An experimental study on connection joints of composite mixed structures consisting of existing R/C buildings retrofitted with exterior steel frames

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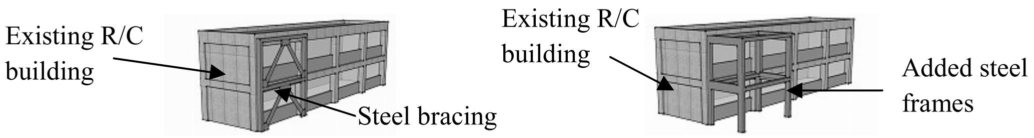
SUMMARY
The seismic performance of a connection joint between exterior steel frames and a reinforced concrete (R/C) building rehabilitated using a "horizontally mixed structural system" is investigated. In this paper, two different types of test specimens for the connection joint consisting of R/C columns, steel columns and beams were constructed. These specimens were designed according to a technical design manual published in Japan for rehabilitation of R/C buildings using a steel bracing system. Results of loading tests indicated unexpected failure mode of the models that the technical manual does not describe. Finally, this paper proposes a plastic analysis model, and it shows good agreement of the test results.

Keywords: Seismic rehabilitation, Horizontally mixed structural system, Static loading test, Connection joint, Post-installed anchor bolt

1. INTRODUCTION

It has been often discussed that old R/C institutional buildings, such as elementary schools and government offices, have poor seismic resistant performance. The number of retrofitted buildings is increasing in Japan with revising an Act on Promotion of Seismic Retrofitting of Buildings in 2005. A steel bracing system is a main method for seismic rehabilitation of R/C buildings (see Fig.1.1(a)). The exterior steel bracing provides an excellent approach for strengthening existing R/C building, yet this system cannot offer solutions to demand for enhancing architectural flexibility and conversion with the seismic rehabilitation. In terms of the flexibility and conversions, the concern over a horizontally mixed structural system has risen. This system is a seismic rehabilitation method that an old R/C building is strengthened by a new steel building (see Fig.1.1(b)). The retrofitted composite building can expand its floor space and acquire architectural changeability and flexibility by the addition of exterior steel frames to the existing R/C building. But, a design procedure and efficiency of seismic rehabilitation in the horizontally mixed structural system have been little investigated. In particular, it is important that the detail construction methods of connection joints between R/C and steel buildings are discussed. To investigate ultimate states of the connection joint, two types test specimens were constructed. First type is an indirect-connection model. The second type is direct-connection model. These details are designed according to the technical design manual for the steel bracing system published by the Japan Building Disaster Prevention Association (herein after referred to as "JBDPA manual"). The objective of this paper is to report the loading test results and propose a plastic analysis model that evaluates strength of the connection joint in the horizontally mixed structural system.



(a) Steel Bracing system (b) Horizontally mixed structural system

Figure 1.1. Rehabilitation methods

2. RESISTANT MECHANISM AND CONFIGURATION OF HORIZONTALLY MIXED STRUCTURAL SYSTEM

2.1. General Description

The horizontally mixed structural system consists of blow parts: existing R/C structures, connection joints between different elements, steel "connection frames" and "bridge beams", as shown in Fig.2.1. This paper remarks on the connection joint. By use of post-installed anchor bolts, details of connection joint models are designed according to the JBDPA manual. These can be classified into two types. The first type is an indirect-connection technique. The second type is a direct-connection technique. Conventional connection joints used for the bracing system are designed under shear force. On the other hand, connection joints used for the horizontally mixed structural system are subjected to a combination of shear and drawing force that originate from bending behaviour of bridge beams. The objective of this paper is investigating seismic behaviour of connection joints under the combination force, as shown Fig.2.1.

2.2. Indirect-connection Technique

The connection joint of the indirect-connection technique consists of blow parts: an existing R/C structures, a steel connection frame, splitting preventive bars, studs, anchor bolts and mortar, as shown Fig.2.2(a).

2.3. Direct-connection Technique

The connection joint of the direct-connection technique consists of blow parts: an existing R/C structures, a steel connection frame, anchor bolts and mortar, as shown Fig.2.2(b).

