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Ultimate Strength of "T"-shaped Connection Sheet Piles for Cellular Sheet Pilings with Straight Web Steel Sheet Piles*

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In cellular sheet piling structures, connection sheet piles, required at the intersection of walls between arc cells and circular cells, are subjected to the most severe stress and deformation conditions among structural components and so they may lead to fatal failures. For the purpose of studying ultimate strength of "T" connection sheet piles, which are used for almost all types of cellular cofferdams in Japan and developing new connection sheet piles with higher strength, a series of two directional simultaneous tensile tests were conducted by using several types of about one-meter-long prototype "T" connection sheet piles. For design purposes, test results obtained were illustrated as interaction curves of ultimate strength at connections concerning hoop tensions in circular cells and arc cells for every structural details, and also estimation methods for ultimate strength of typical types of connections were discussed. Additional tensile tests were also conducted on three types of "T" connection sheet piles for newly developed straight web sheet piles with higher interlock strength than that of conventional ones.

1 Introduction

In cellular sheet pilings, connection sheet piles are required at the intersection of walls between arc cells and circular cells as shown in **Fig. 1**. Usually connection sheet piles for circular cofferdams are either "T" or "Y" sections consisting of a straight web sheet pile to which a sheet pile section is riveted, bolted, welded or connected by a combination of riveting and welding.

Especially, "T" connection sheet piles fabricated with rivets have been conventionally used in Japan. In the design procedure, the rivets on the circular cell and arc cell sides were considered as the ones subjected to tensile axial force and to shearing and bearing force, respectively, and their strength have been checked by using design specification for building structures[1] and/or steel highway bridges[2].

However, as the cell diameter increased, tension axial force acting on the sheet piles (hoop tension) also increased, and consequently, rivet pitches should become very small and, in extreme case, it may become impossible for the sheet pile to secure the required strength due to inadequate net cross section.

From the view point of the fabrication, the decrease in the number of skilled riveters in recent years has made it difficult to assure the quality of the riveted connection itself.

To avoid the above-mentioned design problems, the Japan Port and Harbour Association has recommended the use of standard cross sections of welded or riveted connections as shown in **Fig. 2** as the design conditions on the basis of full-size tensile test results. In case of using these standard cross section, checking for the strength of connection is exempted.

In the present study, attention was paid to the fact that the "T" sheet piles in the cellular structures are simultaneously subjected to tensile force in two directions, i.e., the direction of the circular cell and that of the arc cell. For more economical and exact design and to simulate the actual loading conditions, a series of two directional simultaneous tensile tests was conducted by using conventional 9 types of full-size "T" connection sheet piles with about one meter long. The straight web sheet piles used were **KSP-F** (with web

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** Engineering Division
*** Mizushima Works

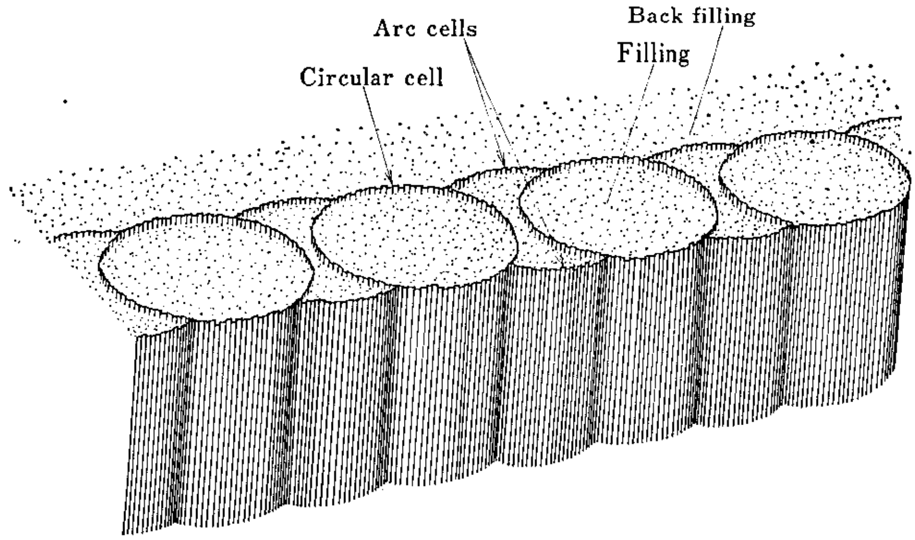


Fig. 1 Circular sheet pile cells

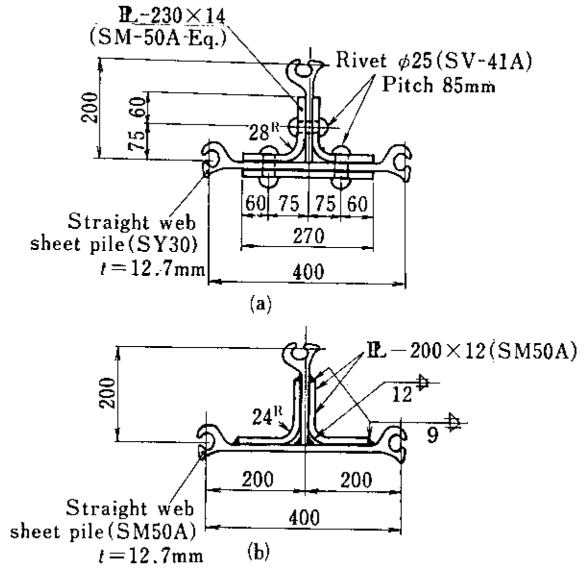


Fig. 2 Cross sections of standard "T" connection sheet piles designated in the standard shown in Reference No. 3

thickness of 9.5 mm) and **KSP**-FA (with web thickness of 12.7 mm), both of which have a guaranteed interlock strength of 400 tf/m.

Furthermore, another series of arc-cell-direction tensile tests was also conducted on 3 new types of "T" connection sheet piles, for the purpose of giving the design data of newly developed high strength straight web sheet piles, **KSP**-FR, with a guaranteed interlock strength of 600 tf/m.

2 "T" Sheet Piles for Straight Web Steel Sheet Piles (KSP–F, FA) with Guaranteed Interlock Strength of 400 tf/m

2.1 Outline of Test

2.1.1 Test specimens

For a combined purpose of manufacture test, a "T" sheet pile of 10 m in full length was produced at Mizushima Works, and cut with a saw into specimens, each about 1 m in length.

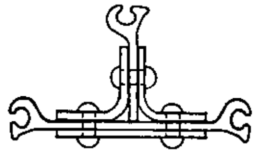
The types of connections of the test specimens included 3 riveted types and 4 welded types, which were based on the standard cross section shown in **Fig. 2**, and 2 high strength bolted (bearing) types made by a connection method considered hopeful in future, giving 9 types in total. **Fig. 3** shows the structural details of the respective types of test specimens.

