UDC 624 . 014 . 27 : 691 . 32

Concrete Filled Tube Columns

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Abstract

A concrete-filled tube (CFT) is a material with excellent performance resulting from the confined effect of steel with concrete and high design versatility and is being employed in more constructions recently. However, designing and processing the beam to column connection with CFT is difficult too. Therefore, a steel tube members with diaphragms (NS column) has been developed as an intermediate part member in which the diaphragms required for the beam to column connection are fitted to the designated positions. This tube members with diaphragms has already obtained the general approval. This report summarizes the steel tube column with diaphragms and the performance research results for the joint to the actual scale that was conducted prior to developing.

1. Introduction

Studies have been conducted on concrete filled tubular steel (CFT) structures from a long time ago. Based on the results of such studies, the Architectural Institute of Japan published its "Recommendations for Design and Construction of Concrete Filled Tubular Steel Structures" in 1967. However, from that time until about 1990, the use of concrete filled steel tubular structures were limited in actual constructions. This may be due to the fact that a design method that reflected the performance particular to such structures was not established or to the fact that the mixing of the concrete fill and fabrication quality control were very difficult.

On the other hand, further studies have resulted in improvements in the design standard[1,2], and the concrete quality has been greatly improved. Moreover, the Association of New Urban Housing Technology has obtained general approval for concrete filled steel tubes. Concrete filled tubular steel structures are thus being employed in more constructions recently. Other countries are also employing concrete filled tubular steel structures in multistoried and high-rise buildings.

2. Features of Concrete Filled Tubular Steel Structure

The concrete filled tubular steel structure excels in load-bearing performance by restraining local buckling, weak point of steel material with the filled concrete during compressive stress. This feature is an advantage commonly obtained in the combined structure of steel and concrete, and it is a dynamically excellent point. In addition, the concrete filled tubular steel structure has superior earthquake-resistant performance for repeated loads. Further, the concrete filled steel tube can provide good cost performance for fabrication in that no molds are necessary for concrete filling.

The column material and the compression member that use concrete filled steel tubes have the following specific advantages[2].

1) Less limitation on width-thickness ratio compared with the hollow steel tube.
2) The concrete fill becomes a three-axis stress state which increases compressive strength. The effect is large especially for the columnar steel tube.
3) The concrete fill increases fire-resistance for members. Fire

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protection can be reduced more than for the steel structural members, and the members can even be designed without any protection.

4) The concrete fill allows dimensions of diaphragms for the joint to be reduced.

These advantages are specifically reflected in the "Recommendations for the Design and Fabrication of Tubular Steel Structures"[3] and "Technical Recommendations for Concrete Filled Tubular Steel Structures" which were published respectively by Architectural Institute of Japan and Association of New Urban Housing Technology.

3. NS Column

The application of a columnar steel tube to a column member requires the joint of a column to a beam to be reinforced by diaphragms. Designing the shape of the diaphragm for each steel tube diameter while considering concrete filling performance is very troublesome. The processing is also very difficult if no special facilities are provided because the member is a columnar steel tube. Therefore, Nippon Steel Corp. has developed and produced the NS column which has diaphragms welded to a specified position (beam joining position) decided in the design of the tubular steel member as shown in **Fig. 1** (see **Photo 1**).

The ranges of steel tube material quality and sizes for NS columns shown in **Table 1** are used as targets according to recent market trends of concrete filled tubular steel structures. The TMCP steel plates (BT325) or forged materials shown in **Fig. 1** and **Table 2** are used for the diaphragms for beam to column connections. The columnar steel tubes and the diaphragms are welded in a plant that has specialized lines for assuring the quality of welded parts.

Next, this report describes the results of actual-scale performance testing regarding the dynamic characteristics of the beam-to-column connections, the quality of the welded joint between the steel tube and the diaphragms, and concrete filling performance.

