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An Experimental Study of Embedded Connection for Lightweight Steel Square Tube Filled with Adhesives

Itsuki Yagi*, Mana Kitahonoki and Takumi Ito

Department of Architecture, Tokyo University of Science, Japan

Abstract

Recently, a various type of steel connection technique has been developed, which aims to possess the multi-demands on steel structures. In this study, a new fitting connection technique for steel square tube is suggested, and this joint consists as follows; lightweight steel square tube is just embedded to steel connector, and an adhesive is filled to the clearance between each member as filler, and a pin is inserted as a fail-safe mechanism against the uplift of the column. The adhesives adopted on this connection are widely used to adhere nonstructural members such as tiles and marbles in Japanese architectural building field. The advantage of this connection is not only improvement of workability due to needless of bolting and welding but also the adjustment of the bending strength and rigidity by filling methods and materials. This study investigates the resistant mechanism subjected to bending experimentally. Herein, the loading test is conducted as parameters with the existence of adhesives, pin and loading path. From test results, it is confirmed that the bending strength and rigidity are improved by the filling effect of adhesives, and the maximum bending strength is enhanced by the resistance of a pin during the ultimate state. Furthermore, the stress diagram subjected to bending is investigated from the test results, and a kinematic model of this connection considering the exfoliations of adhesives is suggested. It can almost evaluate the strength of the test results well.

Keywords: Adhesive; Bending resistant mechanism; Embedded connection; Lightweight steel square tube; Loading test; Steel structure; Stress distribution

Introduction

Generally, bolting and welding are used as joint components in steel structures. In perspective, a connection of steel structures is divided into rigid connection, semi-rigid connection and pin connection by the fixation of the connection. However, the joint with various restoring force characteristics and structural performance are proposed and developed in recent years [1]. For example, the socket connection method not using bolting or welding is suggested, and it is expected to ease the inclination and displacement of jointed materials [2]. A fitting connection method on steel structures is sometimes adopted which aims to possess the multi-demands such as improvement of workability, disassemble, and any other purposes. In this study, a new fitting connection technique for steel square tubes is suggested as shown Figure 1. This proposed method is that a lightweight steel square tube column is just embedded to another member by not using bolting and welding. A clearance between each steel tube is filled with organic or inorganic fillers so as to prevent from the slipping and adjust the bending rigidity and strength for structural design. Herein, inorganic adhesive materials are adopted to fill the clearance as filler on this connection, which adhesives widely used to adhere nonstructural members such as tiles and marbles in Japanese architectural building field. This paper proposes a new type embedded connection method using a lightweight steel square tube, and also, an experimental study is conducted to clarify the resistant mechanism and inelastic behavior of about the connection method Figure 1a. The loading test is performed as parameters with the existence of adhesives, pin and loading path.

Details of Embedded Connection

General description

A construction process of the embedded connection as shown Figure 1b is described below. First of all, adhesives are coated to a connector, and fit a column (an outside steel tube) into the connector. Finally, a pin is inserted as a fail-safe mechanism against the uplift of members. The construction process of embedded connection is simple so that its workability is excellent because of unnecessary of bolting and welding.

Composition of test specimens

Figure 2 shows a specimen of embedded connection. A specimen is consisted of below parts; a connector with spacers, an outside steel tube, a pin and adhesives. Herein, spacers are made spot welding to the connector in order to adjust and maintain a layer thickness of adhesives that are filled between the connector and the outside steel tube. The layout of spacers is arranged over the entire circumference in specimens. Moreover, epoxy resin adhesives are adopted as filler. Epoxy resin adhesives are composed of a based resin containing an epoxy resin and a curing agent containing a modified aliphatic polyamine. In this paper, epoxy resin adhesives are called adhesives.

The Outline of Loading Test

General description

In this study, the loading test was conducted to verify the resistant mechanism of the embedded steel connection. The mechanical properties of steel elements are summarized in Table 1, and adhesive elements are presented in Table 2. In addition, Table 3 summarizes the test specimens. According to Table 3, the existence of adhesives, pin and loading path are considered as parameters.