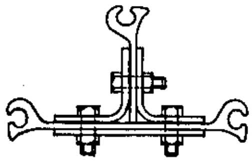
Table 1 shows the mechanical properties and chemical compositions of materials used for the straight web sheet piles **KSP-F**, FA, splice plates, rivets and high strength bolts.

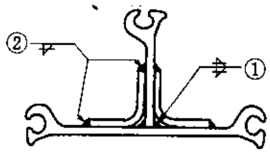
2.1.2 Test method

In general, the "T" connection sheet pile is subjected to simultaneous actions of hoop axial force of the circular cell and that of the arc cell. If the ratio between axial force on the circular-cell side and that on the arc-cell side changes, it is naturally foreseen that the deformation behavior and ultimate strength of the "T" connection sheet pile will also change.

In the present test, therefore, attention was paid to the fact that filling of arc cells was made only after the

Riveted type	Sheet pile		Splice plate		Rivet			Notation
	Type*	Steel grade	Plate thickness (mm)	Steel grade	Dia. (mm)	Steel grade	Pitch (mm)	
	F	SY30	10** (Angle) 6 (Plate)	SS41	ϕ22	SV41A	80	ⓐ
	F	SY30	12	SM50A	ϕ25	SV41A	85	ⓑ
	FA	SY30	14	SM50A	ϕ25	SV41A	85	ⓒ

High strength bolted type	Sheet pile		Splice plate		Bolt			Notation
	Type	Steel grade	Plate thickness (mm)	Steel grade	Dia. (mm)	Steel grade	Pitch (n_B***) (mm)	
	F	SY30	12	SM50A	M22	F10T	150(6) 225(4)	ⓗ
	FA	SY30	14	SM50A	M24	F10T	150(6) 225(4)	ⓘ

Welded type	Sheet pile		Splice plate		Weld condition	Notation
	Type	Steel grade	Thickness of angle (mm)	Steel grade	(Leg length of fillet weld) (mm)	
	F	SY30			① 9	ⓓ
	F	SY30	9	SM50A	① 9 ② 7	ⓔ
	FA	SY30	12	SM50A	① 12 ② 9	ⓕ
	FA	SM50A	12	SM50A	① 12 ② 9	ⓖ

Remarks: * Web thickness F: 9.5 mm, FA: 12.7 mm
** Thickness of hot rolled angles L-100×100t
*** n_B : Number of bolts

Fig. 3 "T" connection sheet pile specimens

filling of circular cells was completed; and while a certain axial force was being applied to sheet piles on the circular cell side, gradually increased axial force was loaded on sheet piles of the arc cells, and the ultimate strength and deformation behavior of the connection were investigated.

Further, for design purposes, test results obtained were illustrated on the graphs as interaction curves of ultimate strength at connections concerning hoop tensions in circular cells and arc cells.

In order to perform simultaneous loading in the circular cell direction and arc cell direction, a loading equipment was employed which consisted of a 1 000 tf structural testing machine and special loading grips on

Table 1 Mechanical properties of tested materials for "T" connection sheet piles with interlock tention strength of 400 tf/m at minimum

Material			Yield strength (kgf/mm²)	Tensile Strength (kgf/mm²)	Elongation (%)
Steel sheet pile F	SY 30	$t_w=9.5$	44	60	21
	SM 50A		44	58	27
Steel sheet pile FA	SY 30	$t_w=12.7$	40	61	23
	SM 50A		43	57	26
Splice plate	SS 41	$t=6$	30	45	31
		$t=9$	38	53	24
	SM 50A	$t=12$	41	56	25
		$t=14$	41	56	25
Rivet	SV 41	$\phi 22$	29	45	33
		$\phi 25$	30	47	32
High-strength bolt	F 10T	M22	103	109	18
		M25	105	112	17

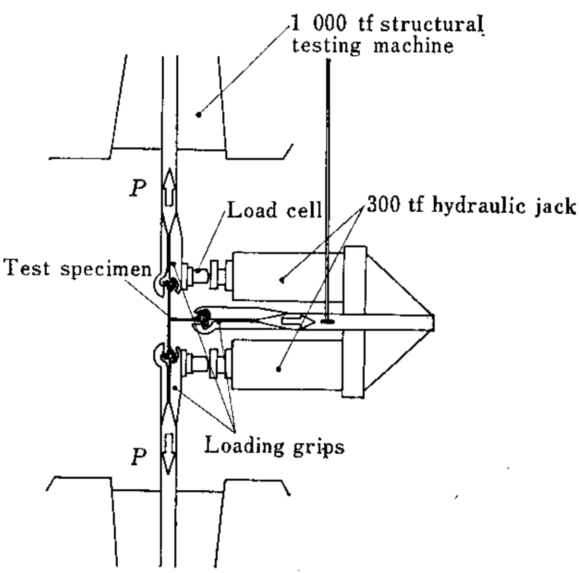


Fig. 4 Loading equipment

which two 300 tf hydraulic jacks were mounted, as shown in **Fig. 4**.

Photo 1 shows the test set-up for 2-dimensional simultaneous tensile tests.

2.2 Outline of Test Results

2.2.1 Ultimate strength

While maintaining the circular-cell-side axial force, P, at prescribed preset load (150 tf/m and 300 tf/m in general case), arc-cell-side axial force, T, was gradually increased until the connection was fractured. Provided that when only the circular-cell-side axial force is applied ($T=0$), one piece each of the straight web sheet pile was inserted over and below the "T" sheet pile to be tested, so that failures at interlocks of steel sheet piles would also be made possible. Then, force was applied only by the 1 000 tf structural testing machine, without fitting the arc cell direction loading grip, and the interlock strength was examined.

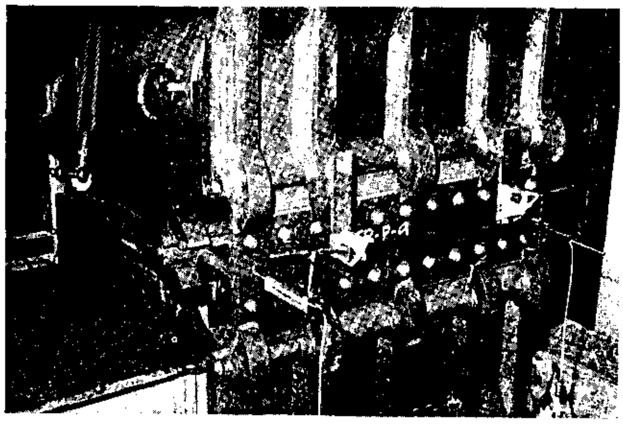


Photo 1 Test set-up for two directional simultaneous tensile tests

Fig. 5 shows the results of the tensile tests as interaction curves concerning the ultimate strength of the circular-cell-direction axial force and arc-cell-side axial force.

