A Study on Productivity and Structural Performance of Steel Embedded Connection Filled with Adhesives

Itsuki Yagi
Department of Architecture, Tokyo University of Science, Tokyo, Japan
Email: 4116655@ed.tus.ac.jp

Yuta Nakaie[1], Takumi Ito[1], Changhoon Choi[1] and Hiroyuki Murata[2]
[1] Department of Architecture, Tokyo University of Science, Tokyo, Japan /
[2] Department of Steel Structural Engineering, Fab-Tec Japan Corporation, Tokyo, Japan
Email: 4117637@ed.tus.ac.jp, t-ito@rs.kagu.tus.ac.jp, musasi73@rs.tus.ac.jp, hiroyuki_murata@j-fab.co.jp

***Abstract*— Recently, a various of steel connection technique has been developed, which aims to possess the multiple demands on steel structures. In this study, a new fitting type connection technique is suggested and this joint consists as follows: steel square tube is just embedded to another steel member, and the filler such as adhesives is filled to the clearance between each member. The advantage of this embedded connection system is not only improvement of workability by needless of bolting and welding on construction site but also adjustment of the bending rigidity and strength by filling materials and methods. Herein, the productivity test is conducted in order to investigate the workability of proposed connection methods. From test results, the workability is improved compared with conventional connection systems. In addition, the loading test and the finite element analysis is conducted in order to clarify the resistant mechanism to the bending moment. From these results, it is confirmed that the bending rigidity and strength is improved by filling effect of adhesives and kinematic model of embedded connection is proposed.**

***Index Terms*—Steel building structures, Embedded connection, Adhesives, Productivity test, Loading test, Finite element analysis**

I. Introduction

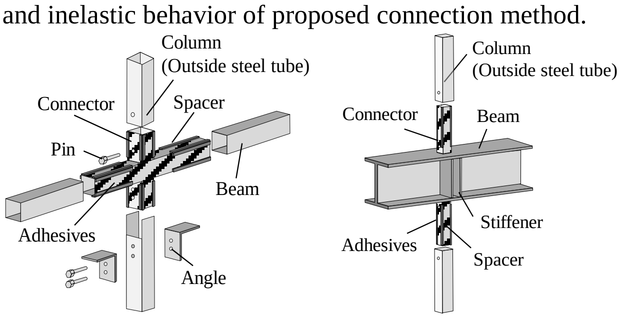
Generally, bolting and welding are adopted as joint components in steel framed structures. In perspective, a connection of steel structures is divided into the rigid connection, semi-rigid connection, pin connection by the fixation of the connection. However, these connection methods have some problems of workability on the construction site. Especially, in Japan, the shortage of skilled technicians becomes one of social problems.

To solve this problem, 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 type connection method is sometimes adopted such as temporary structures which demand shorter construction period as well as greater ease of disassembly. Moreover, this connection method is expected to simplify the construction work, avoid on-site welding and construction errors [3], [4].

In this study, a new fitting connection technique for the steel square tube is suggested as shown Figure 1. This proposed connection is consisted of the column and the beam with connector. The joining method is that the steel square tube is just embedded to another steel member by not using bolting and welding on construction sites.

Furthermore, a clearance is filled with organic or inorganic fillers so as to prevent from the slipping and adjust the bending rigidity and strength for structural designs. Herein, inorganic adhesive materials are adopted to fill the clearance as a filler on this connection, which adhesives widely used to adhere nonstructural members such as tiles and marbles in Japanese architectural building field.

In this paper, a new type embedded connection method using a steel square tube is suggested, and a productivity test is conducted in order to evaluate the workability of the new connection method (see Figure1) by comparison with the conventional bolting connection method. And also, a loading test was conducted to clarify the resistant mechanism subjected to bending moment and inelastic behavior of proposed connection method.



(a) Steel square tube beam (b) H-shaped beam

Figure 1. Conceptual Diagram of Embedded Steel Connection

Manuscript received July 10, 2017, revised October 20, 2017.

doi: 10.18178/ijscer.7.3.220-226

II. DETAILS OF EMBEDDED CONNECTION SPECIMENS

A. General Description

First, a construction process of the conventional rigid connection method of steel building frame is explained. Generally, the bolting connection is adopted as rigid column-beam connection which a column with a beam bracket is joined to a web and flanges of the beam on-site by using high strength bolts and splice plates while managing proper level of the torque.