Test set up and loading test methods

Figure 3 illustrates a loading test set up, and a lateral load was applied to the top of specimens to produce the bending moment at the connection. Test specimens were instrumented with sensors to measure lateral load and displacement at the top of test specimens, and strain of connectors and outside steel tubes.

***Corresponding author:** Itsuki Yagi, Department of Architecture, Tokyo University of Science, Japan, Tel: +81 3-3260-4271; E-mail: 4116655@ed.tus.ac.jp

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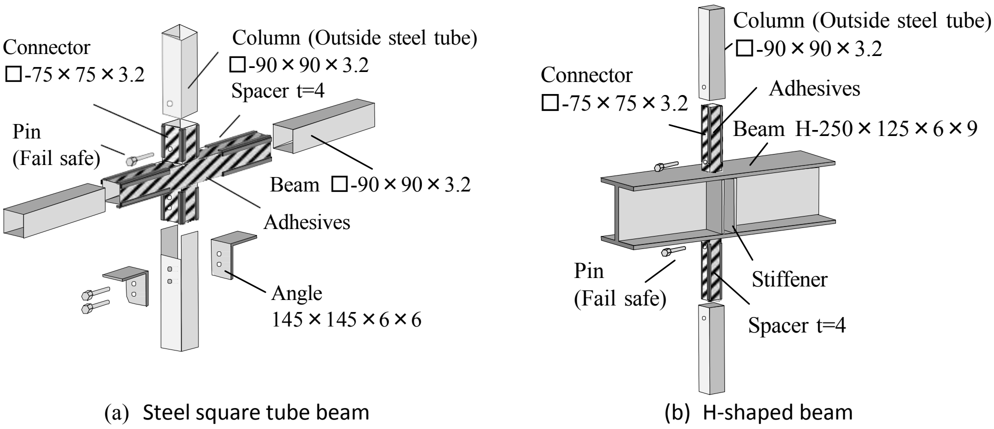

Figure 1: Conceptual diagram of embedded steel connection.

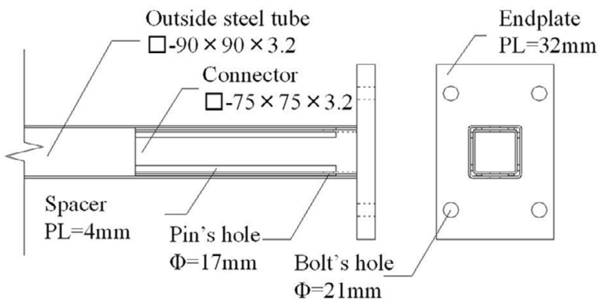

Figure 2: Diagram of test specimens (unit: mm).

Parts	Steel grade (Grade of JIS)	Yield strength (N/mm²)	Tensile strength (N/mm²)	Young's modulus (kN/mm²)
Connecter	STKR400	333	416	212000
Outside steel tube	STKR400	361	443	210000

Table 1: Mechanism properties of steel components.

Thickness of adhesives (mm)	Maximum load (kN)	Shear strength of exfoliations of adhesives (N/mm²)
4	2.48	2.02

Table 2: Mechanism properties of adhesives.

Specimens	Thickness of adhesives	Pin	Loading path
A-P-m	4 mm	Pin	Monotonic
A-P-c			Cyclic
A-nP-m		non-Pin	Monotonic
A-nP-c			Cyclic
nA-P-m	non-Adhesives	Pin	Monotonic
nA-P-c			Cyclic
nA-nP-m		non-Pin	Monotonic
nA-nP-c			Cyclic

Table 3: List of test specimens.

Loading pattern

Monotonic and cyclic loading tests were conducted, herein. The maximum rotational angle of the specimens on monotonic loading tests was 1/10 rad. The maximum rotational angle of the specimens on cyclic loading tests were ±1/300, ±1/200, ± 1/150, ± 1/100, ± 1/75, ± 1/50, ± 1/30 and ± 1/10 rad. (Figure 4).