(1) Riveted "T" connection type

In the riveted "T" connection type, the ultimate strength of the connection sheet pile is not greatly

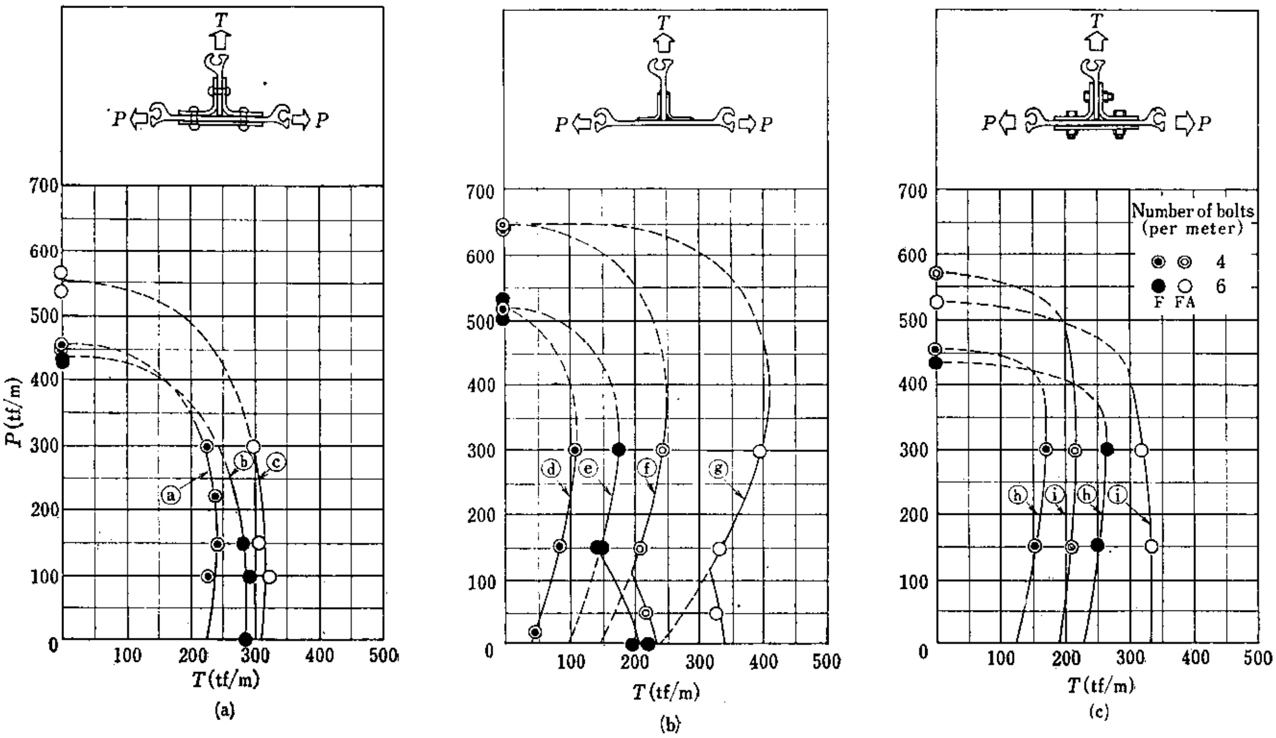


Fig. 5 Interaction curves of hoop tension in circular cells and arc cells concerning ultimate strength of "T" connection sheet piles

dependent on the circular-cell-side axial force, *P*, but is governed only by the shearing strength of rivets on the arc cell side. In design, it was considered that low allowable stress of tensile rivets would pose problems in the riveted tee connection type, but in the present test, it was found that no tensile fracture of rivets on the circular cell side was observed, thereby indicating that the riveted "T" connection type had stable high strength.

When determining the standard cross section in accordance with the standards of the Japan Port and Harbor Association, the maximum cell radius ratio (radius of arc cell/radius of circular cell) to be considered was 2/3. A minimum ultimate strength of 267 tf/m (400 tf/m × 2/3) and over should be guaranteed for an arc cell with this maximum cell radius ratio. This strength can be obtained by arranging rivets with a diameter of 25 mm to a pitch of 85 mm, regardless of the web thickness of the straight web sheet piles. Further, it was found that the conventional type tee connection sheet piles ⓐ, which were reinforced with angles on which rivets having a diameter of 22 mm and a pitch of 80 mm were arranged as shown in **Fig. 5** (a), also had a minimum ultimate strength of 220 tf/m.

The above-mentioned ultimate strength, however, can be obtained only when the steel materials of sheet piles and splice plates are selected in such a way as to have bearing strength higher than the double shear strength of the rivets. Then, in the case that SV41 is used as the rivet material under the present test conditions, it is necessary to select steel materials one grade higher, i.e., 50 kgf/mm^2 or over, for the sheet piles and splice plates.

(2) Welded "T" connection type

The ultimate strength of the welded "T" connection type varies widely depending upon its material, thickness of splice angle plates, web thickness of steel sheet piles (out-of-plane stiffness of web), etc., as shown in **Fig. 5** (b). Particularly, when no reinforcement with splice angle plates is employed, only extremely low ultimate strength was obtained as shown in ⓓ. It was found that the ultimate strength of the welded "T" connection was dependent to some extent on circular-cell-side axial force, *P*, contrary to that in the riveted "T" connection. This is due to the fact, as will be explained later, that the fracture of the welded "T" connection arises from strain concentration on the weld toe due to out-of-plane bending of the circular-cell-side sheet piles. Namely, as the circular-cell-direction axial force increases, the out-of-plane stiffness of the circular-cell-side sheet piles shows an apparent increase. As a result, the bending strain quantity of the weld toe decreases, and ultimate strength against the arc-cell-direction tension will increase. However, if the circular-cell-direction tensile force exceeds the yield axial force of the circular-cell-side sheet pile webs, the apparent increase in the out-of-plane stiffness disappears, and thus the arc-cell-direction tensile strength shows a maximum value in the vicinity of this load. If this circular-cell-direction axial force further increases, the circular-cell-direction tensile axial strain at the weld toe will exceed strain caused by out-of-plane bending, thereby greatly reducing the arc-cell-direction tensile strength. On the other hand, if reinforcement with splice angle plates is employed, the out-of-plane deformation of the circular-cell-side sheet piles will be constrained, thereby great increase of the ultimate strength of the connection can be obtained. Particularly at the area where circular-cell-direction axial force is smaller, that is, where the out-of-plane deformation of the circular-cell-side sheet piles is larger, the angles also deform in a flat plate and exhibit tension-diagonal effects, thereby initiating a marked increase in ultimate strength. The difference in material of steel sheet piles (SY30 and SM50A) exercised great effects on the ultimate strength of the connection, and in ⓖ for which SM50A material having excellent weldability was used, the improvement in the ultimate strength of the connection was most noticeable.