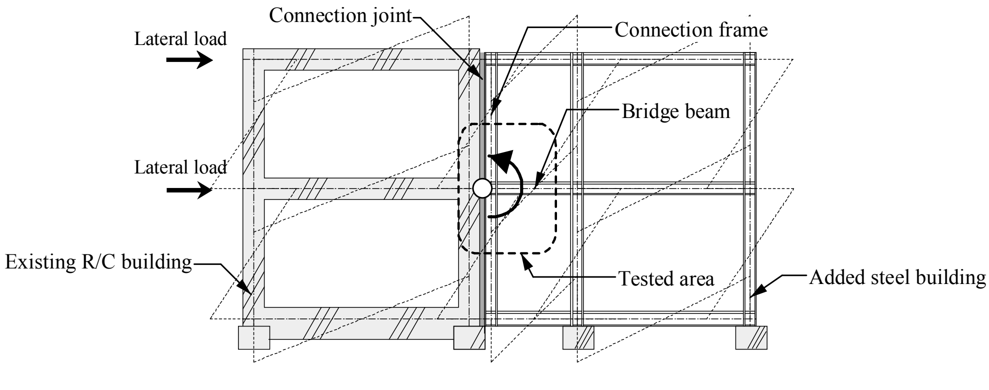


Figure 2.1. Horizontally mixed structural system

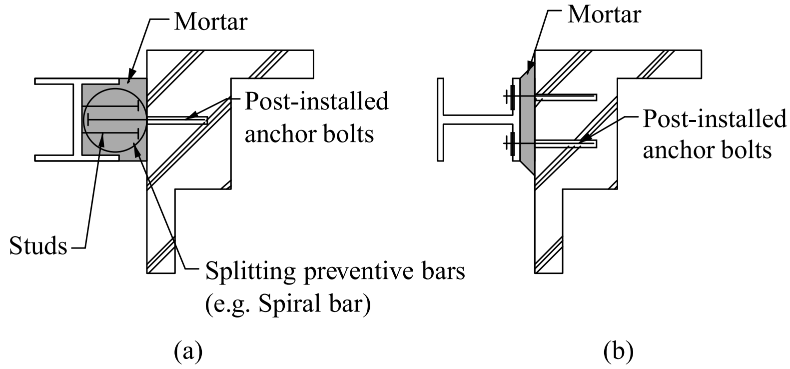


Figure 2.2. Connection joint techniques: (a) Indirect-connection; (b) Direct-connection

3. EXPERIMENTAL STUDY OF CONNECTION JOINT

3.1. General Description

Two test specimens, an indirect-connection type (see Fig.3.1) and a direct-connection type (see Fig.3.2), were constructed. The specimens consist of a R/C element representing an existing R/C building, a steel connection frame and a bridge beam representing the added steel frames, and connection joints. The mechanical properties of the steel elements are summarized in Table.3.1 and concrete and mortar elements are in Table.3.2. Connection joint details were constituted and the strength were calculated according to the JBDPA manual.

3.2. Test Set Up

Fig.3.3 shows an elevation view of the test specimens. The top of the bridge beam was laterally loaded to produce the bending moment at the connection joint. The R/C element is fixed on a reaction frame.

3.3. Measurement Arrangement And Loading Test Method

The specimens were instrumented with sensors for measuring blow items (see also Fig.3.3); lateral displacement at the top of the bridge beam, lateral displacement and vertical displacement in the connection frame, strain in the anchors and the bridge beam bottom, and lateral loads. The models were subjected to lateral loads until the strain of the bridge beam bottom reaches 15,000μ.

