Experimental Study on the force transfer mechanism at the R/C connection surface with post-tension force to develop the soft-landing base-isolation system

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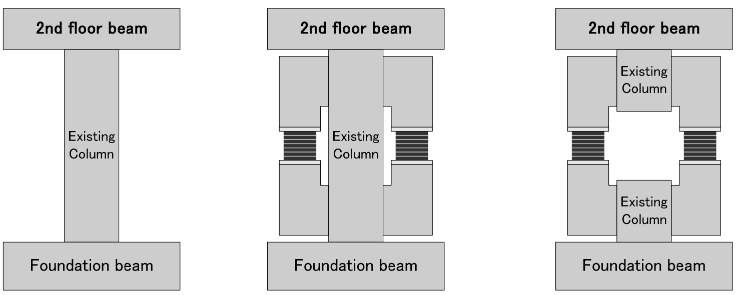
ABSTRACT :

The authors are developing a new retrofitting system for relatively low seismic performance existing buildings, especially for soft-first-story buildings. The new column, which has the base-isolation system at its middle height, is attached to the existing column by the compression force with the PC bars. The existing column will fail in shear during an earthquake, and then the building becomes to be base-isolated. One of the big advantages of this system is that the retrofitting cost can be low compared to the conventional base-isolation retrofitting technique, since the existing columns do not have to be cut prior to an earthquake, which costs a lot. However, the vertical and lateral loads need to be transferred from the existing column to the newly attached column through the connection surface by the friction. In order to design the post-tension force required to the PC bars (the compression force required to the connection surface), the force carrying mechanism at the connection surface under the vertical and lateral loads needs to be studied. Therefore, a series of experimental tests were conducted to propose and verify a connection design criteria.

KEYWORDS: Seismic retrofitting, Punching shear, Torsional moment, Base-isolation

1. INTRODUCTION

The base-isolation system is one of the retrofitting techniques for existing buildings especially for the building that has very low capacity. The building, however, needs to be lifted up to install the base-isolation system to the existing building. Sometimes it costs too much. Therefore, the soft-landing base-isolation system was proposed, which is low cost base-isolation system for existing buildings. The concept of the system is shown in Figure 1.1. New pre-cast columns, which have base-isolation devices at their middle height, are attached to the existing column on the first floor ((a) and (b) in the figure). The existing column fails in shear during an earthquake ((c) in the figure), then the vertical and lateral loads are carried by the new column and the building becomes to be base-isolated. The vertical and lateral forces are transferred through the connection surface. The vertical force is transferred by the direct shear through the surface, and the lateral force is transferred by the twisting moment through the surface. The evaluation method for the capacity of the connection, however, has not been established yet. Therefore, a series of experimental tests was conducted to study the behavior at the connection between the new pre-cast column and the existing column.



(a)Before retrofitting (b) Retrofitted (c) After an earthquake

Figure 1.1 concept of the soft-landing base-isolation system

2. OUTLINE OF THE EXPERIMENTAL TEST

2.1. Specimens

The specimen consists of existing column, new pre-cast columns, and base-isolation devices. The concrete strength for the existing column was 18N/mm^2, and 36N/mm^2 for the new column. The base-isolation device was replaced by the two-directional pin connection. The lower half portion of the soft-landing system was tested (Figure 2.1), since the system is symmetric vertically as shown in Figure 1.1. Two new columns were connected to the surfaces parallel to the loading axis. The specimens were scaled down by 1/3.

Dimensions and bar arrangement of the specimens are shown in Table 2.1. The concrete strength of each specimen and properties of steel measured from material tests are shown in Table 2.2 and Table 2.3, respectively.