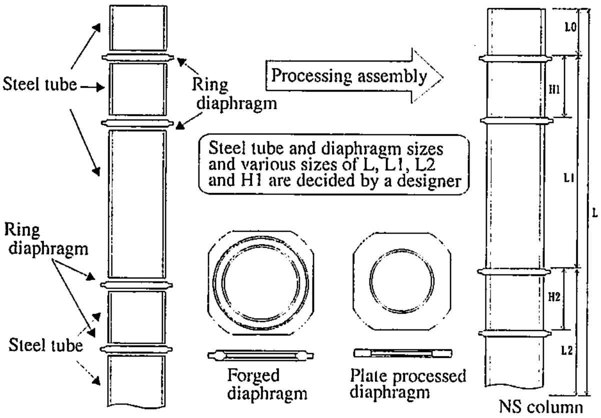

Fig. 1 Outline of NS column

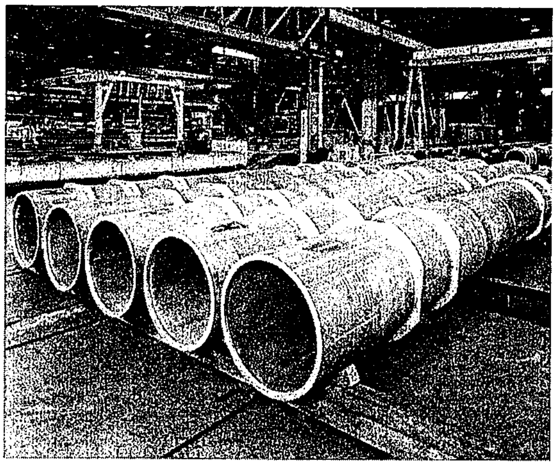

Photo 1 NS column product

Table 2 Material for diaphragm

Kind	Standard number	Symbol of kind
Plate processed member	JIS G 3136	SN400B, SN490B
	JIS G 3106	SM400B, SM490B
	BCJ-S954	BT-HT325B, BT-HT325C
Forged member	BCJ-S1737	STR-SN490C

3.1 Dynamic characteristics of columnar steel tubes with diaphragms

To provide diaphragms for beam-to-column connections in the columnar steel tube, ring-like diaphragms with openings in the center have to be used to allow the inside of the steel tube to be filled with concrete. The beam-to-column connection is the critical part that enables a building to be earthquake-resistant, and the level of the joining performance determines the earthquake-resistance of the structure. The basic performance of the beam-to-column connection includes yield strength and joint rigidity. This report describes joining performance data, obtained through an actual-scale diaphragm tensile test. The performance of the beam-to-column connection was evaluated not only for the concrete filled steel tubes but also for the hollow steel tubes[4].

3.1.1 Test overview

(1) Specimens

There were four kinds of specimens, which include a hollow steel tube and a concrete filled steel tube both having tube diameters of 900 mm, and combinations of diaphragm kinds (made from steel plates and forged materials) as shown in **Table 3**. The shapes of the specimens are shown in **Fig. 2**, and the shapes of the diaphragms are shown in **Fig. 3**. The results of tensile tests for the materials used for the specimens are shown in **Table 4**. The length of the

Table 1 Steel tube material quality and dimension

Material quality	Carbon steel tube for generation construction		JIS G 3444 STK400 STK490
	Carbon steel tube for building construction		JIS G 3475 STKN400W, B STKN490B
	Press bend steel tube (material quality)	Rolled steel for welding construction	JIS G 3106 SM400A, B, C SM490A, B, C
		Rolled steel for building construction	JIS G 3136 SN400B, C SN490B, C
Size	Steel tube outer diameter (D): 30 mm $\leq D \leq$ 1,524 mm		
	Steel tube plate thickness(t_p): 6 mm $\leq t_p \leq$ 40 mm		

Table 3 Specimen list (mm)

Symbol		Steel tube			Ring		Flange	
		Material quality	Dimension (diameter × thickness)	D/t_p	Material quality	Thickness	Material quality	Dimension (thickness × width)
Hollow steel tube	RGS-S	SM490A	900 × 36	25	Forged*1	65	SHY685NS (80 kgf/mm² class steel)	40 × 350
	PLS-S				Steel plate*2			
CFT	RGS-C	SM490A	900 × 19	47.4	Forged*1	65	SHY685NS (80 kgf/mm² class steel)	40 × 350
	PLS-C				Steel plate*2			

Notes 1) *1 Equivalent to SM490B, *2 BT-H325B (TMCP)
2) Filling concrete strength F_c = 360 kgf/cm²

