignored. Thus, contact force t is assumed to be the same as contact normal force t_n.

Practically, detachment is modeled using one of the following two methods: Direct Constrain Method (DCM) or Contact Elements (CE).

In the DCM [20], first, the gap g between the steel plate and the concrete is calculated. When gap g is greater than a specified value ε, shown in Fig. 1**(d)**, the steel and the concrete behave separately. On the other hand, when gap g is smaller than the specified value ε, the steel and the concrete are defined as being in contact.

In the CE method [21], special elements, which are inserted at the interfaces, are used to express the detachment. In this study, the DCM was applied for the surface plate in Fig. 2**(a)**, and the CE method for the stiffeners in Fig. 2**(b)**.

3. Numerical models

3.1. Geometry and materials of the models

In this study, four analytical models, classified in terms of the depth of the concrete and existence of detachment, were utilized. In these models, the depth of the concrete was assumed to be either 2700 mm or 1350 mm.

The models were denominated as follows: Models “F270D” and “F270B” both had a concrete depth of 2700 mm, but only “F270D” considered detachment. Similarly, Models “F135D” and “F135B” both had a concrete depth of 1350 mm, but only “F135D” considered detachment.

Each column had length and width 3000 mm, plate thickness t_s 20 mm, and height h 10,000 mm, as shown in Fig. 3. In addition, each column was stiffened by both longitudinal stiffeners and diaphragms. Specifically, three 300 mm × 18 mm stiffeners were installed in each face of the column and a 16 mm thick diaphragm was located at vertical intervals of 2700 mm on the column.

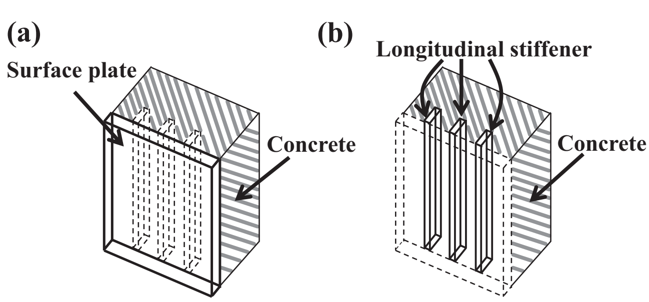

Fig. 2. Steel-concrete interface. (a) Direct constrains method, (b) Contact element.

For the steel plates, grade SM490Y steel was assumed, which has a nominal yield stress $\sigma_y = 355$ MPa, initial Young's modulus of steel $E_s = 206$ GPa, Poisson's ratio $\mu_s = 0.3$, and density $\rho_s = 7.85 \times 10^{-6}$ kg/mm^3. Yielding is defined by the Von Mises yield criteria. After yielding, considering the Bauschinger effect under seismic load, the combined hardening rule was employed. The tangent of the stress-strain relation after yielding was assumed to be $E_s / 100 = 2.06$ GPa

For the concrete, Young's modulus $E_c = 22.50$ GPa, Poisson's ratio $\mu_c = 0.22$, and density $\rho_c = 2.35 \times 10^{-6}$ kg/mm^3. The predicting behavior of the filled-in concrete is difficult due to the confining stress from the steel plates. Ho et al. proposed the constitutive model for the filled-in concrete based on the experimental results [22,23]. However, according to [2,5], when the concrete depth is below 30% of the column height, no damage is exhibited on the concrete. Therefore, we assumed that no crack and collapse arise on the concrete under seismic load, and the concrete behaves elastically.

The current numerical model has a width-thickness ratio R of 0.82 and slenderness ratio λ of 0.22. These ratios are defined as follows:

$$R = \frac{b}{t_s}\sqrt{\frac{12(1-\nu_s^2)\sigma_y}{k\pi^2 E_s}} \tag{2}$$

$$\lambda = \frac{1}{\pi}\sqrt{\frac{\sigma_y}{E_s}}\frac{2h}{r} \tag{3}$$

where b is the steel plate width, t the steel plate thickness, k the buckling coefficient of the plate, E_s the Young's modulus of the steel, ν the Poisson's ratio of the steel, σ_y the yield stress of the steel, r the radius of gyration of the column, and h the column length.

The model was discretized with the three types of elements illustrated in Fig. 4**(a)**. Specifically**,** rectangular shell elements were used for the steel plates, longitudinal stiffeners. and diaphragms. The upper part of the column was discretized with 2-node beam elements to reduce the degree of freedom. For the filled-in concrete, 8-node solid elements were employed.

The analysis condition was based on a single degree of freedom system. Specifically, the bottom part of the column was fixed, whereas at the top a mass m of 1400 t was considered to correspond to the superstructure of the viaduct. The dead load mg ($g = 9.8m/s^2$) and seismic load for the North-South direction of the seismic motion a_{NS}, for the East-West direction a_{EW}, and for the Up-Down (Vertical) direction a_{UD} were applied as shown in Fig. 4**(b)**.

3.2. Natural frequency and damping factor

Rayleigh damping was applied to express the damping of the columns. Rayleigh damping is defined as

$$[C] = \alpha[M] + \beta[K] \tag{4}$$

where $[C]$ denotes the damping matrix, α and β are the arbitrary constant coefficients, and $[M]$ and $[K]$ are the mass and stiffness matrices, respectively. To calculate the arbitrary constant coefficients, it is necessary to have the eigenvalue of the column. Therefore, the eigenvalue