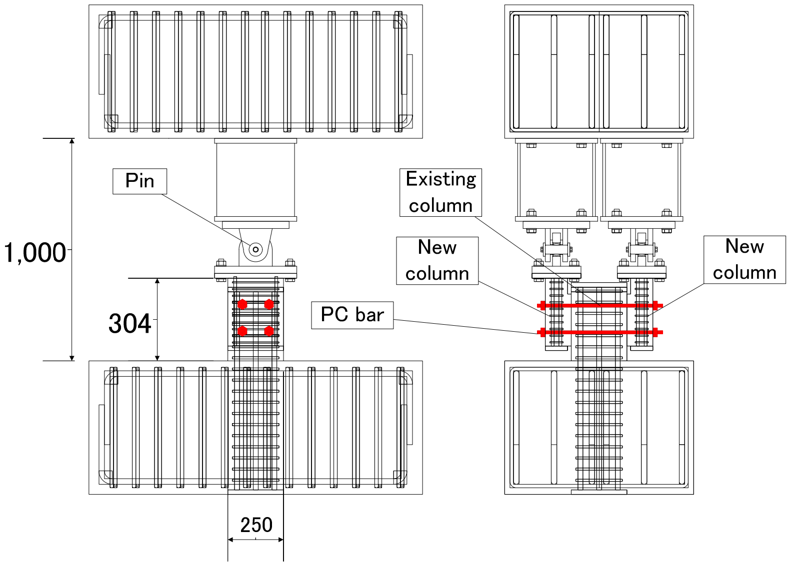


Figure 2.1 Specimen

Table 2.1 Dimensions and bar arrangement of the specimen

	b×D (mm)	h (mm)	Main bar (σ_y=345N/mm^2)	Hoop (σ_y=345N/mm^2)
Existing column	250×250	308	Deformed 13	Deformed 6
New column	100×250	304.3	Deformed 22	Deformed 13

Table 2.2 Concrete strength

	Concrete strength
Existing column	22.6 N/mm^2
New column	40.0 N/mm^2

Table 2.3 Properties of steels

	Young's modulus (N/mm^2)	Yield strength (N/mm^2)	Yield strain (%)	Tensile strength (N/mm^2)
D6	2.056×10^5	343.6	0.379	494.8
D13	1.812×10^5	376.8	0.437	534.5
D22	2.057×10^5	372.7	0.463	555.4

2.2. Capacity of the connection and compression force

The AIJ standard proposes Equation (2.1) to evaluate the capacity of the column-slab connection of the flat-slab system. Where, V_u is the vertical load, M_u is the twisting moment strength at the vertical load of V_u, V_0 is the ultimate vertical strength under only vertical load, and M_0 is the ultimate twisting moment strength without vertical load. The perfect yielding twisting moment strength is applied for M_0.

$$\frac{V_u}{V_0} + \frac{M_u}{M_0} \leq 1 \tag{2.1}$$

The resistant mechanism of the connection is different from that of the flat-slab system, since the flat-slap system is monolithic, while the new column with the base-isolation system is pre-cast member and no reinforcement bar but un-bonded PC bars go through the connection. Therefore, the force transfer mechanism of the connection can be only the friction at the connection for the vertical force and twisting moment for the lateral force.

The perfect plastic twisting moment is applied for M_0 calculated with Equation (2.2).

$$M_0 = \frac{a^2}{2}\left(b - \frac{a}{3}\right)\tau_u \alpha \tag{2.2}$$

Where a and b are the edge lengths of the connection ($a < b$). τ_u is the ultimate shear stress. The ultimate shear stress magnification factor α of 6 is recommended by AIJ for the flat-slab.

The ultimate vertical strength of the connection is calculated with Equation (2.3).

$$V_0 = \tau_u ab \tag{2.3}$$

Both M_0 and V_0 depends on τ_u and dimension of the section. M_u and V_u are demand moment and vertical load combination at the design. They are calculated as follows in real scale with a seven-story prototype structure of which base-shear coefficient was assumed as 0.2.

$$V_{ud} = 843.8\,kN \tag{2.4}$$

$$M_{ud} = V_{ud} \times 0.2 \times 0.95 = 160.3\,kN \cdot m \tag{2.5}$$

The required ultimate shear stress at the connection, τ, is calculated as 1.82 N/mm^2 by substituting the values of M_u and V_u to Equation (2.1). The values of V_0 and M_0 are calculated as 954.6 kN and 1381.0 kN・m in the real scale, respectively. The compression stress by the PC bars, σ_0, is calculated as 1.82 N/mm^2 with the friction coefficient, μ, of 1.0 and Equation (2.6). The compression force due to PC bar N is calculated as 106.1kN.

$$\tau_u = \mu\sigma_0 = \frac{\mu N}{ab} \tag{2.6}$$

The compression force of 106.1kN was applied for specimen No.3, and the high and low compression forces based on specimen No.3 were applied for specimens No.1 to No.7. The compression force for specimen No.8

was 350kN, which is 1/3 of concrete strength of existing column. The applied compression force for the PC bars is shown in Table 2.4.