Results of Test Study

Test result of monotonic loading

Figure 5 shows the moment-rotation angle curves of connection (M-θ curve) under monotonic loading tests. In addition, Figure 5 shows collapse modes and exfoliation of adhesives decided by the

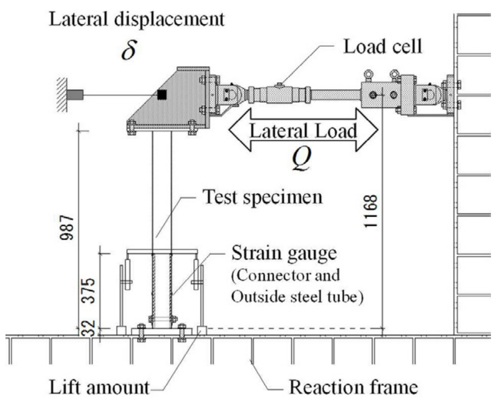

Figure 3: Set up of loading test.

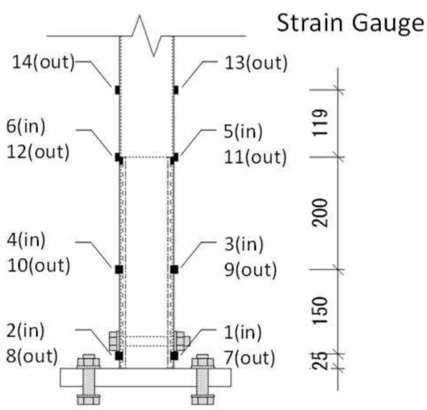

Figure 4: Position of strain gauges.

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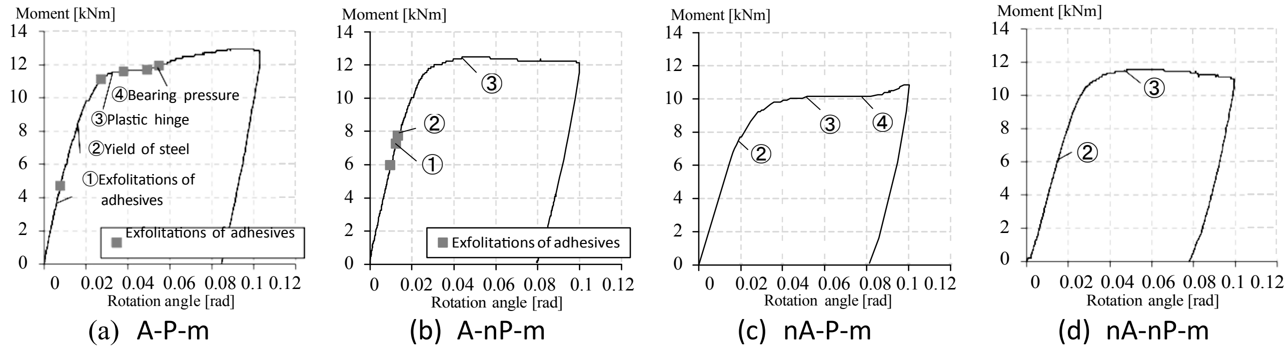

Figure 5: Test results of M-θ curve of monotonic loading.

Specimens	Bending Strength (kN)			Bending Rigidity (kNm/rad)
	Exfoliations of Adhesives	Yield Strength	Maximum Strength	
A-P-m	4.67	9.46	-404	579
A-nP-m	5.95	7	12.5	579
nA-P-m	0	8.06	0	413
nA-nP-m	-	6.31	11.6	404

Table 4: Test results of monotonic loading test.