On the other hand, the construction process of the embedded connection as shown Figure 1 is described below. First of all, the filler such as adhesives are coated to a connector, and fitted a column (an outside steel tube) into the connector. The construction process of embedded connection becomes simple so that its workability is excellent because of unnecessary of bolting and welding on-site. As a result, it is expected that the construction period is shorter than conventional construction process.

B. Composition of Specimens

In this paper, partial frame test specimens and element test specimens were prepared to conduct experiments. To evaluate the productivity of this joint technique, the partial frame test specimen is designed with assumption of a low-rise building. And to investigate the structural the resistant performance, the element test specimens are designed which the experimental study is conducted subjected to bending moment.

Fig. 2 shows the partial frame test specimen of conventional bolting connection. A specimen is consisted of following parts; a steel square tube column with through diaphragm, H-shaped steel beam, splice plates and bolts.

Figs. 3, 4 show the test specimens of the embedded connection. Fig. 3 shows an element test specimen of the embedded connection consisted of following parts; connectors, a steel square tube column (outside steel tube) and adhesives. Moreover, the specimen of Fig. 3 presents a partial frame consisted of following parts; a H-shaped beam with connectors, a steel square tube column (outside steel tube) and adhesives.

Herein, spacers of both test specimens are made by spot welding method in order to adjust and keep a layer thickness of adhesives filled between the connector and the outside steel tube. The layout of spacers is arranged over the entire circumference in test specimens. And, epoxy resin adhesives are adopted as a filler, which is composed of a based resin containing an epoxy resin and a curing agent containing a modified aliphatic polyamine, and it is hardened if mingle them together.

III. PRODUCTIVITY ANALYSIS

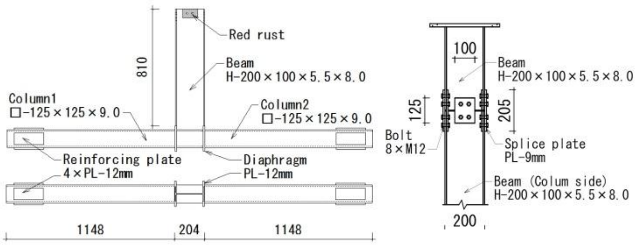
A. General Overview of Productivity Analysis

As described above, this embedded connection method is expected to improve the workability on comparison to conventional connection methods such as on-site bolting and welding. In this study, the productivity analysis is conducted to evaluate the workability of the embedded connection method, through comparison with the bolted connection method.

B. Workability Measurement Method

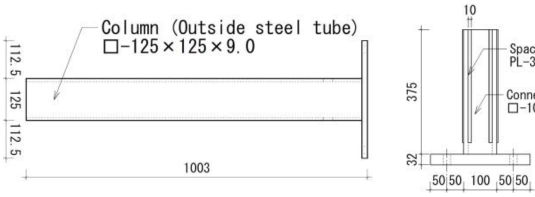
In this study, the assembly of a partial frame test specimen of each connection method was recorded by camera. From this recording, each connection method was analyzed and divided into elementary operations, which were again divided into smaller units of work. In addition, the units of work were classified as either main work or incidental work, and analyzed as such [5].

The on-site connection work of conventional connection method consists of bolting splice plates of the beam web and flange while managing torque, on the other hand, the on-site connection work of the embedded connection method consists of mixing adhesives and coatings for connectors, and fitting columns (outside steel tubes) into connectors. These connection work were conducted under actual condition with columns kept vertical as shown in the Figure 5.