Table 2.4 Applied compression force for the PC bars

Specimen	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
Applied fore N (kN)	56.5	79.3	107.6	132.1	162.3	214.7	265.0	356.7
	2/4 N	3/4 N	N	5/4 N	6/4 N	8/4 N	10/4 N	1/3 Fc

2.3. Loading and measuring system

Loading system is shown in Figure 2.3. The lateral force was applied at the mid-height of the specimen in order to keep the reflection point at the mid-height of the specimen. Two hydraulic jacks (A in the figure) were used for the lateral loading. Other two hydraulic jacks (B and C in the figure) were used to maintain the loading beam parallel to the ground and to apply the vertical force. The lateral and vertical loadings were controlled by force until the maximum strength and after reaching the maximum strength, controlled by lateral displacement.

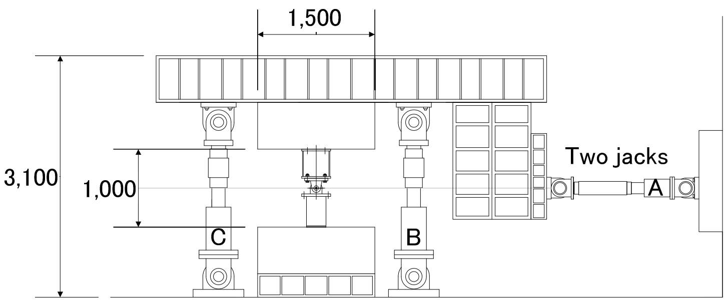


Figure 2.3 Loading system

Lateral and vertical forces applied to the specimen, vertical and lateral deformations of the specimen, vertical and lateral relative displacement of the new column to the existing column, and strains of steel bars and the PC bars were measured during the test. Firstly, all specimens were loaded by vertical force to obtain τ_u. Secondly all specimens were loaded by the lateral force to obtain a. It will be mentioned later in detail, but the obtained τ_u and a were different from the assumed values during the design.

3. EXPERIMENTAL TEST RESULTS

3.1. Vertical load carrying capacity

Figure 3.1 show the relationship between relative vertical displacement (between existing and new columns) and vertical force at one connection surface. The vertical force was increased to investigate the vertical strength. It can be said that the vertical behavior of the connection was stable even after reaching the maximum vertical strength. The results of other specimens also showed stable behaviors.

The row (1) in Table 3.1 V_0 shows the vertical maximum strength of the one connection surface Equation (2.3). Specimen of higher applied compression for the PC bars showed much higher strength although the concrete strength of all specimens was the same. It can be said that the vertical strength of the connection depends not on the concrete strength but on the applied compression force with the PC bars.

Figure 3.2 (a) shows the relationship between applied compression force with the PC bars and the ultimate vertical shear stress. The ultimate shear stress is proportional to applied compression force.

The row (3) of Table 3.1 and Figure 3.2 (b) show the measured friction coefficient of the connection surface calculated with Equation (2.6). The friction coefficients of all specimens were almost the same (0.58 to 0.66). It can be said that the friction coefficient does not depend on the applied compression force with the PC bars but was constant. Therefore, the friction coefficients can be suggested as Equation (3.1) the for ultimate strength design method.