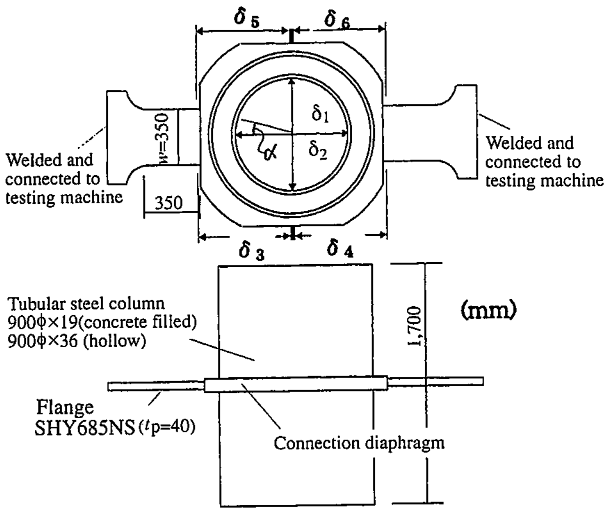

Fig. 2 Specimen shape

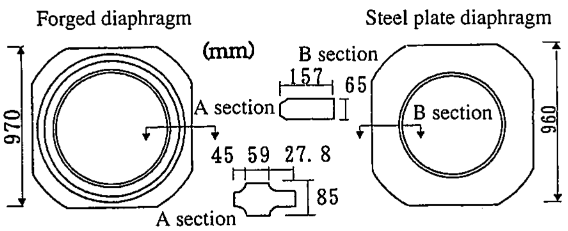

Fig. 3 Connection diaphragm shape

steel tube is 1,700 mm (about $2D$ with respect to steel tube diameter D, see **Fig. 2**) because of the limitation of the testing machine. Also, a length of a parallel part equivalent to a beam flange is 350 mm ($1W$ with respect to beam flange width W) because of the limitation of the testing machine. As this test is for evaluating the yield strength of the diaphragms, the steel material used for the flange is 780 N/mm² class. A similar steel material is also used for a welding material.

(2) Measuring and loading methods

For the tensile test of the beam-to-column connection, as shown in **Photo 2**, the specimen was set in the 4,000 ton horizontal tensile testing device and tensile loads were applied from both sides. The loading was carried out at a slow speed and continued until breaking occurred. Displacement measuring places in the tensile test are shown in **Fig. 2**. Changes in the distances between the flanges fitted to both sides were measured. For hollow steel tubes, the deformation inside the steel tube was also measured.

Table 4 Result of tensile test for used material

Place	Material quality	Thickness (mm)	Yield point (N/mm²)	Tensile strength (N/mm²)	Elongation (%)	Note
900mmφ × 19mm	SM490A	19	382	546	45.5*1	Tension after tube fabrication
900mmφ × 36mm	SM490A	36	462	550	50.9*1	Tension after tube fabrication
Forged diaphragm	Equivalent to SM490B	65	434	571	34*2	Mill sheet value
Forged diaphragm	BT-HT325B	65	376	524	36*2	Mill sheet value
Flange	SHY685NS	40	813	855	24*2	Mill sheet value

*1 JIS No. 5 test piece (test after tube fabrication)
*2 JIS No. 4 test piece (mill sheet value)

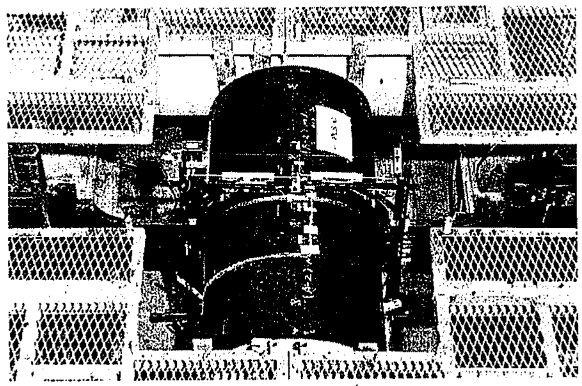

Photo 2 Specimen set up situation

3.1.2 Test results

The tensile test results for the beam-to-column connection are shown in comparison with the yield strength of the respective specimens calculated using the results of the material tensile tests (**Table 4**) in **Table 5**. Load-deformation relationships for the respective specimens of the hollow steel tubes and the concrete filled steel tubes (CFT) are shown in **Figs. 4** and **5**. The yield strength was evaluated based on a point where a tangential gradient becomes 1/3 of the initial gradient in the load-deformation relationship. The yield strength P_u was calculated by the following expression presented in "Recommendations for the Design and Fabrication of Tubular Steel Structures" of the Architectural Institute of Japan. In the expression, A_r denotes a ring cross-sectional area, F_1 and F_2 yield strength of the diaphragm and the steel tube, B_f a flange width, D a steel tube diameter, t_p a steel tube plate thickness, and α an angle shown in **Fig. 2**. For the hollow steel tube, the yield strength was also evaluated based on "the ring yield strength expression" from previous experimental studies, and the results of this evaluation are also shown in the Table.

Table 5 Result of connection tensile test (tonf)

Symbol		Ring kind	Yield strength (short time) σ_y			Maximum yield strength (last stage)			Breaking*2
			Experiment value*1	Calculated value	Experiment value/ calculated value	Experiment value	Calculated value	Experiment value/ calculated value	Position
Hollow steel tube	RGS-S	Forged	370	517	0.72	509	778	0.65	R
	(Ring yield strength expression)*3		–	306	1.21	–	492	1.03	
	PLS-S	Steel plate	352	566	0.62	542	857	0.63	F + R
	(Ring yield strength expression)*3		–	331	1.06	–	492	1.10	
CFT	RGS-C	Forged	670	666	1.00	985	882	1.12	R
	PLS-C	Steel plate	680	675	1.01	1,057	934	1.13	R

Notes *1 For the experiment value of yield strength, a tangential load having a 1/3 gradient of an initial gradient is employed.
*2 R of a breaking position is a ring, F is a flange.
*3 The lower yield strength evaluation calculated values for the hollow steel tube are obtained by "ring yield strength expression".