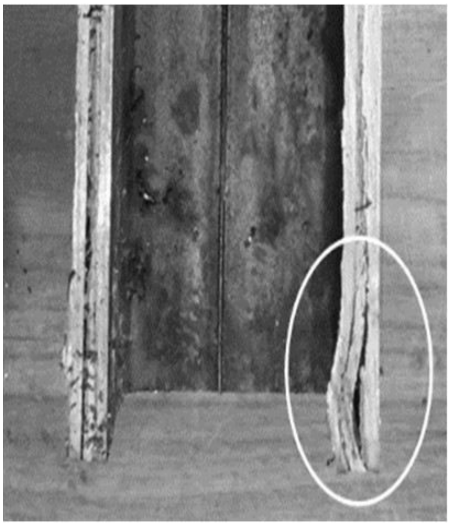

Figure 6: Section of test specimens.

noise, observation and behavior of strain during loading test. And also, Table 3 shows the test results (Exfoliations of adhesives, yield strength, maximum strength, and bending rigidity). Collapse modes of the embedded connection were observed as follows;

1. Exfoliation of adhesives
2. Yield of steel
3. Plastic hinge of connector
4. Bearing pressure of steel tube by pin.

Figure 6 shows a picture of section of specimens after monotonic loading test. From this figure, the exfoliations of adhesives were occurred in boundary layer between adhesives and an outside steel tube. According to Figure 5 and Table 4, in case of A-P-m and A-nP-m, the bending strength and rigidity were improved by the filling effect of adhesives. Figure 7 presents the test results of stress distribution of web. From this results in case of non-adhesive (metal touch), the stress was only transmitted little from connector to outside steel tube. By contrast, if adhesives were used as filler, the stress from connector to outside steel tube was increased by the filling effect. As a result, in case of adhesives filling, the bending strength and rigidity became high. From the result of Figure 5, it is confirmed that the bending rigidity shows almost same in both case of pin and non-pin, however, the maximum bending strength was enhanced during ultimate state in case of using pin. The pin's whole deformation was observed after the loading test, thus the specimen is resisted bending moment by bearing pressure of a pin.

Test result of cyclic loading

Figure 8 shows the moment-rotation angle hysteresis curves (M-θ curve) under cyclic loading tests. And also, Table 5 shows the test results (Yield strength, Maximum strength, Bending rigidity). From the results of Figure 8 and Table 5, it is confirmed that adhesives prevent the slipping, and it improves the bending strength and rigidity at moment 0 in case of A-P-c and A- nP-c. Furthermore, in case of A-P-c and nA-P-c, the bending rigidity shows almost same; however the bending strength was enhanced at ultimate (Figure 9).

The bending moment distribution of embedded connection

From the results of Figure 10, it is confirmed that the outside steel tube resisted the bending moment at height from 375 mm to 1200 mm. The bending moment was decreased toward column base (height 0mm), on the other hands, the bending moment of connector was increased. Consequently, it is confirmed that the bending moment of connector showed the maximum value at height 0mm. At height 375 mm, the stress of outside steel tube became large because the outside steel tube was contacted with the connector and received reaction force. Moreover, in case of A-P-m and nA-P-m, the sum of bending moment of connector and outside steel tube corresponds with the bending moment of specimen regardless of adhesives. However, in case of A-nP-m and nA-nP-m, the bending moment of connector was corresponded with the bending moment of specimen. Therefore, the connector and the outside steel tube collaborated to resist the bending moment when a pin was used. On the other hand, in case of non-pin, the connector mainly resisted the bending moment. Furthermore,

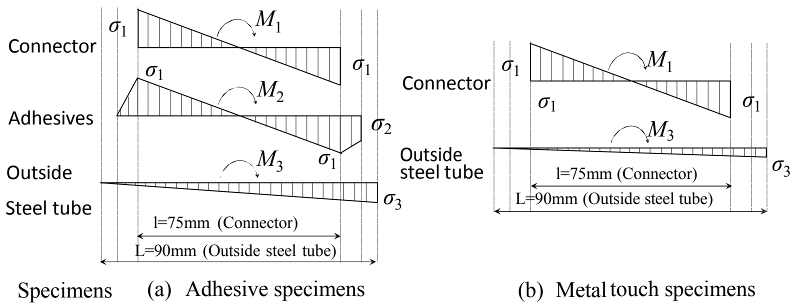

Figure7: Test results of stress distribution of web.