$$\mu = 0.5 \tag{3.1}$$

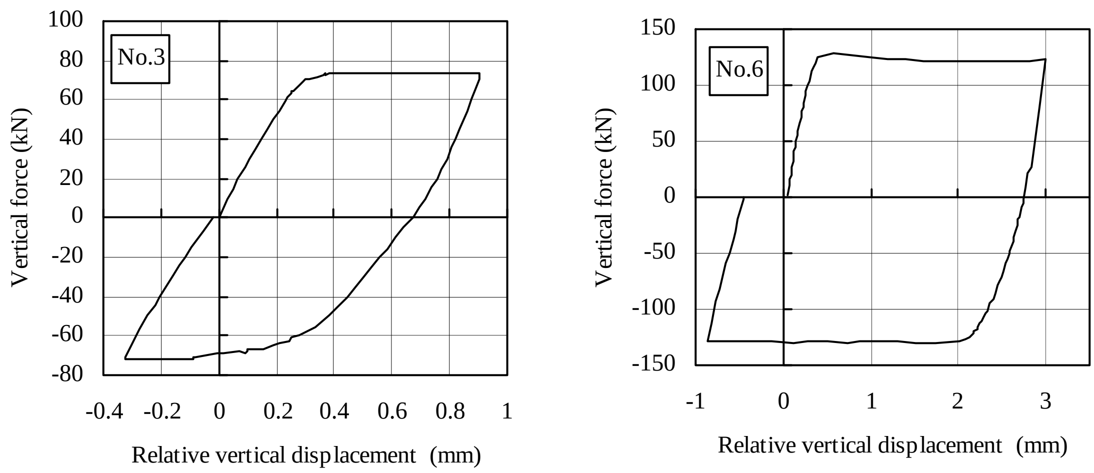
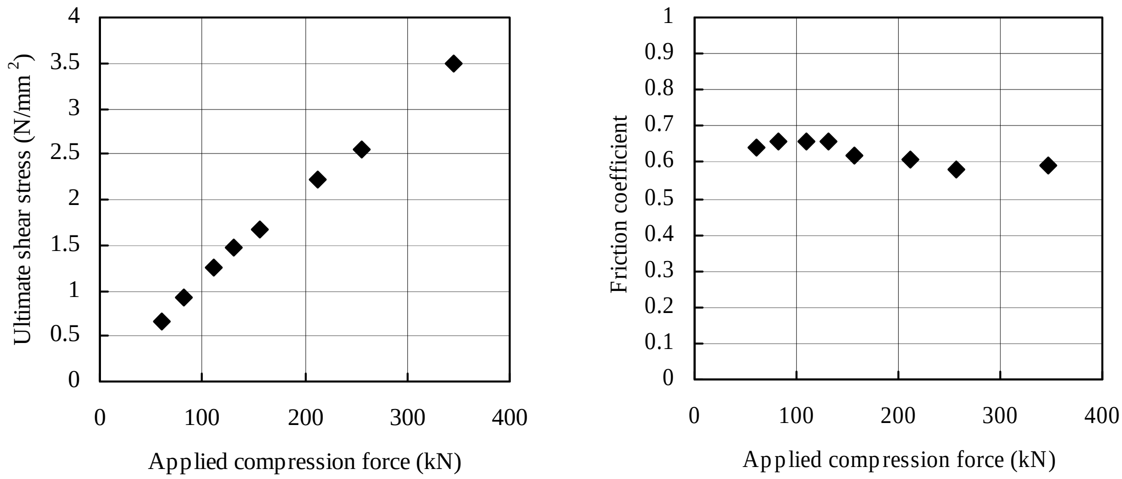


Figure 3.1 Relationship between relative displacement and vertical force (one connection)

Table 3.1 Vertical strength and friction coefficient

Specimen		No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
(1)	V_0 (kN)	38.4	53.8	73.1	86.3	96.7	129.3	148.6	204.3
(2)	τ_u (N/mm^2)	0.66	0.92	1.25	1.48	1.66	2.22	2.55	3.50
(3)	μ	0.64	0.66	0.66	0.66	0.62	0.61	0.58	0.59

(1) : vertical strength of one connection surface, (2) : ultimate shear stress (=V_0 / area), and (3) : friction coefficient (=V_0 /applied compression force for the PC bars)



(a) (b)

Figure 3.2 Ultimate shear stress and friction coefficient

3.2. Lateral load-relative rotational angle relationship

The relationships between the lateral load and the relative rotational angle of the new column to the existing column of No.3 and No.6 are shown in Figure 3.3. The behavior under the lateral load was stable even after the twisting moment reached its strength and started to slip at the connection. The results of other specimens also showed stable behavior.

The row (1) in Table 3.2 M_0 shows the perfect plastic twisting moment of one connection surface. The specimen with higher compression for the PC bars showed much higher strength. It can be said that the vertical strength of the connection depends on the applied compression force with the PC bars.