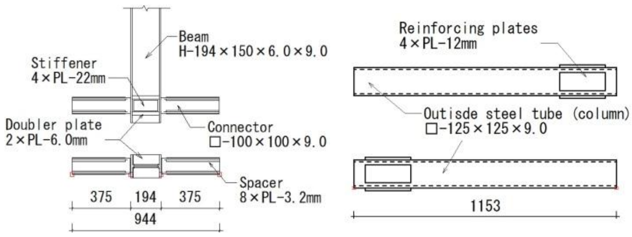
(a) Column with through diaphragm (b) Beam

Figure 2. Partial Frame Test Specimen of Bolting Connection



(a) Column (Outside steel tube) (b) Connector

Figure 3. Element Test specimen of Embedded Connection



(a) Beam with connector (b) Column (Outside steel tubes)

Figure 4. Partial Frame Test Specimen of Embedded Connection

(a) Bolting connection method (b) Embedded connection method

Figure 5. Connection Work of Partial Frame

C. Productivity Test Results

Table I shows the productivity test results of the bolting connection method, and Table II shows the test results of the embedded connection method. As seen in the measured results, the work time of the bolting connection method was about 16 minutes and 27 seconds, while the work time of the embedded connection method was about 11 minutes and 4 seconds.

These results show that the embedded connection method was superior to the conventional connection method in terms of on-site workability because the work time of the embedded connection method was shorter than bolting connection method. Therefore, the embedded connection method is expected to shorten the total construction period by reducing on-site work time. It is thought that, since the embedded connection method only requires fitting each member together, bolt fastening and complicated torque managing labor on-site can be avoided.

Moreover, although the work of mixing adhesives was performed by knife this time, if a mixer was used in order to mix adhesives, the work time of the embedded connection would improve and become shorter than the current result. Furthermore, it is thought that the connecting work time of the metal to metal embedded connection without adhesives is much shorter than the bolting connection method because it requires no time for adhesives preparation.

IV. Loading Test Study

A. General Description of Loading Test

Herein, the loading test was conducted to verify the resistant mechanism of the embedded connection. Mechanical properties of steel elements are summarized in Table III, and one of adhesives are presented in Table IV.

Table V shows the theoretical yield strength ($M_y=\sigma_y\times Z$, yield stress σ_y, modulus of section Z), and it shows the theoretical plastic strength ($M_p=\sigma_y\times Z_p$, plastic section modules Z_p). In the partial frame test specimens, the strength of the connection is designed higher than the strength of H-shaped beam.

TABLE I. Work Time of The Bolting Connection Method On-site

Elementary Task	Unit Movement	Measuring time (Minute:Second)	Ratio (%)	Classifiction
1.Temporarily fix splice plate and member				
	1-1.Registration of column and beam	01:25.0	8.8 %	Incidental work
	1-2.Remove the nuts and washers from bolts	02:20.5	14.6%	Incidental work
	1-3.Insert bolts with splive plates and hand-clapping nuts	03:20.1	20.8%	Main work
2.First tighten the high strength bolts				
	2-1.First tighten bolts with torque wrench	04:15.9	26.6%	Main work
3.Marking the high strength bolts				
	3-1.Marking high strength bolts with a white marker	01:34.4	9.8 %	Incidental work
4.Tightening the high strength bolts				
	4-1.Tighten bolts tightly with the shear wrench	03:05.5	19.3%	Main work
	Σ =	**16:01.4**	**100.0 %**	

TABLE II. Work Time of The Embedded Connection Method On-site

Elementary Task	Unit Movement	Measuring time (Minute: Second)	Ratio (%)	Classifiction
1.Mingling Epoxy resin adhesives				
	1-1.Pour epoxy resin and curing agent into a container	01:00.4	9.1 %	Incidental work
	1-2.Mingle adhesives by knife	00:48.2	7.3 %	Incidental work
2.Coating adhesives to members				
	2-1.Coating adhesives to connectors by knife	04:38.2	41.9%	Main work
	2-2.Removing excessive adhesives	**00:17.0**	**2.6 %**	Incidental work
3.Embedding columns into connectors				
	3-2.Embedding columns into connectors by chainblock	**04:20.5**	**39.2 %**	Main work
	Σ =	**11:04.3**	**100.0 %**	

TABLE III. Mechanical Properties of Steel Components

Parts	Steel Grade (Grade of JIS)	Yield stress [N/mm^2]	Tensile stress [N/mm^2]	Young’s modulus [N/mm^2]
Connector	STKR400	411	475	2.09×10^5
Outside Steel tubes	STKR400	414	470	1.96×10^5
H-shaped beam flange	SN400B	303	434	1.96×10^5
H-shaped beam web	SN400B	313	431	2.01×10^5