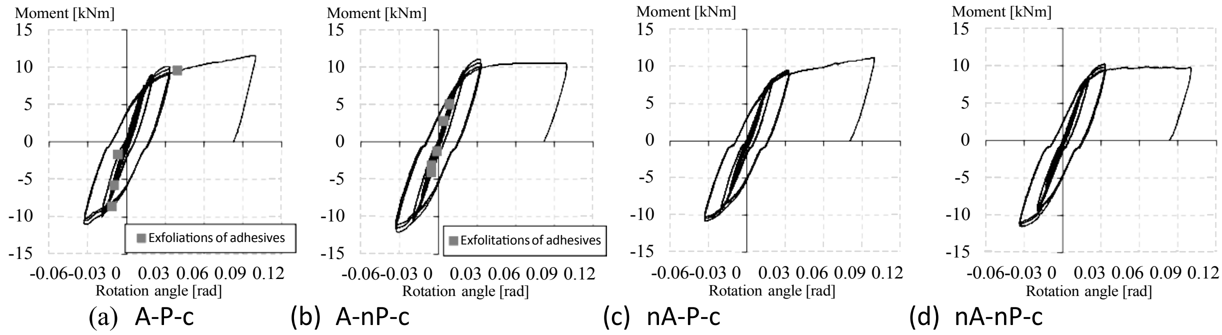

Figure 8: Test results of M-θ hysteresis curve under cyclic loading.

Specimens	Bending strength [kNm]		Bending rigidity [kNm/rad]
	Yield strength	Maximum strength	
A-P-c	-6.66	W	541
A-Np-c	4.79	11.0	540
nA-P-c	-8.99	W	474
nA-Np-c	3.62	-11.6	481

Table 5: Test results of cyclic loading test.

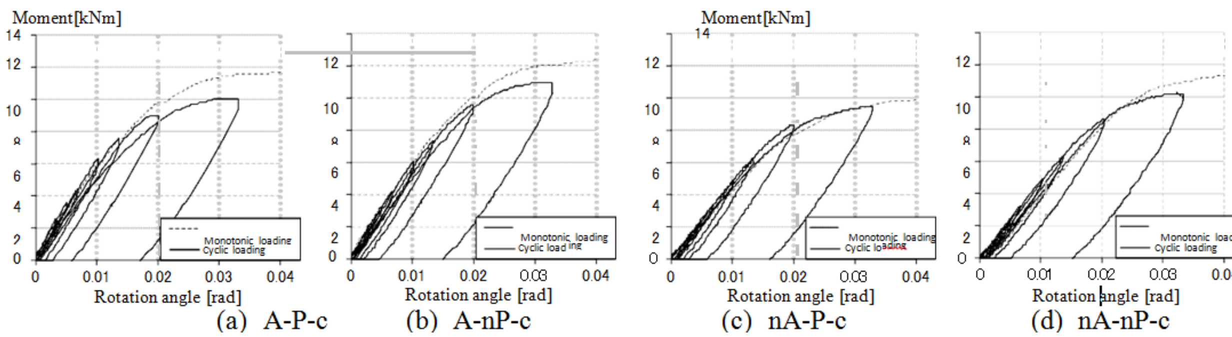

Figure 9: Comparison of envelope curves and M-θ curve of monotonic loading.