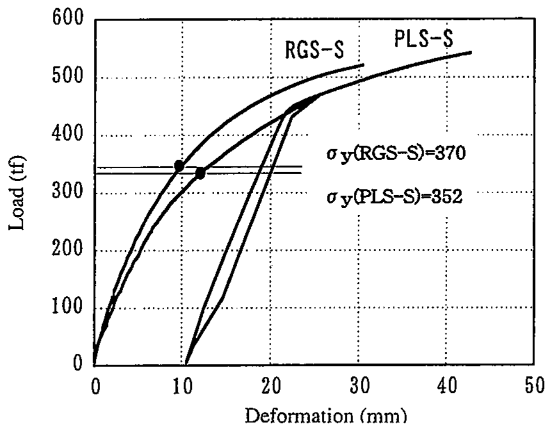

Fig. 4 Load-deformation relationship (hollow steel tube)

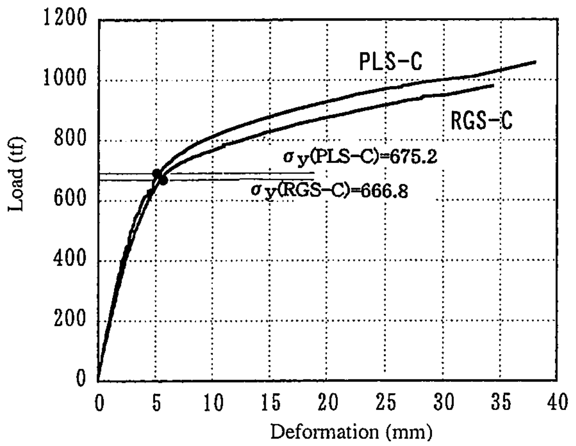

Fig. 5 Load-deformation relationship (concrete filled steel tube)

For the hollow steel tube,

$$P_a = \left(3.28\,\frac{B_f}{D} + 1.43\right)\cdot t \cdot \sqrt{A_r}\cdot F \quad \cdots\cdots\cdots(1)$$

t: Steel tube plate thickness, F: Yield strength of steel tube

For CFT,

$$P_a = 1.24\sqrt{2\sin^2\alpha + 1\,A_r}\cdot F_1 + 2.16\sin\alpha\left\{\left(0.63 + 0.88\frac{B_f}{D}\right)\sqrt{D\cdot t_p}\right\}t_p\cdot F_2 \quad \cdots\cdots\cdots(2)$$

In **Table 5**, all test results of the concrete filled steel tubes show that the experiment values exceed the calculated values. For steel tubes with diameters of 900 mm, the expression of the Architectural Institute allows connection yield strength to be evaluated conservatively. On the other hand, for the hollow steel tubes, the experiment values are much lower than the calculated values. According to the "ring yield strength expression" from previous experiments, however, the experiment values can be considered good.

Breaking conditions of the specimens using the steel plate diaphragms in the last stages are shown in **Photos 3** and **4**. Cracks occurred in the welded ends of the diaphragms and the beam flanges in all the specimens, and the cracks developed in the diaphragms. For steel plate diaphragms with almost constant diaphragm plate thickness, cracks propagated at about 45° angles toward the centers of the steel tubes. For the forged diaphragms with uneven sections, some cracks developed in a direction at which the plate thickness of the diaphragms changes slightly (nearly in parallel with the flange welding lines). In all specimens, the diaphragms were very plasticized, and reductions in plate thickness were observed.

Next, for the hollow steel tubes, the deformation $\{(\delta_3 + \delta_4 + \delta_5 + \delta_6)/2\}$ between the flanges and deformations (δ_1 and δ_2) inside the steel tubes are shown in comparison in **Fig. 6**. The tensile

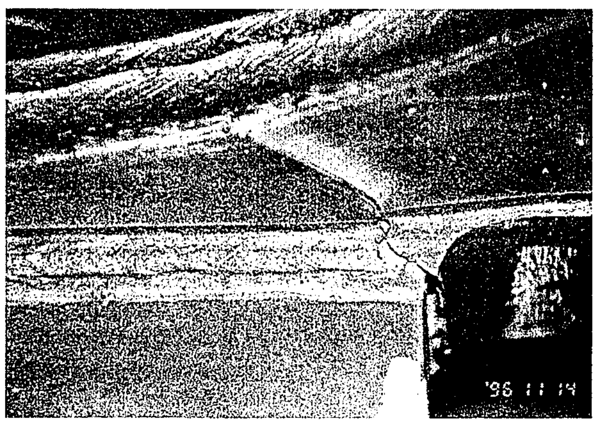

Photo 3 Specimen breaking situation (PLS-S)