TABLE IV. Mechanical Properties of Adhesives

Thickness of adhesives [mm]	Shear strength of exfoliations of adhesives [N/mm^2]	Young’s modulus [N/mm^2]
3.2	4.98	1870

B. Loading Test Set Up and Loading Test Method

Figure 6 illustrates a test set up of the element test specimens. The lateral load was applied to the top of the outside steel tube to produce as bending moment at the connection. The monotonic loading test was conducted in case of the element test specimens, and the maximum rotational angle was 1/10 rad. Herein, the existence of adhesives was considered as the experimental parameter.

And also, Figure 7 illustrates a test set up of the partial frame test specimen. Both ends of the columns were fixed as pin connections by jig, and the lateral load was applied at the end of the cantilever beam in order to produce the bending moment at each connection as shown Figure7. The cyclic loading test was conducted in case of partial frame test specimens, and the rotational angle of the test specimens on the cyclic loading test were ±1/300, ±1/200, ±1/150, ±1/100, ±1/75, ±1/50, ±1/30 rad (repeat three times at each rotation angle), at last, the load is applied until the limit of the jack stroke.

Each test specimen was instrumented with sensors to measure lateral load, displacement at the top of the test specimens, and strains of a beam, connectors and outside steel tubes.

C. Loading Test Result of Element Test Specimen

Fig. 8 shows the moment-rotation angle curves (M-θ curve) under the monotonic loading test. The collapse modes of the embedded connection were observed as follows; ① Exfoliation of adhesives ② Yield of the connector ③Yield of the outside steel tube. After loading test, it was confirmed that the exfoliation of adhesives was occurred in the boundary layer between adhesives and the outside steel tube, and the bending rigidity was deteriorated after the exfoliation of adhesives. From Figure 8, the bending rigidity and strength was improved by filling effect of adhesives, therefore, this result shows the possibility of the adjustment the bending rigidity and strength of the connection for the structural design.

In addition, Figure 9 shows M-θ curve and the strength of the connector in case of adhesives test specimen. In this graph, the bending moment was multiplied the lateral load by the length of the test specimen, and the bending strength of the connector and the outside steel tube were calculated from the bending rigidity and strains from the test result. From this graph, the bending moment of the connector was closed to the total bending moment of the test specimen in elastic area. Therefore, it is confirmed that the strength of the embedded connection was depended on the strength of the connector and the outside steel tube was not almost resisted to the bending moment.

D. Loading Test Results of Partial Frame Specimen

Fig. 10 shows M-θ curves at the end of beam in case of partial frame test specimens under the cyclic loading test, the observed collapse modes are presented. And also, each bending strength of the loading test (Exfoliations of adhesives, Yield strength, Plastic strength, Bending rigidity) is summarized in Table VI. The collapse modes of the embedded connection were observed as follows; ① Exfoliation of adhesives at embedded part, ②Yield of the H-shaped steel beam, ③Yield of the panel zone, ④Yield of connectors, ⑤Yield of outside steel tubes. From Table VI and Fig. 10, the yield strength of experimental result was much lower than the theoretical value of Table V. Therefore, it can be examined why the yield strength value of H-shaped beam was low in case of embedded connection at Section V.

In addition, the skeleton curve of restoring force characteristics of each test specimen was compared in Fig. 11. From this result, the bending rigidity of the test specimen of the embedded connection was decreased after the exfoliation of adhesives as well as the elemental test result.

Fig. 12 shows the skeleton curve and the bending strength of the connector at column base. From this result, the plastic strength of test specimen shows good agreement to the plastic strength of H-shaped beam, and the plastic strength of the connection is higher than the strength of the beam. Therefore, the collapse mode of this partial frame test specimen was the sideway of the beam mechanism.