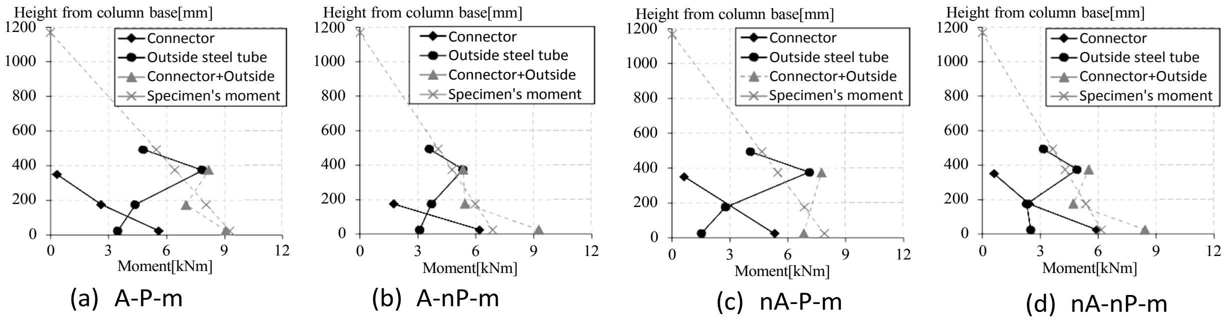

Figure 10: Bending moment distribution of embedded connection.

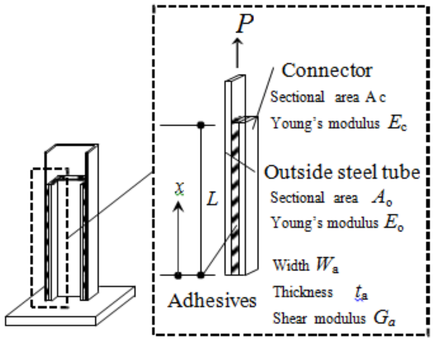

Figure 11: Dynamic model.

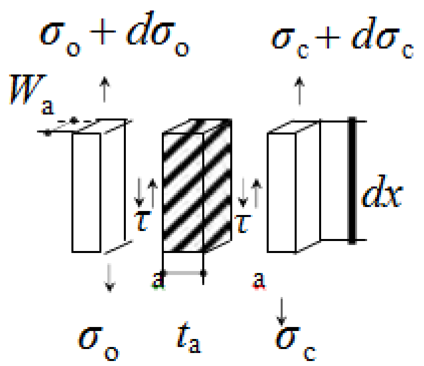

Figure 12: Small elements of members.

Parts	A-P-m	A-np-m	nA-P-m	nA-nP-m
Connector	5.59	6.16	5.31	5.91
Outside steel tube	3.48	3.08	1.52	2.51
Connector + Outside	9.06	-	6.82	8.43
Specimen's moment	9.25	6.86	7.88	6.17

Table 6: Test results of bending moment.

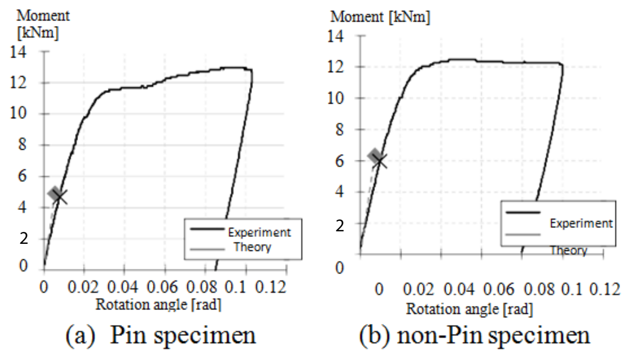

Figure 13: Comparison between experiment and theory.

adhesives itself were not resisted bending moment because the bending strength of A-nP-m was close to one of nA-nP-m.

Analytical Studies

General description of analytical method

In this section, from the observation of test results, theoretical equations of bending strength and rigidity at the exfoliation of adhesives are proposed. Here in, each bending strength of the flange and the web is calculated, and the sum of them is the whole bending strength of embedded connection from principle of superposition.