(3) High strength bolt connection (bearing-type connection)

In the high strength bolt connection, the bearing-type connection was advantageous, when only the ultimate strength is discussed. Such a case is basically considered to be a riveted connection employing high strength material. In the concept of general bearing-type high strength bolt connection, frictional strength is expected from it during normal load, but for emergency load such as earthquakes, not only frictional strength but also shearing strength of the bolts and bearing strength of splice plates are expected[4]. As a result, when the friction-type connection shifts to the bearing-type connection, sliding occurs, which arises from the difference between the axial diameter of the bolt and the hole diameter of the splice plate. This sliding quantity is obtained as the limit of clearance from the allowable limit of the structure, and in order to minimize the sliding quantity, methods are employed such as using special bolts, e.g. drive-in bolts. In building construction, the degree of redundancy is high and a minute sliding of the joint is liable to disturb the balance in the force of the entire structure. In the steel sheet pile cellular structure, it is considered that the structure itself has a large deformability and the out-of-plane deformation of the "T" connection sheet piles is comparatively larger. For the present test specimens, therefore, no special bolts were used in order to suppress the sliding, but ordinary high strength bolts were used after exercising control on their hole diameters and hole slipping in conformity with the Specification for Highway Bridges[2]. Regarding the number of bolts, 4 and 6 bolts per unit length (1 m) were used for steel sheet piles F (t_w=9.5 mm) and FA (t_w=12.7 mm), respectively, taking into consideration the fact that the tensile strength of high strength bolt material (F10T) is about 2.5 times higher than that of rivet material (SV41A). Bolts were fastened by an electric wrench made by Mitsubishi Electric and according to the "Slope Detection Method[5]", but since no frictional strength was expected here, no blasting on the connection surface was performed. **Fig. 5** (c) shows the test results. As can be seen from the figure, FA which has thicker splice plates and higher out-of-plane stiffness reveals that arc-cell-direction connection strength T_{max} is not affected by the magnitude of axial force, *P*, on the circular-cellside, and connection strength of about 210 tf/m and about 325 tf/m for 4 bolts/m and 6 bolts/m can be obtained, respectively.

For the F-type sheet pile, which has a larger out-of-plane deformation than FA, the increase in the connection strength caused by the increase in circular-cell-side axial force, *P*, is noticeable. This trend is found to be conspicuous when the F-type high strength bolt connection is compared with the F-type riveted connection (**Fig. 5** (a)), and the high strength bolted connection, for this type of sheet piles may be said to be similar to that of the welded type connection (**Fig. 5** (b)). The reason for this is considered as follows: In the riveted "T" connection, additional bending deformation of the rivets, which is caused by out-of-plane bending of the circular-cell-side steel sheet piles is completely absorbed by the elongation of the rivet material, thereby showing no decrease in shear strength; whereas in the high strength bolted "T" connection, high strength bolt axial force is introduced at the initial stage, and moreover, the elongation of the high strength bolt material is not sufficient to cope with additional bending to the bolts. As the result, the ultimate strength decreases at the area having greater out-of-plane deformation, namely, within the range of smaller *P* value as in welded "T" connection.

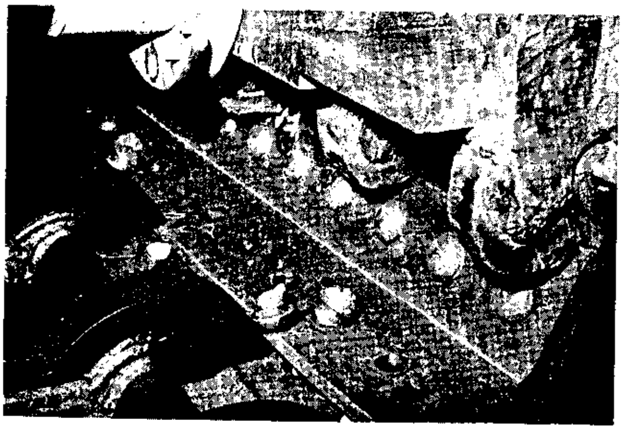


Photo 2 Typical failure mode of riveted "T" connection sheet piles subjected to two-directional tension

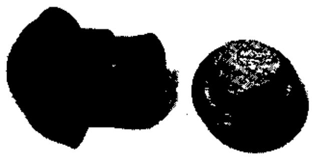


Photo 3 Shear failure of rivet

2.2.2 Failure modes

(1) Riveted connection type

For the riveted "T" connection, ultimate strength is governed entirely by the shear strength of arc-cell-side-rivets. **Photo 2** and **3** show the tested "T" connection sheet piles and its rivet after failure, respectively. In general when "T" connection sheet piles are designed to be rivet-connected, it is assumed that the circular-cell-side rivets are tensile rivets and arc-cell-side rivets are shearing or bearing ones, and the strength of the connections is checked by using a smaller value of the two types of rivets. **Table 2** shows all types of allowable stress applicable to riveted connections of steel sheet piles. When these values are used in designing "T" connection sheet piles in order to obtain the guaranteed interlock strength of 400 tf/m, it is found that strength is insufficient. And no valid design based on the allowable stress will become possible, even if tensile rivets on the circular cell side are driven in the minimum pitch, on the assumption that the allowable tensile strength of straight web steel sheet pile is 150 tf/m, and the radius of the arc cell is 2/3 that of the circular cell[6]. For the cellular structure with straight web steel sheet piles, the allowable tensile strength is determined by allowing a certain safety factor

Table 2 Allowable stress of riveted connection[3]