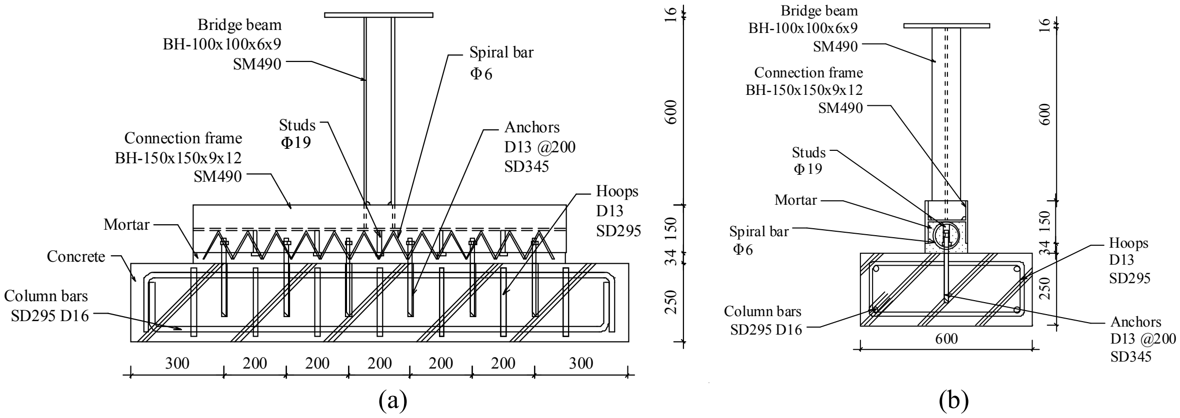


Figure 3.1. Test specimen of indirect-connection type: (a) Elevation; (b) Section (dimensions in millimetres)

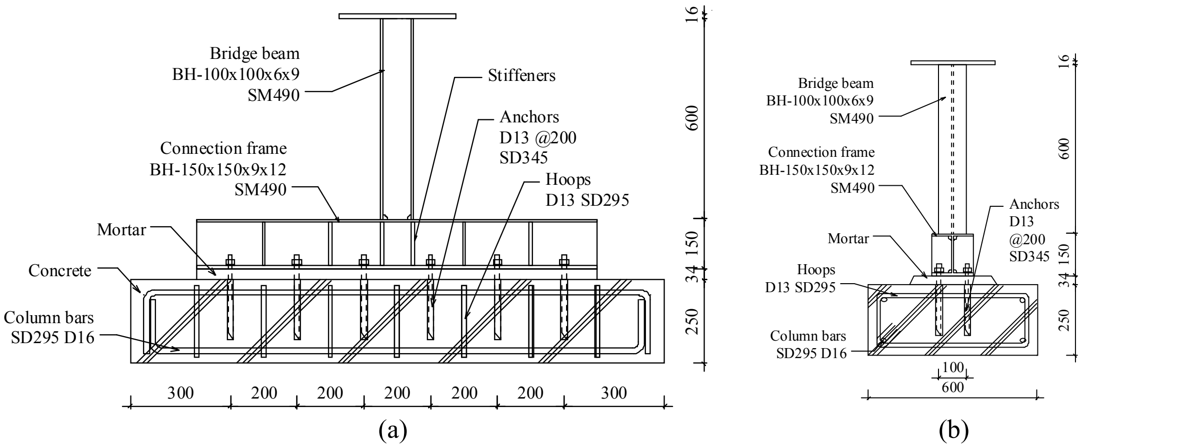


Figure 3.2. Test specimen of direct-connection type: (a) Elevation; (b) Section (dimensions in millimetres)

Table 3.1. Mechanical properties of steel elements

Parts	Size	Steel grades*	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)
Webs of bridge beam	PL-6mm	SM490	414	549	209
Flanges of bridge beam, Webs of connection frame	PL-9mm	SM490	390	535	199
Flanges of connection frame	PL-12mm	SM490	420	532	206
Anchors	D13*	SD345	429	591	217
Column bars	D16*	SD295	391	534	-
Hoops	D13*	SD295	397	533	-
Studs	ϕ19mm	-	261	425	-
Spiral bars	ϕ6mm	-	-	556	-

*Japanese Industrial Standards (JIS)

Table 3.2. Mechanical properties of concrete and mortar elements

Parts	Materials	Compressive Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's modulus (kN/mm^2)
R/C	Concrete	21.0	-	23.0
Connection joint	Mortar	49.5	6.56	47.6