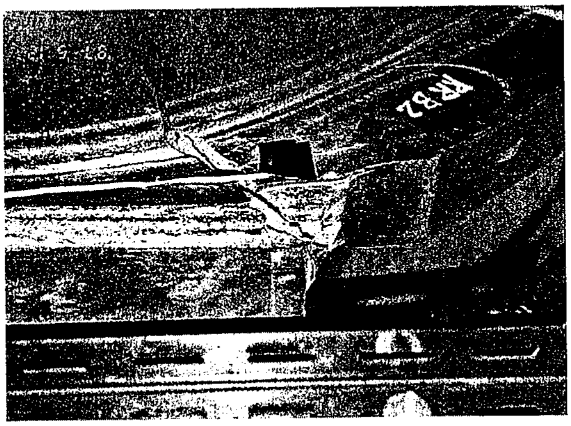

Photo 4 Specimen breaking situation (PLS-C)

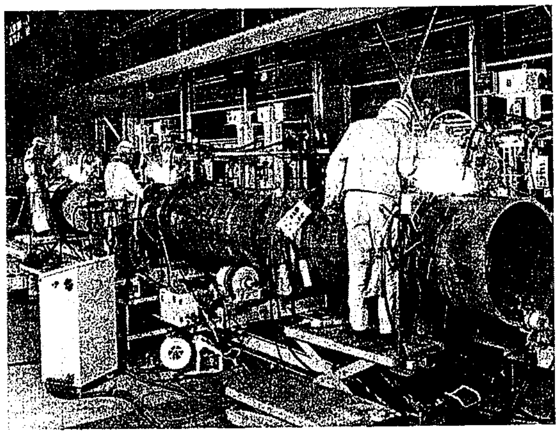

Photo 5 Diaphragm welding situation (1)

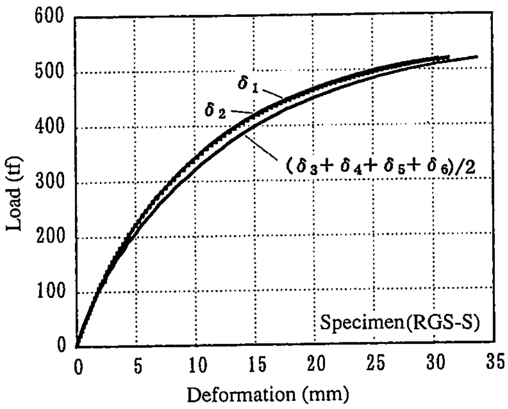

Fig. 6 Load-deformation relationship (steel tube inside and flange)

Type A direction displacement (δ_1) and the displacement (δ_2) of a direction orthogonal to the tension measured in the steel tubes have values substantially equal to each other. In addition, the deformation between the flanges includes the deformation of the diaphragms and the flanges with respect to the deformation inside the steel tubes, and this deformation is about 10%.

3.2 Welded part performance test for steel tubular column with diaphragms

The tubular steel columns are connected to the diaphragms by automatic welding in a specialized line. The diaphragm welding conditions are shown in **Photos 5** and **6**. This report describes the results of research conducted on the welded part quality of the NS column diaphragms and the steel tubes which were assembled in the above manufacturing line.

3.2.1 Test overview

A specimen welding of the steel tube 900 mmϕ × 36 mm and diaphragms shown in **Fig. 7** was manufactured, and performance including welded joint tensile strength, impact characteristic values, and so on, was investigated. The groove shapes of the welded parts are shown in **Fig. 7**, and the welding conditions are shown in **Table 6**. The shapes of the test pieces corresponding to the items to be tested for the performance investigation are shown in **Fig. 8**.

3.2.2 Test results

(1) Flat shape tensile test

For the flat shape test pieces of the steel tube-diaphragm welded

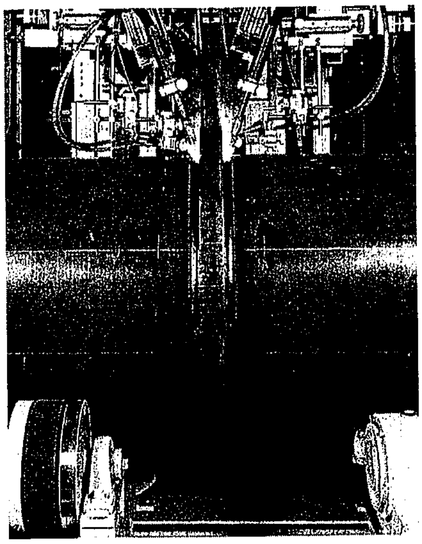

Photo 6 Diaphragm welding situation (2)