Stress category	Grade of steel plate	Grade of rivet steel	Type of rivet	Allowable stress (kgf/cm^2)
Axial tension		SV34	Shop rivet	550
			Field Rivet	490
		SV41A	Shop rivet	700
			Field rivet	630
Shear	SY24	SV34, SV41A	Shop	1 100
			Field	900
	SY30	SV41A	Shop	1 500
			Field	1 200
	SY40 SM50, SM50Y SM53, SMA50	SV41A	Shop	1 500
			Field	1 200
Bearing	SY24	SV34, SV41A	Shop	2 400
			Field	1 900
	SY30	SV41A	Shop	3 000
			Field	2 400
	SY40 SM50, SM50Y SM53, SMA50	SV41A	Shop	3 200
			Field	2 600

on the interlock strength of 400 tf/m specified in JIS[7], and thus it is considered necessary to guarantee that a certain safety factor is maintained against failure. One of the objectives of the present test is to check this safety factor with respect to failure. In order to perform general safety checking, it is necessary to examine which one of the failure modes explained in this section is the critical failure mode that gives the minimum ultimate strength. **Fig. 6** shows 4 conceivable failure modes. Now, let us denote the diameter of the rivet hole by d' (mm), the tensile strength of the rivet by σ_{UR} (kgf/mm^2), its shearing strength by $\tau_{UR} = \alpha \cdot \sigma_{UR}$ (kgf/mm^2), the web thickness of the steel sheet pile by t_W (mm), its tensile strength by σ_{US} (kgf/mm^2), the bearing strength of the rivet by $\sigma_{bR} = \beta \cdot \sigma_{UR}$ (kgf/mm^2), the pitch of rivets on the circular cell side by P_1, that on the arc cell side by P_2 (mm), and the ratio between the tensile strength of the steel sheet pile and that of the rivet (strength ratio) by $\gamma = \sigma_{US}/\sigma_{UR}$. Since the numbers of steel sheet piles per unit length (1 m) are, on the average, $n_1 = 2 \times 1\,000/P_1$ on the circular cell side and $n_2 = 1\,000/P_2$, on the arc cell side, the rivet strength T_T is given as follows:

(Case 1) $$T_T = n_1 \times \frac{\pi d'^2}{4} \times \sigma_{UR} = 500 \times \frac{\sigma_{UR} \cdot \pi d'^2}{P_1} \text{ (kgf)}$$

The shearing strength of the rivet on the arc cell side T_{SR} is given as follows:

(Case 2) $$T_{SR} = n_2 \times 2 \times \frac{\pi d'^2}{4} \times \tau_{UR} = 500 \times \frac{\alpha \cdot \sigma_{UR} \cdot \pi d'^2}{P_2} \text{ (kgf)}$$

The bearing strength of the rivet on the arc cell side, T_B, is given as follows:

(Case 3) $$T_B = n_2 \times d' \cdot t_W \times \sigma_{bR} = n_2 \times d' \cdot t_W \times \beta \cdot \sigma_{UR} = \frac{1\,000 \times \beta \cdot d' \cdot t_W \cdot \sigma_{UR}}{P_2} \text{ (kgf)}$$

The shear strength of the arc-cell-side sheet pile, T_b in case of failure at the hole edge, is given by the following equation:

(Case 4) $$T_b = n_2 \times 2 \times e \cdot t_W \cdot \tau_{US} = \frac{2\,000 \times \alpha \cdot e \cdot t_W \cdot \sigma_{US}}{P_2} \text{ (kgf)}$$

where e is the distance from the rivet center to the plate edge as shown in **Fig. 6.** It is said that shearing strength of steel material τ_U is generally $1/\sqrt{3}$ to 0.5 of tensile strength σ_U[2]. On the other hand, the ratio α between the mean shearing strength and tensile strength which is observed in the results of the simplified shearing test on the riveted con-

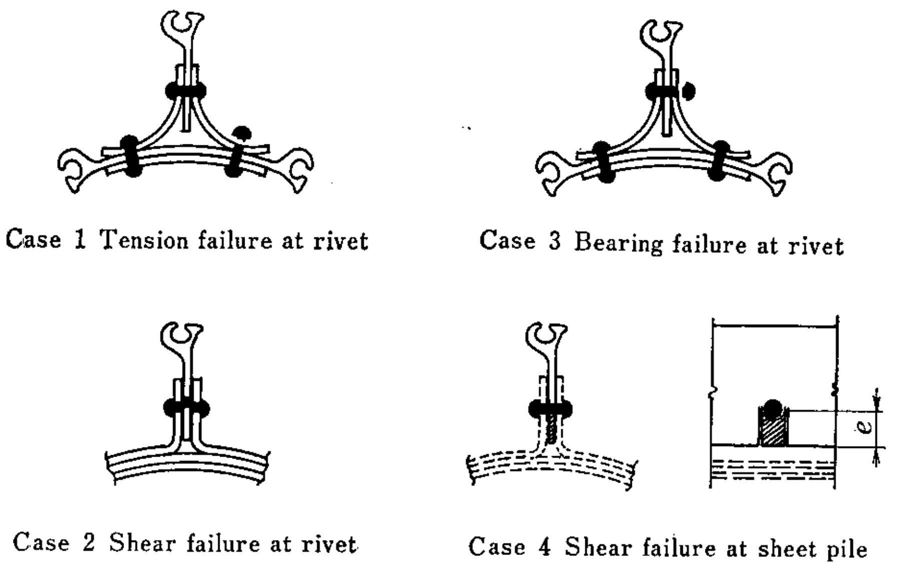


Fig. 6 Typical failure modes of riveted "T" connection sheet piles

nection[8], shows the value of 0.72 to 0.89 and sometimes shows a 20 to 50% higher value. In this paper, "$1/\sqrt{3}$" is used as a general value, α. For the fracture caused by bearing, it is considered that no anomaly will appear until the base metal yields. Moreover, since fracture caused by bearing is a sort of compressive fracture, judgment on it is very difficult. If the value β is estimated by referring to the ratio between the allowable tensile stress and allowable bearing stress of structural, steel material, it will be a value of about 4.

On the basis of the above-mentioned assumption, and also by assuming that the ultimate strength of the "T" connection is dependent on the circular-cell-side axial force, fracture becomes all shearing fracture, the ultimate strength of the test specimens is calculated as $T_{max} = 236$ tf/m for sepcimen ⓐ, $T_{max} = 293$ tf/m for specimen ⓑ, and $T_{max} = 293$ tf/m for specimen ⓒ. Now, it was found from **Fig. 5** (a) that the average strength of these connection types were 233 tf/m, 289 tf/m and 317 tf/m, respectively, which agreed with the respective calculated values with errors below 10%. This drop in error was maximum at the calculated value of strength for the type ⓐ having the minimum out-of-plane stiffness. In order to obtain the strength equal to the calculated value, the drop in strength due to deformation must be prevented by increasing the out-of-plane stiffness of the circular-cell-side sheet piles to a certain extent.