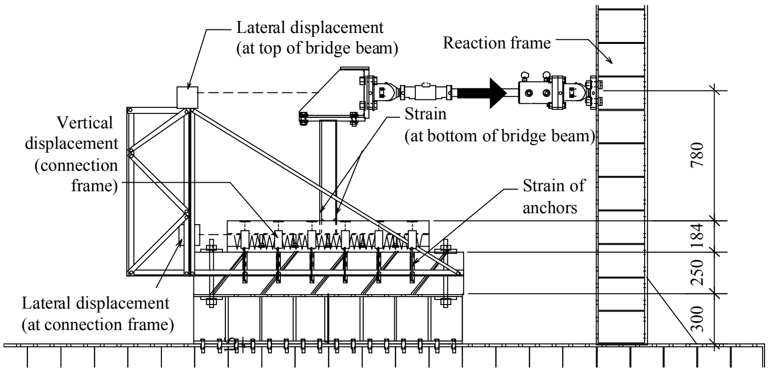


Figure 3.3. Elevation of test set up and location of sensors (dimensions in millimetres)

(a) Indirect-connection type (b) Direct-connection type

Figure 3.4. Test set up

4. RESULTS OF TEST STUDY

4.1. General Description

The load-lateral displacement curves at the top of bridge beam are shown in Fig.4.1, the distribution of uplift in the connection frame are shown in Fig.4.2, the distribution of strain in the anchors are shown in Fig.4.3, and the ultimate states of the specimens are shown in Fig.4.4. Under the loading test of indirect-connection model, the following behaviours were observed: uplift in the connection frame was observed at a load of 23.1kN, strain in anchors began at a load of 35.6kN, the bridge beam yielded at a load of 45.6kN, and an anchor yielded at a load of 49.6kN (see Table.4.1). Under the loading test of the direct-connection model, the bridge beam yielded at a load of 44.8kN. The lateral displacement in the indirect-connection model was larger than that of the direct-connection model.

4.2. Failure Mode of Test Specimens

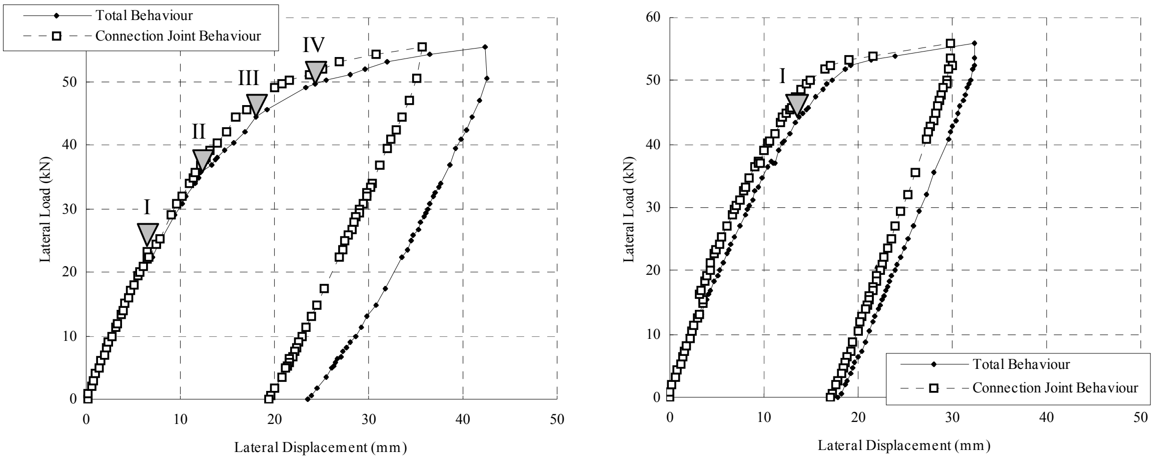
In the indirect-connection model, the maximum uplift point in the connection frame was at an edge of the model. However, strain in the anchor at this point remained little compared with the others, as shown in Fig.4.3(a). This failure mode is similar to the mode described in a paper by Ohtani et al. (2007). In that paper, it is observed that cracks in the mortar remove the restriction and prevent the transmission of strain to anchors, and the vertical cracks in the mortar occurred in element tests of indirect-connection. On the contrary, lateral cracks in the mortar occurred along the web of the connection steel frame, as shown in Fig.4.4(a) in the present study. The anchors yielded in the indirect-connection model, however, all anchors remained elastic in the direct-connection model.

4.3. Deformation of Connection Joint Model

The deformation of uplift in the indirect-connection model originated from the cracks in the mortar and this did not occurred in the direct-connection model. To investigate the ratio of the connection joint behaviour to the total deformation of the model, analytical models were presumed as shown in Fig.4.5. Fig.4.1 shows the load-lateral displacement curves of the connection joint and the total model. The ratios of connection joint deformation in total deformation of a specimen were 0.18 in the indirect-connection model and 0.05 in the direct-connection model.