TABLE V. SECTION PERFORMANCE OF EACH MEMBER

Member	Modulus of section [mm^3]	Yield strength [kNm]	Plastic section modules [mm^3]	Plastic strength [kNm]
Connector	8.16×10^4	33.6	1.00×10^5	41.1
Outside Steel tubes	1.38×10^5	57.1	1.67×10^5	69.0
H-shaped beam	2.71×10^5	82.0	3.01×10^5	91.1

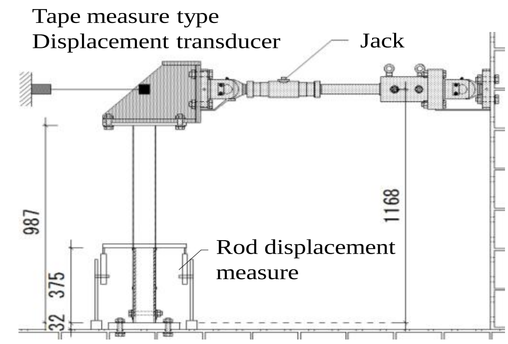


Figure 6. Set Up of Element Test Specimen

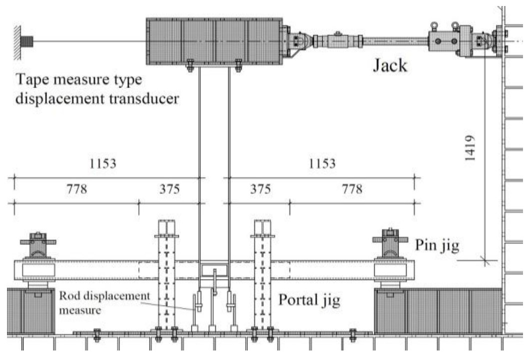


Figure 7. Set Up of Partial Frame Test Specimen

Besides, Fig. 13 shows the M-θ curve at the end of beam and the bending strength of the connector in case of the partial frame test specimen, which the bending strength of the connection are calculated from beam model as shown Fig. 14. According to Fig. 13, it was confirmed that the bending strength of the embedded connection was also depended on the strength of connectors as well as element test result as Figure 9.

V. Analytical Study of FEM

A. General Description of FEM

During the loading test, the H-shaped steel beam of the embedded connection test specimen showed low yield strength not reaching the theoretical strength. In addition, it was difficult to clarify the ultimate behavior of members and an interaction behavior between the connector and the outside steel tube by filling effect of adhesives. For these reasons, a finite element method analysis (FEM analysis) is conducted to clarify the resistant mechanism of embedded part in detail [6].

Herein, three-dimensional analysis is performed by “MSC Marc-2013” as the general nonlinear finite element method analysis program.

B. Analytical Model and Method

Analytical model is shown Fig. 15. In case of element specimen, the maximum width of analytical model elements is 5mm and the total number of elements is 55,000, whereas, in case of the partial frame specimen, the maximum width of analytical model elements is 15mm and the total number of elements is 63,900. The true stress-true strain curves obtained from the material testing results are adopted, and the Poisson’s ratio is assumed 0.3. In addition, the hardening rule is the isotropic hardening, and the yield condition is used von Mises.

Fig. 15 (b) shows the analytical model of the embedded part in detail. The contact condition of steel elements is considered friction surface, and the coefficient of friction is 0.2. Furthermore, the contact condition of adhesives elements is glue, and the contact type of glue is destruction [7], [8].

The boundary condition of the element test specimen is rigid at the endplate, while the boundary condition of the partial frame analytical model is pin around 250mm from the end of outside steel tubes on condition same as set up of the experiment. In addition, the out-of-plane deformation of the load jig is restriction and applied forced displacement of the loading program is same to the experiment.

C. Result of FEM Analysis

Fig. 17 shows the moment-rotation angle curves of comparison between the test result and the analytical result in case of the element test specimen. From Fig. 17, it is confirmed that the test result can be reproduced by the FEM analysis, so it can be said that the analytical condition and method are appropriate. In addition, Figure19 shows the resistant mechanism of the embedded connection from experimental and analytical result. It is confirmed that the stress area of adhesives is changed and larger than metal touch connection method. Therefore, the contact force and friction force are increased by filling effect of adhesives as shown Figure 17. If the clearance size of each member is narrow, the mechanical properties is increased so that the contact and friction force of the embedded part is also increased. As a result, it is thought that the bending rigidity and strength of the proposed connection are increased by adhesives.