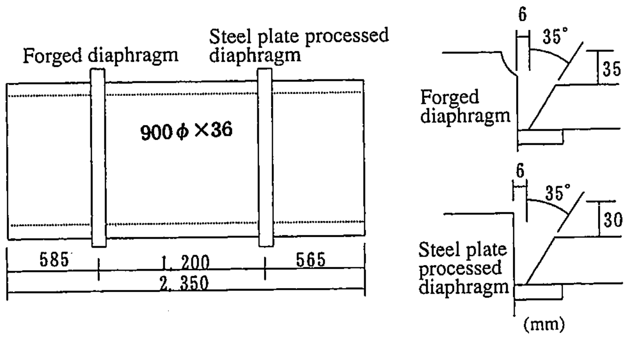

Fig. 7 Specimen for welding property and performance qualification test

Table 6 Welding condition

Welding wire	YM-26 (JIS Z 3312-YGW11), 1.6mmϕ
Current	380A
Voltage	36V
Heat input	24 - 37kJ/cm

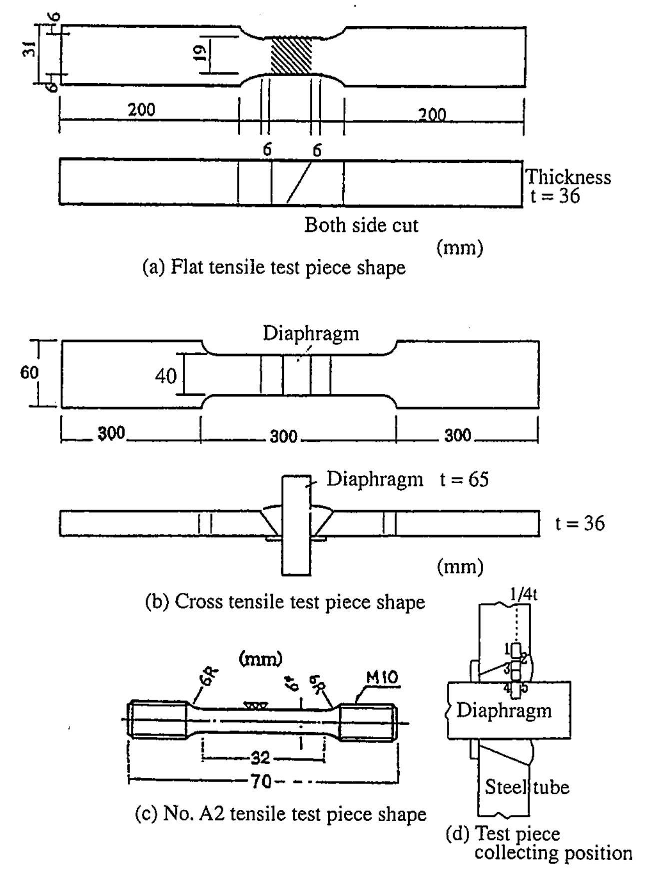

Fig. 8 Welded part test piece

parts, No. 4 test pieces were prepared by JIS Z 3121 "butt welded joint tensile test method" shown in **Fig. 8(a)**. Two pieces respectively of the steel plate and forged diaphragms were tested. The test results are shown in **Table 7**. In all test results, breaking occurred in the steel tube base materials, and sound welded joints were confirmed.

(2) Cross tensile test

The cross tensile test piece of the steel tube-diaphragm-steel tube welded part has the shape shown in **Fig. 8(b)**, which was obtained by modifying the No. 1A test piece of JIS Z 2201 "metallic material tensile test pieces". Two pieces respectively of the steel plate and forged diaphragms were tested. The test results are shown in **Table 8**. In all test results, breaking occurred in the steel tube base materials, and sound welded joints were confirmed.

Table 7 Result of flat shape tensile test

Diaphragm	Test piece symbol	0.2% yield strength (N/mm^2)	Tensile strength (N/mm^2)	Breaking position
Forged	TA-1	433	556	Steel tube base material
	TA-2	431	552	Steel tube base material
Plate processed	PA-1	436	568	Steel tube base material
	PA-2	442	568	Steel tube base material

GL = 50mm

(3) All weld metal tensile test

The all weld metal tensile test piece with the shape shown in **Fig. 8(c)** was cut off from the steel tube-diaphragm welded part, and its tension was tested. The number of test pieces were two respectively for the steel plate and forged diaphragms. The test results are shown in **Table 9**. All test pieces showed good performance above the base material standard value.

(4) Charpy impact test

For the Charpy impact test, a test piece was cut off from the surface of the steel tube where the plate thickness reduces to 1/4 as shown in **Fig. 8(d)**, and it was impact-tested. The test temperature was 0°C and the number of repetitions was three. Absorbed energy and percent brittle fracture obtained by the test results are shown in **Table 10**. All impact values exceeded 27 J.