The reason for this is thought to be as follows: in case that constraint on the out-of-plane deformation is small, the arc-cell-side rivets come to be subjected to tensile force, which was induced with the extreme deformation of the splice plates, in addition to the shearing force, and, as a result, the pure shearing condition of the rivet can not be satisfied. Next, it was found that the tensile rivets, which gave critical allowable stress in the design calculation, still had sufficient margin of strength, because no fracture of tensile rivets occurred in the present test. This may be attributable to the fact that although the tensile rivets for the tee connection sheet piles are subjected to tension and shearing simultaneously owing to the deformation of the steel sheet piles, the rivets indicate sufficient deformability owing to the elongation of the rivet material and also to the ultimate strength which is approximate to the axial-direction tensile failure strength of the rivets.

(2) Welded connection type

Photos 4 and **5** show the welded "T" connection type specimens with and without splice angles after fracture, respectively. As shown in **Fig. 7**, all the failures of welded "T" connection types originated from the crack initiating at the weld toe on the circular cell side of the fillet weld between the sheet piles on the circular cell side and those on the arc cell side. This crack occurred because the bending strain caused by out-of-plane deformation of the sheet piles on the circular-cell side was concentrated on the weld toe[9]. This failure type of the weld is closely related to the degree of strain concentration near the weld toe and the deformability of the welded joint[10]. If only the deformability at this position is sufficiently provided, the weld

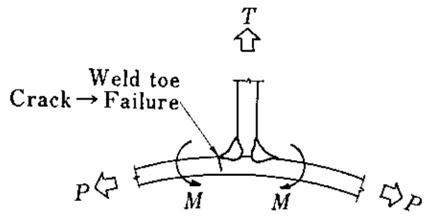


Fig. 7 Failure mode of welded "T" connection sheet piles

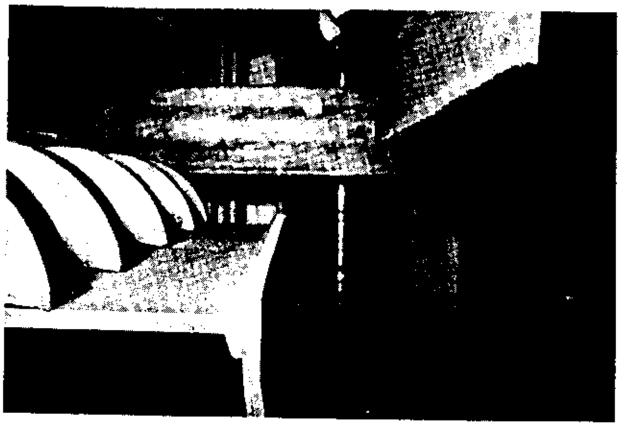


Photo 4 Typical failure mode of welded "T" connection sheet piles without splice plates

Photo 5 Typical failure mode of welded "T" connection sheet piles with splice plates

failure is, in ideal terms, governed by the tensile strength of the arc-cell-side sheet piles or shearing strength of the fillet weld. In general, previous studies[9-11] reported that the bending deformability of weld was comparatively small. In the present test, the welded tee connection sheet piles reinforced with splice angles also generated a weld toe crack and fractured when load of about 50% (SY30) to 60% (SM50A) of the tensile yield load of the steel sheet piles was applied. However, the standard cross section (see **Fig. 2** (b)) stipulated by The Japan Port and Harbour Association using SM50A fully satisfies the required ultimate strength, i.e., 267 tf/m, for the maximum cell diameter ratio, 2/3. Therefore, if the material of steel sheet piles having good weldability (i.e., good elongability) is used, no problem will occur in ultimate strength. In order to improve the ultimate strength of welded type "T" connection sheet piles, it is necessary to delay the initiation of a crack caused by concentration of bending strain on the fillet weld toe as mentioned above, and the following methods are conceivable to achieve such a delay:

(a) Using materials having excellent fracture elongation at the heat affected zone of base metal at the weld toe in order to prevent initiation of a macro-crack caused by concentration of bending strain.

(b) Minimizing the flank angle, θ, of the weld toe and obtaining smooth weld toes free of undercut and overlap.

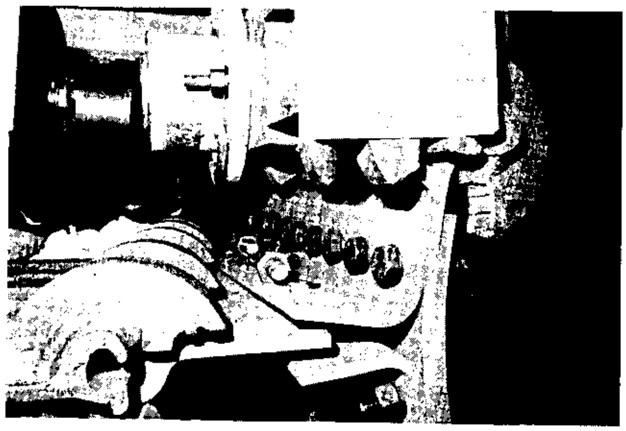
(c) Using backing stiffeners or making a structure with increased efficiency of coaction between splice angles and sheet piles, in order to increase the out-of-plane stiffness and to decrease the strain of circular-cell-side steel sheet piles against the arc-cell-side tensile load.

(3) High strength bolted connection type

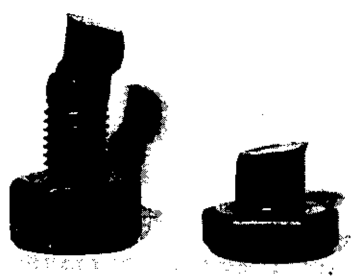
In the case of riveted "T" connection, the ultimate strength of the connection was governed entirely by the shear fracture of rivets, even if they were arranged in the minimum standard pitches, because the strength of the rivet itself is lower than that of the steel sheet pile. In the case of the high strength bolted connection, however, different fracture modes from that of riveted connections appears because bolt strength is high. They are shear fracture from bolt holes on the steel sheet piles (see **Fig. 6**, Case 4) or tensile fracture starting from the base material from which the hole portions have been removed. In the present test, F-type test specimens with web thickness of 9.5 mm —to which a circular-cell-side axial force of 300 tf/m (both for cases having 4 bolts/m and 6 bolts/m) and of 150 tf/m (4 bolts/m) were subjected,—developed base-material-side fracture as shown in **Photo 6** (shear fracture starting from bolt hole). The bolts after this testing showed great shear deformation, thereby indicating that the combination of material strength values in the present test lay on the border separating the failure mode Cases 3 and 4 shown in **Fig. 6.** The shear failure strength, T_{SS}, from the hole of the sheet pile can be obtained, as in the case of riveted tee connection steel piles, as follows:

$$T_{SS} = n_B \times 2 \cdot e \cdot t_W \cdot \tau_{US}$$
$$= 2 \cdot \alpha \cdot n_B \cdot e \cdot t_W \cdot \sigma_{US} \text{ (kgf/m)}$$

where n_B is the number of bolts (pcs/m). Now if the value of $1/\sqrt{3}$ is assumed for α, values T_{SS} = 155 tf/m (n_B = 4) and T_{SS} = 233 tf/m (n_B = 6) can be calculated for the F-type. On the other hand, the α value of the high strength bolt was also alleged to be about $1/\sqrt{3}$[4]. Now if it is assumed