TABLE VI. Results of Partial Frame Loading Test

Specimens	Bending strength [kNm]			Bending rigidity [kNm/rad]
	Exfoliation of adhesives	Yield strength	Plastic Strength	
Bolting Connection	-	52.6	71.0	3730
Embedded Connection	14.8	38.5	93.1	4240

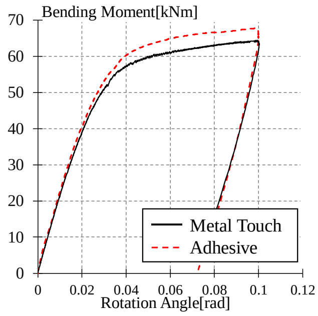


Figure 8. Loading Test Result of Element Test

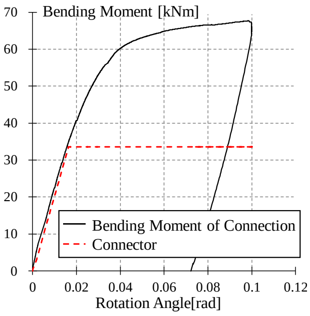
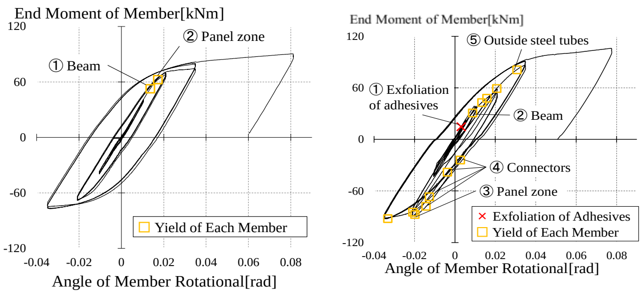


Figure 9. The Strength of Connector in Case of Element Test



(a) Bolting connection (b) Embedded connection

Figure 10. Loading Test Results of Partial Frame Test

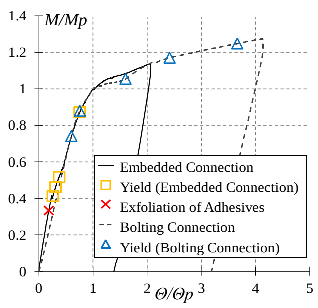


Figure 11. Comparison of Skeleton Curve

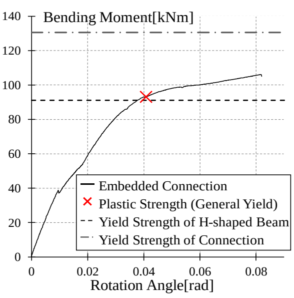


Figure 12. The Strength of Each Member

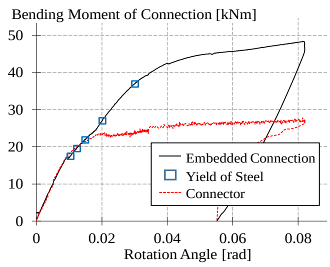


Figure 13. The Strength of Connector in Case of Partial Frame Test

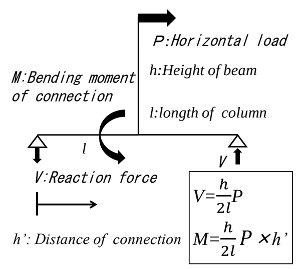


Figure 14. Beam Model of specimen

Fig. 18 compares skeleton curves of the loading test result and the analytical result in case of the partial frame model, it is confirmed that the test result can be reproduced by the FEM analysis as well as element results. Figure 19 shows the stress diagram of the H-shaped steel beam, and it is confirmed that the stress concentration is occurred at the H-shaped steel beam flange by contact with an outside steel tube. Especially, the central part of the beam flange becomes too large stress and strain gauges were attached the central part of the beam flange, so the experimental yield strength value is lower than the theoretical one because of the concentration of the stress.