(5) Vickers hardness test

Vickers hardness was measured for the steel tube-diaphragm welded part in a position 2 mm from the surface and back faces of the steel tube and in the position where the thickness of the plate is half as shown in **Fig. 9**. The test load was 98 N, measuring spaces were 0.5 mm for the weld heat-affected zone (HAZ) and the weld interface and 1 mm for the others. The test results are shown in **Fig. 9**. Highest hardness appeared in each measuring position, mainly in the HAZ, and its value was 250 to 260. No softened parts appeared.

Table 8 Result of cross tensile test

Diaphragm	Test piece symbol	0.2% yield strength (N/mm^2)	Tensile strength (N/mm^2)	Breaking position
Forged	TB-1	398	532	Steel tube base material
	TB-2	393	530	Steel tube base material
Plate processed	PB-1	381	528	Steel tube base material
	PB-2	384	527	Steel tube base material

GL = 200mm

Table 9 Result of weld metal tensile test

Diaphragm	Test piece symbol	0.2% yield strength (N/mm^2)	Tensile strength (N/mm^2)	Reduction of area (%)
Forged	TC-1	499	588	71
	TC-2	481	571	71
Plate processed	PC-1	476	571	65
	PC-2	516	604	68

GL = 24mm

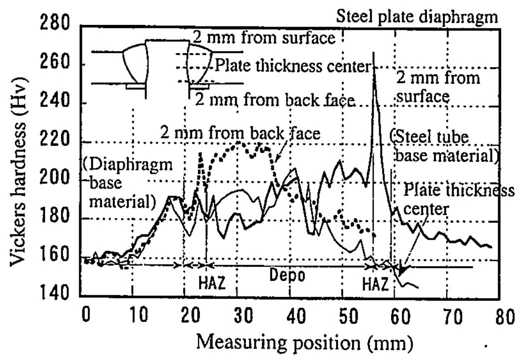

Fig. 9 Vickers test result

Table 10 Result of Charpy impact test (0°C)

Diaphragm	Test piece symbol	Notched position*	Absorbed energy (J)				Percent brittle fracture (%)			
			①	②	③	Average	①	②	③	Average
Forged	TS1	Steel tube side HAZ	107	132	129	123	45	40	50	45
	TS2	Steel tube side bond	105	148	128	127	50	30	30	55
	TS3	Weld metal	64	33	65	54	60	60	70	63
	TS4	Diaphragm side bond	82	72	74	76	60	60	50	57
	TS5	Diaphragm side HAZ	116	64	92	91	25	55	50	43
Plate processed	PS1	Steel tube side HAZ	118	133	140	130	50	35	40	42
	PS2	Steel tube side bond	57	47	69	58	60	55	55	57
	PS3	Weld metal	29	49	30	36	65	65	60	63
	PS4	Diaphragm side bond	101	123	87	104	45	30	55	43
	PS5	Diaphragm side HAZ	233	230	235	233	0	0	0	0

* Corresponding to the position of Fig. 8(d)

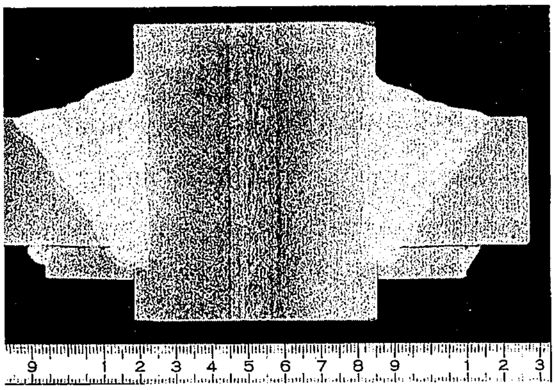

Photo 7 Welded part section macro structure

(6) Macro photograph

The macro section of the steel-diaphragm welded part is shown in **Photo 7**. A good weld was confirmed.

3.3 Concrete filling performance test

To investigate the concrete filling performance of the NS column using the ring-like diaphragms protruding in the steel tube, specimens with various diaphragms in a steel tube with a diameter 600 mm shown in **Fig. 10** were manufactured, and concrete press-fitting was tested. The concrete mix used for the test is shown in **Table 11.**

One week after concrete filling, the steel tubes near the diaphragms and the diaphragms were removed and concrete fill conditions were investigated. The fill conditions are shown in **Photos 8** and **9**. All diaphragms had good concrete fill performance without depending on the existence of tapering for the internal holes, and no difference was observed. For diaphragms spaced 250 mm from each other, good filling performance was confirmed.

3.4 Fabrication example

The NS column has already been employed in several projects, and some examples are shown in **Photos 10** and **11**. In these examples, steel tubes with 1,117.6 mmϕ × 22 mm are used, and diaphragms using plates are the connection parts.