The bending strength valuation plan at exfoliation of adhesives

The Figure 11 shows the analytical model assumed from test results. When axial force P by bending moment is loaded, it is assumed that shear stress distribution by adhesives is applied at tension side as Figure 12. Thus, following equation is established by condition of forces.

$$A_o \times d\sigma_o = \tau_a \times dx \times W_a \;,\; A_c \times d\sigma_c = \tau_a \times dx \times W_a \qquad (1)$$

Ao, σo: Sectional area and stress of outside of steel tube.

Ac, σc: Sectional area and normal stress of connector.

Wa, τa: Width and shearing stress of adhesive.

$$d\tau_a = G_a \times d\gamma_a = \frac{G_a}{Et_a} \times (\sigma_o - \sigma_c)\, dx \qquad (2)$$

E: Young's modulus of outside steel tube and connector.

Ga: Shear modulus of adhesives.

Following equation (3) is equation (2) integrated.

$$\tau_a = \frac{KP}{W_a} \times \frac{1}{\sinh KH} \times \frac{A_O \cosh(KH-kx) + A_c \cosh kx}{A_o + A_c}$$

$$K^2 = \frac{G_a W_a}{Et_a} \times \frac{A_o + A_c}{A_o A_c} \qquad (3)$$

From equation (3), the bending strength of flange Mf is expressed by equation (4).

$$M_f = \frac{\tau_a \times W_a \times (A_o + A_c) \times \sinh KH}{K \times \{A_o \cosh(KH-kx) + Ac \cosh kx\}} \times B \qquad (4)$$

From Figure 7, the bending moment of web of outside steel tube and connector (Mwo, Mwc) at exfoliation of adhesives is calculated from the following equation (5).

$$M_{wo} = \frac{\sigma_3 \times L}{2} \times t_o \times \frac{2L}{3} \times 2,\;\; M_{wc} = \frac{\sigma_1 \times I_c}{1/2} \times 2 \qquad (5)$$

to: Plate thickness of outside steel tube

Ic: Geometrical moment of area of connector

According to section 6.3 about the bending moment distribution of embedded connection, connector and outside steel tube collaborate to resist the bending moment if a pin is installed. On the other hand, in case of non-pin specimen, the connector mainly resists the bending moment. Therefore, the bending strength of embedded connection is calculated by equation (6).

$$\begin{aligned} M &= M_f + M_{wo} + M_{wc} \quad (\text{Pin}) \\ M &= M_f + M_{wo} \times \beta + M_{wc} \quad (\text{non}-\text{Pin}) \end{aligned} \qquad (6)$$

β: Apportioning rate by stress transmitting.

Table 6 shows the comparison between theoretical and experimental value. The bending strength at exfoliation of adhesives is good agreement.

The Bending rigidity of embedded connection at exfoliation of adhesives

The displacement of embedded connection at exfoliation of adhesives is calculated by elastic curve equation.

Part of connector $$\frac{d^2y_1}{dx^2} = \frac{P \times (L - x)}{E \times \{I_o + (1 - x/H) \times I_c\}} \quad (7)$$

Part of outside steel tube $$\frac{d^2y_2}{dx^2} = \frac{P \times (L - x)}{E \times I_o} \quad (8)$$

Figure 13 shows that the comparison between experimental results and theoretical results. The theoretical equation shows good agreement from the comparison of Figure 13.

Conclusions

In this paper, loading tests of embedded connection for lightweight steel square tube filled with adhesives were conducted to clarify the resistant mechanism and inelastic behavior as parameters with the existence of adhesives and pin. The main conclusions of this paper are:

1) If adhesives were used as filler, the stress from connector to outside steel tube was increased by the filling effect. As a result, in case of adhesive filling, the bending strength and rigidity became high.

2) The bending rigidity showed almost same in both case of pin and non-pin, however, the maximum bending strength was enhanced during ultimate state by bearing pressure in case of pin.

3) The connector and the outside steel tube collaborated to resist the bending moment when a pin was used. On the other hand, in case of non-pin, the connector mainly resisted the bending moment.

4) Theoretical equations of the bending strength and rigidity at the exfoliation of adhesives are proposed, and they are good agreement.

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