The row (3) of Table 3.2 shows the ultimate shear stress magnification factor α calculated with Equation (2.2). The ultimate shear stress magnification factor α of all specimens were almost the same (0.95 to 1.29). It can be said that the ultimate shear stress magnification factor α does not depend on the applied compression force with the PC bars but it is almost constant. It can be said that the stress state of the soft-landing base-isolation system is similar to the perfectly elasto-plastic state of the sand-heap analogy (suggested by A. Nadai, 1923). Therefore, the resistant mechanism of the connection is different from that of flat-slab system, since the resistant mechanism of the connection is not monolithic. It can be said that the ultimate shear stress magnification factor α is Equation (3.2).

$$\alpha = 1 \tag{3.2}$$

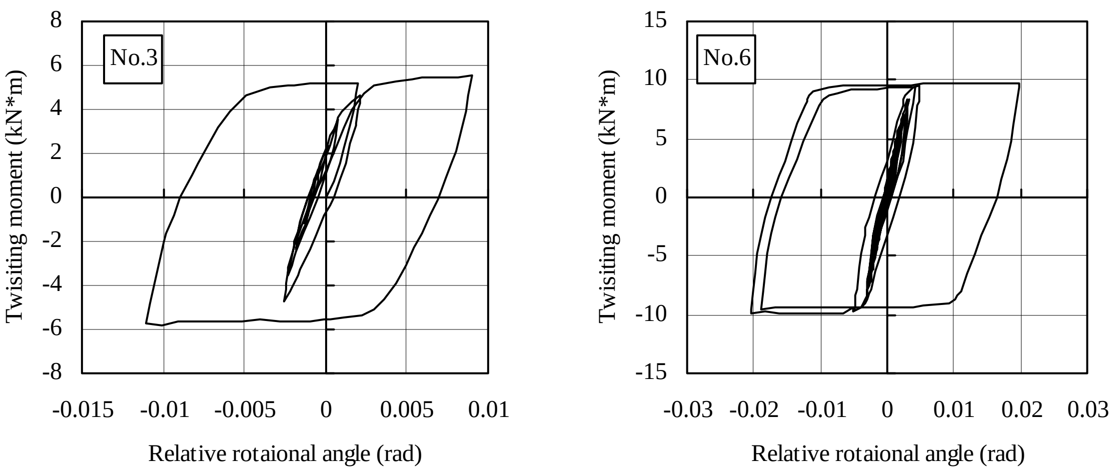


Figure 3.3 Relationship between relative rotational angle and twisting moment

Table 3.2 The perfect plastic twisting moment and the ultimate shear stress magnification factor α

Specimen		No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
(1)	M_0 (kN*m)	3.62	4.50	5.66	5.60	6.99	9.83	10.60	16.62
(2)	τ_u (N/mm^2)	0.66	0.92	1.25	1.48	1.66	2.22	2.55	3.50
(3)	α	1.17	1.04	0.96	1.15	1.05	0.95	1.29	1.08

(1) : The perfect plastic twisting moment, (2) : ultimate shear stress (=V_0 / area), and (3) : the ultimate shear stress magnification factor (calculated from Equation (2.2), (1) and (2))

3.3.Analysis of design equation

In this section, the validity of the design criteria of Equation (2.1), (2.2) and (2.3) are evaluated. The row (1) in Table 3.3 V_0 shows the vertical strength of the one connection surface by experiment. The row (2) in Table 3.3

V_0 shows the vertical strength of the one connection surface calculated Equation (3.3).The row (3) in Table 3.3 M_0 shows the perfect plastic twisting moment of the one connection surface by experiment. The row (4) in Table 3.3 M_0 shows the perfect plastic twisting moment of the one connection surface calculated Equation (3.4).

$$V_0 = \tau_u ab = \mu N = 0.5N \quad (3.3)$$

$$M_0 = \frac{a^2}{2}\left(b - \frac{a}{3}\right)\tau_u \quad (3.4)$$

Table 3.3 The perfect plastic twisting moment and the ultimate shear stress magnification factor α

Specimen		No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
V_0 (kN)	(1)	38.4	53.8	73.1	86.3	96.7	129.3	148.6	204.3
	(2)	30.0	40.7	55.4	65.4	78.0	106.0	128.1	173.1
M_0 (kN*m)	(3)	3.62	4.50	5.66	5.60	6.99	9.83	10.60	16.62
	(4)	2.41	3.27	4.45	5.25	6.26	8.51	10.29	13.90

(1) : vertical strength of one connection surface by experiment, (2) : vertical strength of one connection surface calculated Equation(3.3), (3) : The perfect plastic twisting moment by experiment, and (4) : The perfect plastic twisting moment calculated Equation(3.4)

Figure 3.4(a) show the relationship between applied compression force with the PC bars and V_0. Figure 3.4 (b) show the relationship between applied compression force with the PC bars and M_0. It can be said that Equation (3.3) and (3.4) can estimate the vertical strength and the perfect plastic twisting moment of the one connection surface, therefore the value of experiment is higher than calculated.