(a)



(b)

Photo 6 Typical failure mode of high-strength bolted "T" connection sheet piles (a) and shear failure of high-strength bolts (b) that $\alpha = 1/2$ in the high strength bolted tee connection sheet piles, taking into consideration its special structural characteristics that bending is unavoidably applied on the bolt head, its double shear strength, T_{SB}, is given by the following equation:

$$T_{SB} = n_B \times 2 \times \frac{\pi d^2}{4} \times \tau_{UB}$$

$$= \frac{\pi d^2}{4} \times n_B \times \sigma_{UB} \text{ (kgf/m)}$$

where d denotes the diameter of the bolt. By using the above equation, followings are obtained.

$$T_{SB} = 166 \text{ tf/m } (n_B = 4),$$

$$T_{SB} = 250 \text{ tf/m } (n_B = 6)$$

The calculation of the above equation makes it possible to infer that shear failure of the base-material holes is predominant. Bolt failure occurred only in the case of F-type ($n_B = 4$) ⓖ having a circular-cell-side axial force of $P = 150$ tf/m. This may be attributable to the fact that since the out-of-plane deformation of the circular-cell-side sheet piles is larger, bending applied to the above-mentioned bolt head became larger, thereby lowering the α value below the assumed value of 1/2. For the FA-type, $T_{SB} = 202$ tf/m ($n_B = 4$) and $T_{SB} = 303$ tf/m ($n_B = 6$) were obtained for $T_{SS} = 211$ tf/m ($n_B = 4$) and $T_{SS} = 317$ tf/m ($n_B = 6$), respectively, and all the bolts will develop shear failure, thereby giving good agreement with test results. As mentioned above, by estimating the shear strength at 1/2 of the tensile strength for high strength bolts and at $1/\sqrt{3}$ of the tensile strength for steel sheet piles, the ultimate strength of high strength bolt (bearing) "T" connection sheet piles can be calculated. Then, on the basis of nominal tensile strength (minimum guaranteed strength) when F8T and F10T high strength bolts are respectively used, the required number of bolts can be calculated as shown in **Table 3**. This table indicates that high strength bolted tee connection is much more effective than the riveted (SV41) "T" connection for preventing decrease in ultimate strength caused by hole exclusion on the circular cell side sheet piles and for reduction in the number of rivets or bolts.

3 "T" Sheet Piles for Straight Web Steel Sheet Piles (KSP-FR, FX) with Guaranteed Interlock Strength of 600 tf/m

3.1 Outline of Test

3.1.1 Test specimens

As the cell diameter increases, the conventional straight web sheet piles with interlock strength of 400 tf/m cause insufficient ultimate strength in design, as mentioned above; thus new straight web sheet piles (FR, FX) have been developed which can guarantee an interlock strength of 600 tf/m and over. In order to apply such sheet piles to cellular structures, it is necessary to guarantee the ultimate strength of 400 tf/m and over for the arc-cell-direction connection of the tee sheet piles, assuming that the arc-cell-diameter is 2/3 and under of circular-cell-diameter in the same way as before. In view of the above, 3 types of connection-detail test specimens were developed by referring to the failure modes of tee connection sheet piles mentioned in the previous Section, as follows: ① The rivet and welding combination type as shown in **Fig. 8** in which coaction of steel sheet pile webs and splice angles is enhanced and out-of-plane deformation is constrained, thereby anticipating improvement in the "T" connection strength, ② plug weld type and ③ wavy-edged splice welding type. For sheet piles, the High Interlock Strength Straight Web Steel Sheet Piles; **KSP**-FR having a guaranteed interlock strength of 600 tf/m and over were used. For steel grades, SY30 and SM50A were used for the rivet and welding combination type, SY30 for other 2 types.

Table 3 Required number of rivets and high-strength bolts for "T" connection sheet piles (per meter)

		Minimum tensile strength (kgf/mm^2)	Estimated shear strength (kgf/mm^2)	Steel sheet pile	Required number (Per meter)	Reduction of area by drilling holes (%)
Rivet	SV41(ϕ22)	41	23.7	F(SY30)	15	34.5
High strength bolt	F 8T(M22)	80	40.0	〃	9	20.7
〃	F 10T(M22)	100	50.0	〃	7	16.1
Rivet	SV41(ϕ25)	41	23.7	FA(SY30)	12	31.2
High strength bolt	F 8T(M24)	80	40.0	〃	8	20.0
〃	F10T(M24)	100	50.0	〃	6	15.0