Although the stress concentration is occurred at the central part of the H-shaped beam flange. From the result of the FEM analysis, it is confirmed that the whole flange of the H-shaped beam is not yield. Table VII compares the theoretical results and the analytical results of yield strength. From this comparison, the analytical yield strength shows good agreement with the theoretical value while average strains of the beam flange were reached the yield strain, so it is considered that the original yield strength is close to the theoretical bending strength.

VI. Conclusion

In this paper, the production test and the loading test of the embedded connection for steel square tubes filled with adhesives were conducted. The results obtained from the experimental and analytical study in this paper are:

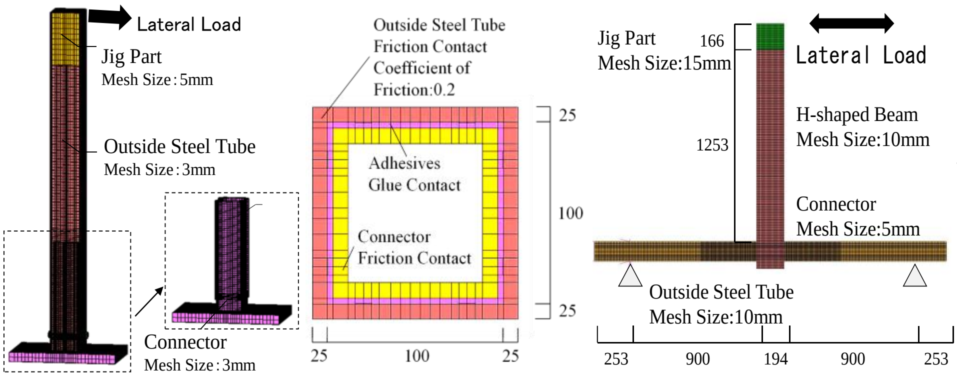
1) The work time measurement was implement and classified the work units of single connection into main and incidental work, so the embedded connection method can be expected to improve the workability compared to the bolting connection

2) If adhesives are used as filler, the bending stiffness and strength are increased by filling effect from the loading test result.

3) The resistant mechanism model of the embedded connection is clarified by FEM analysis, and it is confirmed the contact force and friction force is increased by filling effect of the adhesives.

TABLE VII. Yield Strength of Embedded Connection

	Analytical Value [kNm]	Theoretical Value [kNm]	Analysis/Theory
Yield Strength	76.0	82.0	0.927



(a) Element specimen

(b) Detail of embedded part

(c) Partial frame specimen

Figure 15. Analytical Model of Embedded Connection

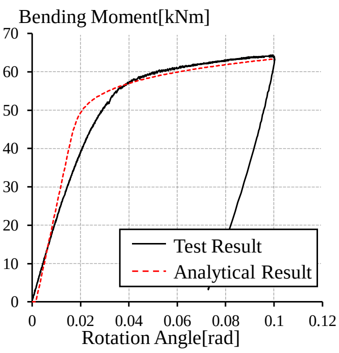
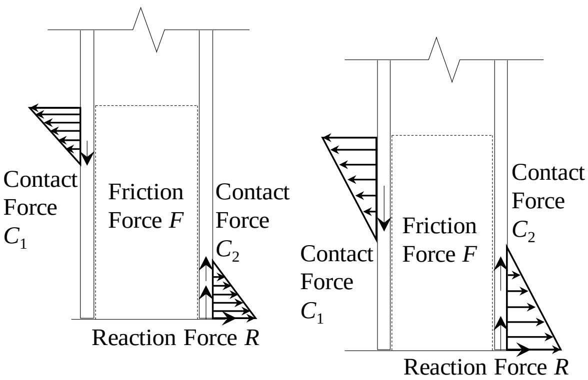