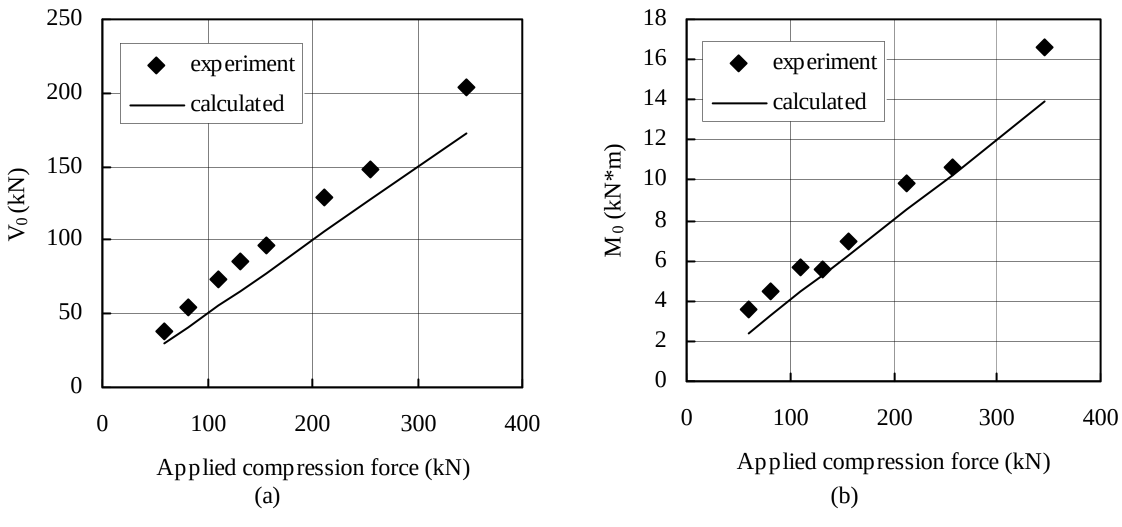


Figure 3.4 Relationship between applied compression force, V_0 and M_0

From the above Equation (2.1) can be transferred as Equation (3.5) with Equation (3.3) and (3.4).

$$\frac{V_u}{V_0} + \frac{M_u}{M_0} \le 1 \quad (2.1)$$

$$\Leftrightarrow \frac{V_u}{0.5N} + \frac{M_u}{\frac{a^2}{2}\left(b - \frac{a}{3}\right)\frac{0.5N}{ab}} \le 1$$

$$\Leftrightarrow N \ge 2V_u + \frac{12bM_u}{a(3b-a)} \tag{3.5}$$

$$M_u = C_B V_u h \tag{3.6}$$

$$N \ge \left\{2 + \frac{12bC_B h}{a(3b-a)}\right\}V_u \tag{3.7}$$

where, C_B is base-shear coefficient, and h is distance between the center of the base-isolation system and the center of the connection surface.

Equation (3.5) can be transferred as Equation (3.7) with Equation (3.6). It can be said that the applied compression force for design can be calculated by the vertical load, base-shear coefficient, and dimension.

4. CONCLUSIONS

The series of experimental tests was conducted to study the behavior at the connection between the new pre-cast column and the existing column to achieve the soft-landing base-isolation system. Results obtained from the investigation can be summarized as follows;

1. The vertical behavior of the connection was stable even after reaching the maximum vertical strength.
2. The vertical strength depends on the applied compression force with the PC bars.
3. The behavior of the connection under the lateral load was also stable even after reaching the maximum twisting strength.
4. The applied compression force for design can be calculated by the vertical load, base-shear coefficient, and dimension.

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