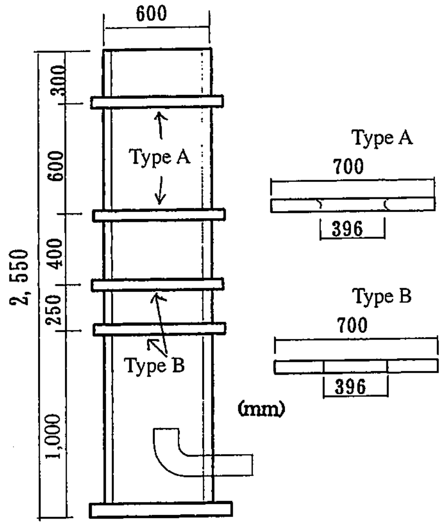

Fig. 10 Specimen for concrete filling performance test

Table 11 Concrete mixing table

W (kg/m³)	C (kg/m³)	W/C	S (kg/m³)	G (kg/m³)	S/a	High performance AE water reducing agent C×(%)	Thickener (kg/m³)
185	463	40	798	861	50	1.5	0.3

Notes 1) Placing time slump flow 41 cm × 41 cm
2) Slump 23.5 cm
3) Air amount 1.6%

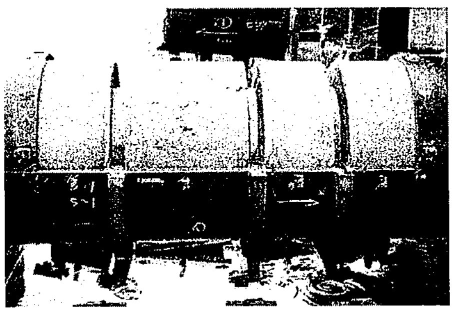

Photo 8 Concrete filling situation (1st and 2nd stages are types B, and 3rd stage is a type A)

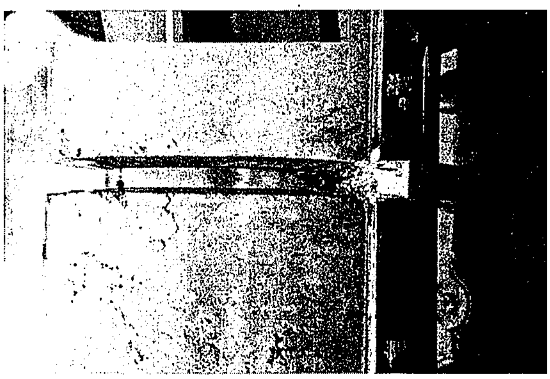

Photo 9 Filling situation in the vicinity of a type B diaphragm

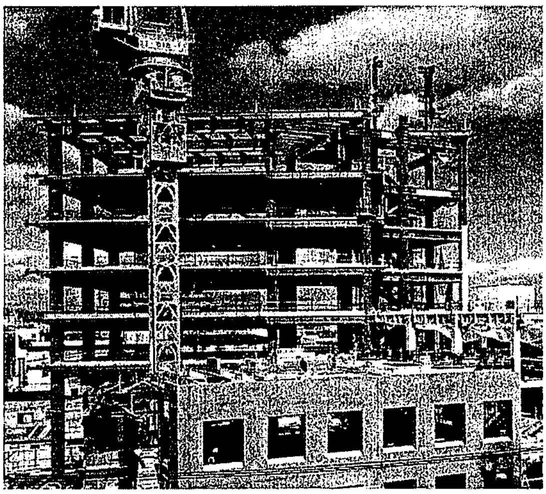

Photo 10 Fabrication example

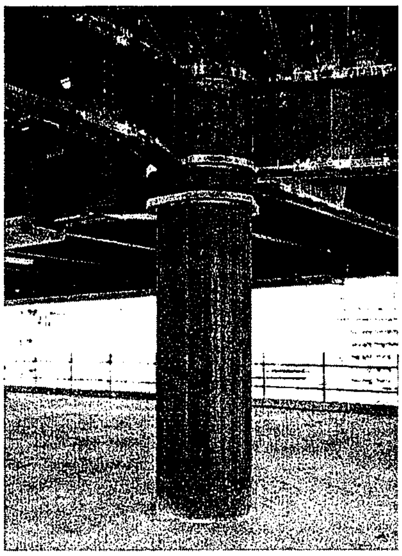

Photo 11 Fabrication example

4. Conclusions

The concrete filled steel tubs have several advantages such as versatile design, and their use has been steadily increasing recently. If a designer decides to employ tubular steel columns, the NS column with standardized connection diaphragms combined with beam members enables simplified design. Since the steel tubes and the diaphragms are welded together at specialized plants, the NS column is a product with assured quality of the welded members. The forged diaphragms and welded part quality of steel tube columns with diaphragms (NS column) were evaluated by the Architectural Center of Japan based on various performance test data described in this report, and the NS column has obtained general approval from the Minister of Construction.

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