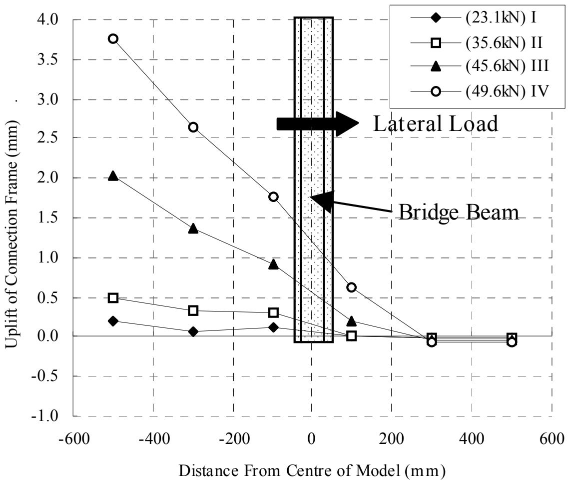
Table 4.1. Behaviour of test specimens

No.	Indirect-connection Model		Direct-connection Model	
	Lateral Load	Behaviour	Lateral Load	Behaviour
I	23.1kN	Uplift in the connection frame was observed	44.8kN	Bridge beam yielded
II	35.6kN	Strain in anchors began	-	-
III	45.6kN	Bridge beam yielded	-	-
IV	49.6kN	Anchor yielded	-	-