Figure 16. Comparison between Test and Analytical Results of Element



(a) Metal touch

(b) Adhesives

Figure 17. Kinematic Model of The Embedded Connection

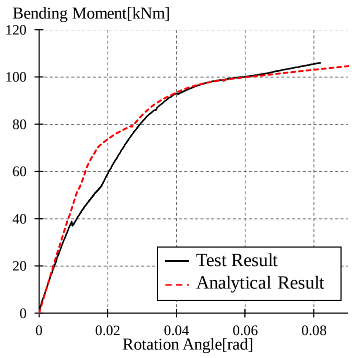


Figure 18. Comparison between Test and Analytical Results of Partial Frame

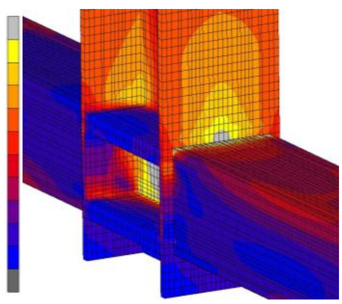


Figure 19. Stress Condition of H-Shaped Beam

ACKNOWLEDGMENT

This work was carried out with research sponsorship of the Japanese Society of Steel Construction and Japanese Society of Steel Construction and Takenaka subsidy. Therefore, we would like to express our deepest gratitude to their kindly support us.

REFERENCES

[1] Suita K, “Recent Experiments for Development of New Steel Joint System”, Annual Meeting of Architectural of Japan Tohoku, pp4-15, August 2009

[2] Kuwamura H, Ito T, Tomioka Y, “Study on Steel Cone-to-Cylinder Socket Connections”, Journal of Structural Engineering vol598, pp155-162, December 2005

[3] Eguchi S, “Study on Design Method of Joint Panels for Hybrid Railway Rigid-frame Bridges”, Quarterly Report of RTRI vol44, pp86-91, May 2003.

[4] Horigoe H, “Research and Development of Ring-Panel at Mixed Construction”, Annual Meeting of Architectural of Japan Hokuriku, pp1079-80, August 2002

[5] *Recommended Practice for Method Improvement on Construction Work*, Architectural Institute of Japan, 1990.2.

[6] Afendi M, “Effect of Bond Thickness on Fracture Behavior of Interfacial Crack in Adhesive Joint of Dissimilar Materials”, Journal of the Adhesion Society of Japan vol45, pp471-477, May 2009

[7] Ishii D, “Evaluation of Strength for Beam to Column Connection by Filling with Mortar for Steel Members”, Journal of Structural and Construction Engineering vol74, pp1513-1521, April 2009

[8] Sugiura H, “Analytical Study on The Bonding Method of Carbon Fiber Sheets in The Repair of Corroded Steel Members”, Journal of the Japan Society of Civil Engineers vol64, pp806-813, November 2008

Itsuki Yagi was born in Japan in 1993. He received Bachelor of Engineering degrees from Department of Architecture in 2016 at Tokyo University of Science, Japan. Currently, he is a master’s degree course in the Dept. of Arch at Tokyo University of Science and investigated about steel structural engineering. He published following articles: ”An Experimental Study of Embedded Connection for Lightweight Steel Square Tube Filled with Adhesives”, Journal of Civil and Environmental Engineering, July 24.2016. He has membership in the architectural Institute of Japan and he won an excellence award in the architectural Institute of Japan at Kanto branch.

Yuta Nakaie was born in Japan in 1993. He received Bachelor of Engineering degrees from Department of Architecture in 2016 at Tokyo University of Science, Japan. Currently, he is a master’s degree course in the Dept. of Arch at Tokyo University of Science and investigated about steel structural engineering. He has membership in the architectural Institute of Japan.

Takumi Ito is associate professor, Tokyo University of Science. He received the Dr. Eng. Deg. from the University of Tokyo in 2004. His research interests are building structure, experimental methodology, and numerical simulation. He has published 42 papers, 57 proceedings, and other papers or reports. He received some paper awards of Architectural Institute of Japan or Japan Society of Steel Construction in 2003, 2004, and 2006.

Hiroyuki Murata is the subsection chief of the steel structural engineering department of Fab-Tec Japan Corporation (known for working on the Fukushima nuclear plant covering project which used the steel embedded connection in main structures). He received a Bachelor of Engineering Degree from Tokyo University of Science and is also a member of the Architectural Institute of Japan.

ChangHoon Choi is assistant professor, Tokyo University of Science. He received the Dr. Eng. Deg. from Waseda University in 2013. His research interests are the work process, the repair and reinforcement construction method, improvement of repair process, work planning, Value Engineering, building construction. He won a prize for commendation by contribution of the Value Engineering development from the Korean Incheon Metropolitan City head in 2014.