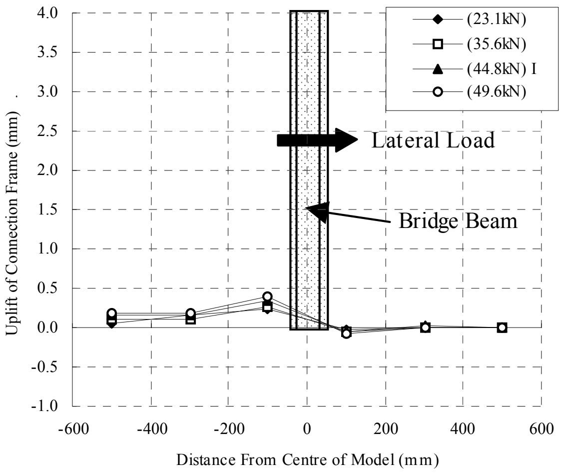


(a) Indirect-connection model (b) Direct-connection model

Figure 4.1. Load-lateral displacement curve

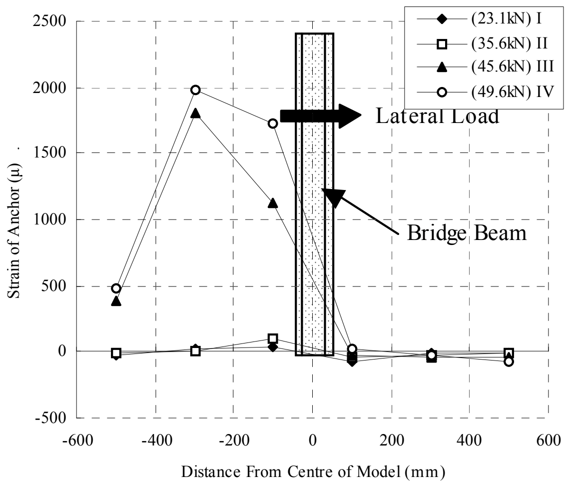


(a) Indirect-connection model

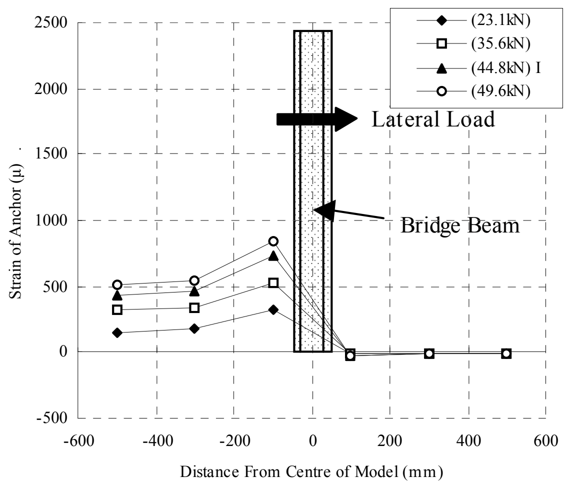


(b) Direct-connection model

Figure 4.2. Distribution of uplift in connection frame

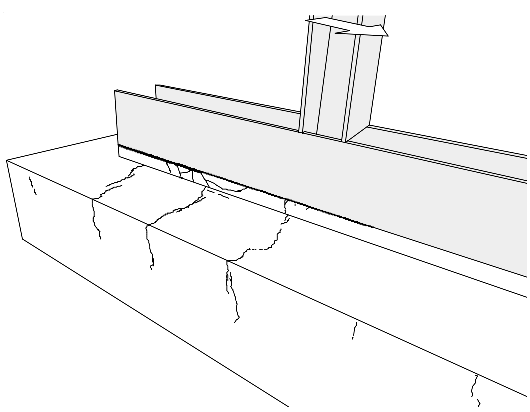


(a) Indirect-connection model

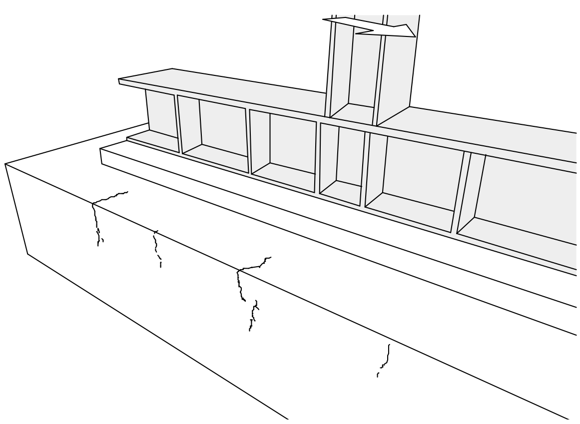


(b) Direct-connection model

Figure 4.3. Distribution of strain in anchors



(a) Indirect-connection model



(b) Direct-connection model

Figure 4.4. Ultimate state

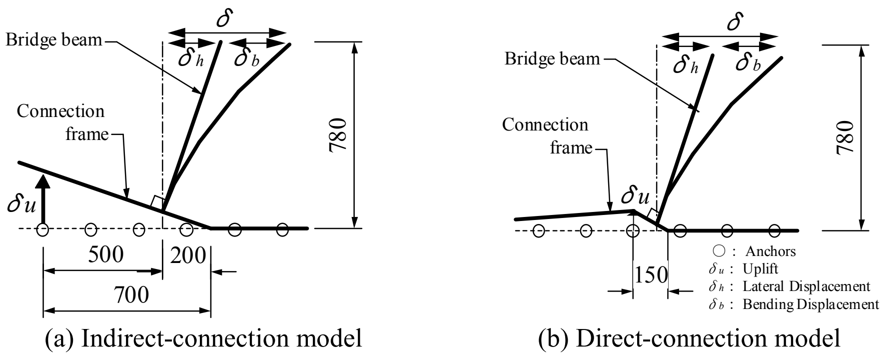


Figure 4.5. Analytical model (dimensions in millimetres)

5. EVALUATION OF STRENGTH IN CONNECTION JOINT MODEL

5.1. General Description

The strengths of the connection joints were calculated using JBDPA manual formulas. In comparison with test results, effectiveness and adaptability of the existing formulas for the horizontally mixed structural system are discussed in this section.

5.2. Assumption of Stress Distribution in Connection Joint Model

The connection joint models are subjected to a combination of shear and drawing force. A stress distribution model of the connection joint, as shown in Fig.5.1, was assumed in a phase of designing the test specimens. In this assumed model, the drawing force T and compressive force C for the connection joint were distributed to anchors in the edges. And also, the shear forces Q are equally distributed to all anchors in the connection joint.

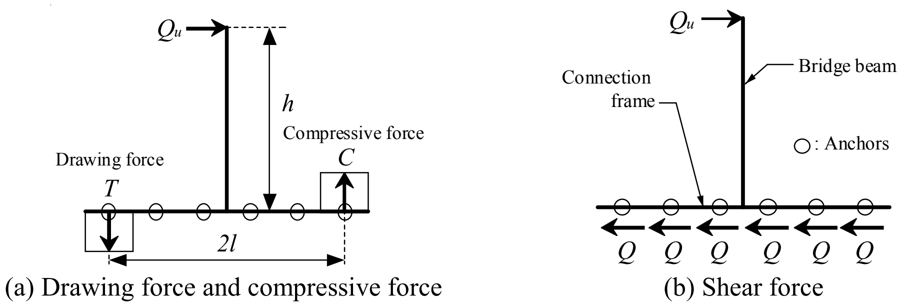


Figure 5.1. Analytical model

Moment equilibrium of the model (Fig.5.1(a)) requires:

$$Q_u = (T + C)\,l/h \qquad (5.1)$$

where h is the length of the bridge beam and l is the half distance between the point of action T and C. Also, the following relationship between the ultimate lateral strength Q_u and the shear strength of each anchor Q is obtained based on the Fig.5.1(b):

$$Q_u = nQ \qquad (5.2)$$

where n is the number of anchors in the connection joint.

The JBDPA manual describes the following formula that evaluates the combination force in the indirect-connection joint.

$$\left(\frac{T}{T_{a0}}\right)^{\alpha}+\left(\frac{Q}{Q_{a0}}\right)^{\alpha}=1 \tag{5.3}$$

where T_{a0} is the tensile strength of an anchor and Q_{a0} is the shear strength of an anchor that are described in the next section. A factor α is typically taken as 2 in the JBDPA manual.
Assuming that $T = C$, the ultimate lateral strength Q_u is determined from (5.1)-(5.3) as:

$$Q_u=\frac{2nQ_{a0}T_{a0}}{\sqrt[\alpha]{\left(n\frac{h}{l}Q_{a0}\right)^{\alpha}+\left(2T_{a0}\right)^{\alpha}}} \tag{5.4}$$

5.3. Formula of Strength in Anchors

5.3.1. Tensile strength of anchor
According to the JBDPA manual, the tensile strength of an anchor T_{a0} is determined by:

$$T_{a0}=\min\left(T_{a1},T_{a2},T_{a3}\right) \tag{5.5}$$
$$T_{a1}=a_0\ \sigma_y \tag{5.5.1}$$
$$T_{a2}=0.23\ A_c\ \sqrt{\sigma_B} \tag{5.5.2}$$
$$T_{a3}=\pi\ d_a\ l_e'\ \tau_a \tag{5.5.3}$$

where a_0 is the cross section of an anchor, σ_y is the yield strength of an anchor, A_c is the projected area of the concrete cone failure, σ_B is the compressive strength of a concrete, l_e' is the effective bonding length of an anchor that is determined by: $l_e'=l_e-2d_a$ (where d_a is the diameter of an anchor), τ_a is the bonding strength of an anchor that is determined by: $\tau_a=0.5\ \tau_{b,ave}\left(c/l_e+1\right)$ (where c is the edge distance and l_e is the effective length of an anchor), and $\tau_{b,ave}$ is the bonding strength of an anchor that is determined by: $\tau_{b,ave}=10\sqrt{\sigma_B/21}$.

5.3.2. Shear strength of anchor
According to the JBDPA manual, the shear strength of each anchor Q_{a0} is determined by:

$$Q_{a0}=\phi_s\min\left(Q_{a1},Q_{a2}\right) \tag{5.6}$$
$$Q_{a1}=0.7\ a_e\ \sigma_y \tag{5.6.1}$$
$$Q_{a2}=0.4\ a_e\ \sqrt{E_c\ \sigma_B} \tag{5.6.2}$$

where ϕ_s is the reduction factor to prevent shear deformation (ϕ_s=0.7), a_e is the cross section of an anchor and E_c is the Young's modulus of concrete.

5.4. Comparing Strength Formulas To Test Results

The ultimate lateral strength Q_u was determined from (5.1)-(5.6) to be 63.0kN at the indirect-connection model and 126.0kN at the direct-connection model, according to the mechanical properties (Table.3.1 and 3.2). Also, the lateral load of the bridge beam at yielding was 41.0kN. The analytical result implies that a failure mode of the yielding in the bridge beam should appear at first under the loading tests. However, the uplift mode in the connection frame appeared at a load of 23.1kN in the test result of the indirect-connection model. It can be presumed that the cracks in the mortar weakened the confinement around the edge anchors and prevent the strain transmission to them.

Evaluations of the stiffness on the indirect-connection joint mechanisms are investigated by Ohtani (Ohtani et al. 2007). However, there has been little study done concerning force transfer mechanisms. Thus, researches regarding the cracks at the mortar in the indirect-connection are needed in future studies.
In the test result, the behaviour of the direct-connection model was subject to the bending behaviour of the bridge beam. The maximum strain of anchors measured near the bridge beam and all anchors remained elastic. From these observations, the assumed stress distribution model is different from the test results, i.e. the model should be improved.

6. ANALYTICAL STUDY OF PLASTIC ANALYSIS MODEL

In the following section, a plastic analysis model in Fig.6.1 was assumed to understand the behaviour of the indirect-connection model.
Two anchors near the bridge beam are subjected to drawing force T in the analytical model.

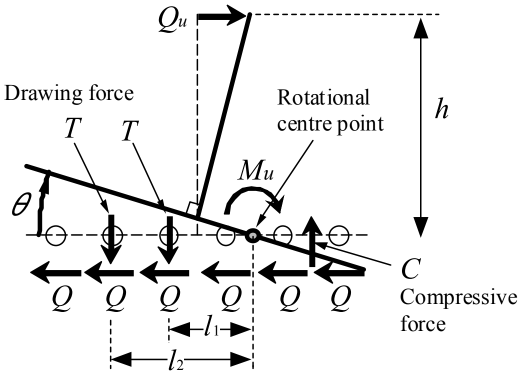


Figure 6.1. Analytical model

According to the principle of virtual work in Fig.6.1, the following relationship between Q_u and T is obtained.

$$Q_u = \frac{(l_1 + l_2)}{h} T \tag{6.1}$$

where h is the length of the bridge beam and l is the distance between the rotational centre point and anchors.
The shear strength of an anchor in the mortar of the indirect-connection proposed by Ohtani (Ohtani et al. 2007) is shown in Eq. (6.2):

$$\left(\frac{T}{T_{a0}}\right)^{5/3} + \left(\frac{Q}{Q_{a0}}\right)^{5/3} = 1 \tag{6.2}$$

The ultimate lateral strength Q_u is obtained as Eq. (6.3), based on Eqs. (5.2), (6.1) and (6.2):

$$Q_u = \frac{nQ_{a0}T_{a0}}{\sqrt[5/3]{\left(n\frac{h}{l_1 + l_2}Q_{a0}\right)^{5/3} + {T_{a0}}^{5/3}}} \tag{6.3}$$

The ultimate lateral strength Q_u determined from (6.3) is 50.0kN, while the observed Q_u was 49.6kN in the indirect-connection model. Thus, this analytical model accurately evaluates the test result.

7. CONCLUSIONS

In the present study, the loading tests of the connection joint models used in the horizontally mixed structural system were carried out. Also, the plastic analysis model to evaluate the strength of connection joint was proposed.

7.1. Indirect-Connection Model

Significant cracks on the mortar along the connection frame web occurred in the tensile side of model. However, the load-lateral displacement curve of the model was subject to the bending behaviour of the bridge beam. From the test results, it is concluded that cracks in the mortar remove the restriction and prevent the transmission of strain to anchors. This failure mode in not considered in the JBDPA manual. To evaluate the failure mode, the plastic analysis model was proposed. The lateral load at the top of the bridge beam calculated by the analysis model was 50.0kN, while the lateral load from test result was 49.6kN. Thus, this analysis model can effectively evaluate the strength of the indirect-connection joint model used for the horizontally mixed structural system.

7.2. Direct-Connection Model

The direct-connection model behaved in stable through the test with no failures either in mortar or anchors. The vertical displacement of the connection frame were less than those measured in the indirect-connection model. The total behaviour was subject to the bending behaviour of the bridge beam. This test result behaved as same as intended in the design that connection joint is stronger than the bending yield of the bridge beam.

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