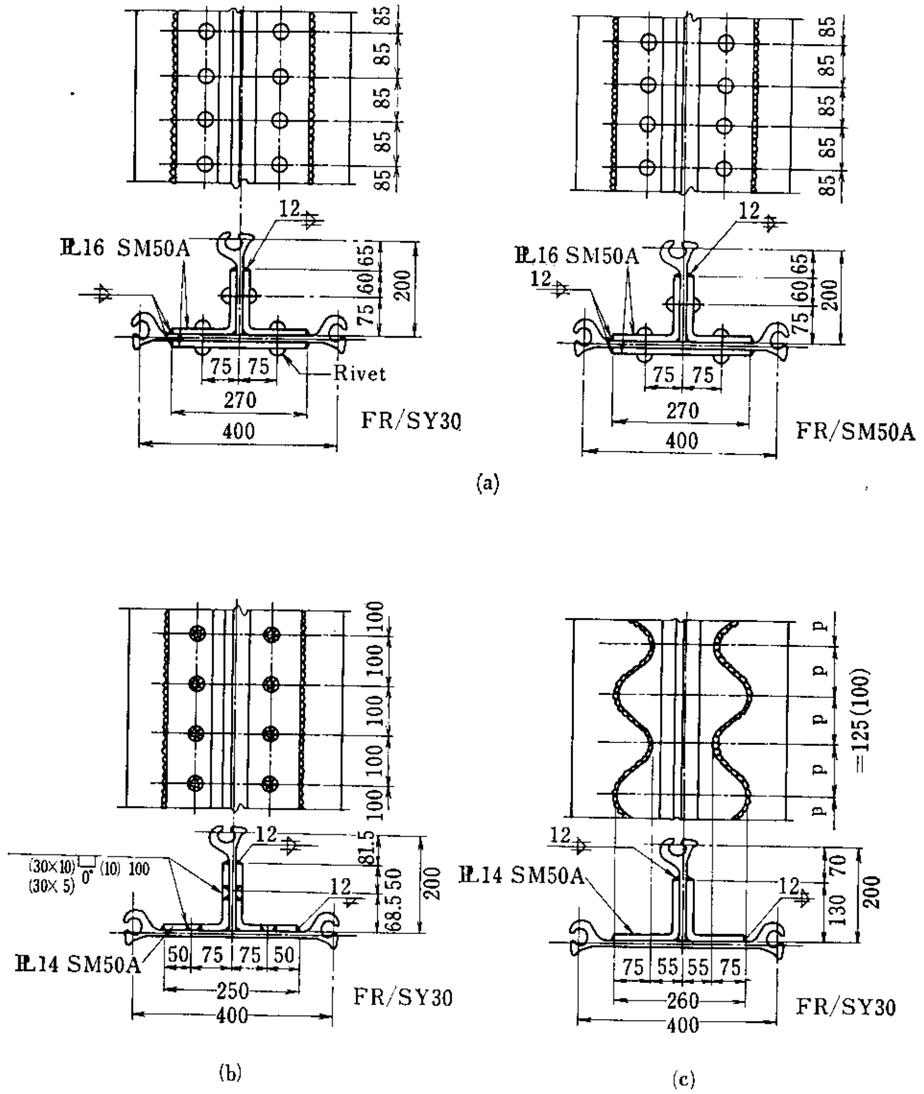


Fig. 8 Cross sections of "T" connection sheet pile specimens for straight web sheet piles with high interlock tension

Major structural characteristics of the 3 types are explained below.

(1) Rivet and welding combination type
Rivets are used for achieving coaction of splice angles and steel sheet piles, and ultimate strength is improved by welding splice angles to the steel sheet piles.

(2) Plug welding type
To avoid the decrease in ultimate strength due to rivet hole exclusion in the rivet and welding combination type, rivets are replaced by plug welds, thereby achieving coaction of splice angles and steel sheet piles in order to reduce man-hours required for riveting.

(3) Wavy-edged splice welding type
The above-mentioned concept of the plug welding type is further advanced, and splice angles whose edges are gas-cut into wavy-tooth shapes are continuously welded along the edges of the steel sheet piles, thereby achieving improvement in ultimate strength due to coaction of angles and steel sheet piles, and an increase in the welding length. Since changes in wave pitches are considered to affect the ultimate strength, the wave length was varied to 200 mm and 250 mm. **Table 4** shows the mechanical properties of sheet piles, splice plates and rivets which were used in the test specimens.

Table 4 Mechanical properties of tested materials for "T" connection sheet piles with minimum interlock tension of 600 tf/m

Material			Yield strength (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)
Sheet pile FR	SY30	t_W=12.7	37	58	23
	SM50A		42.3	57.1	26
Splice plate	SM50A	t=14, 16	42.9	55.6	25
Rivet	SV41	ϕ 25	28	43	34

3.1.2 Test method

The present test was primarily aimed at developing "T" connection sheet piles for the high interlock strength straight web steel sheet piles which can ensure a minimum tensile strength in the arc-cell-direction of 400 tf/m. Therefore, no 2-direction simultaneous tensile test was performed, but separate 2 single-direction tensile tests were performed by using separate tensile grips for tension in the arc-cell-direction and that in the circular-cell-direction as shown in **Fig. 9**. Dummy steel sheet piles were inserted between the tensile grip and "T" specimens which were made from the same lot as "T" sheet piles, so that failure at interlocks might occur when the connection strength of sheet piles is higher than the interlock strength.

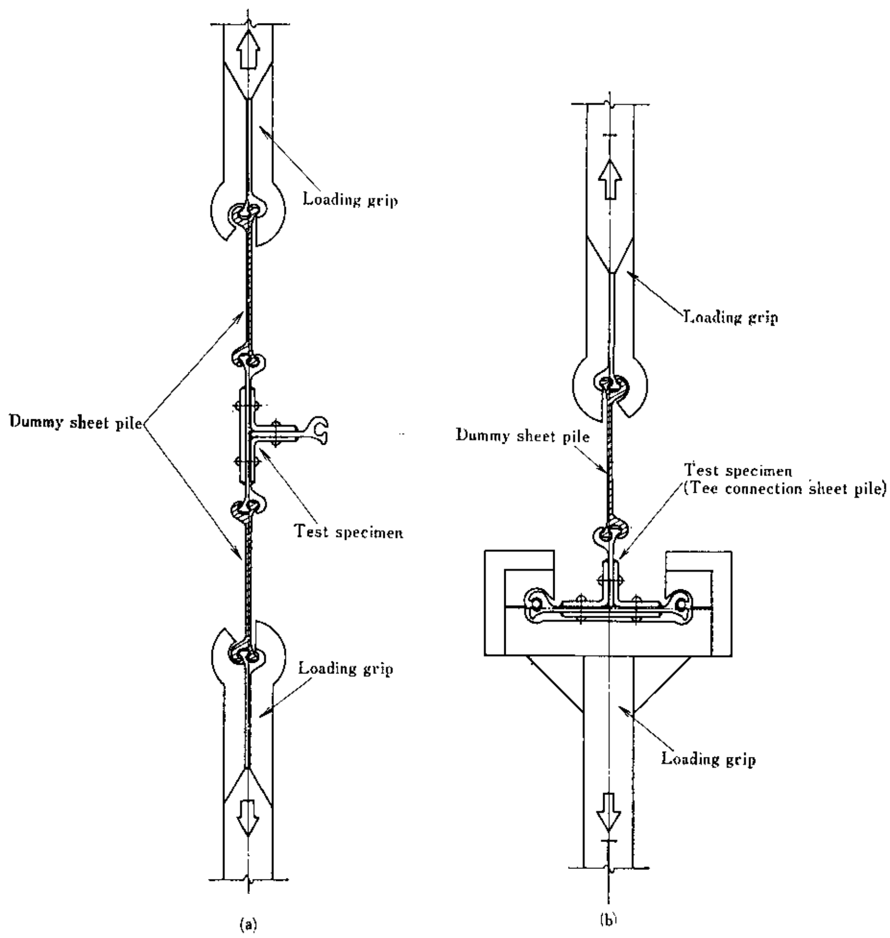


Fig. 9 Testing method for "T" connection sheet pile specimen consisted of straight web steel sheet piles with high interlock tension

3.2 Test Results

The results of the tensile test are summarized in **Table 5**. **Photos** 7 to 9 show typical failure modes of the respective types. As can be seen from the table, the required arc-cell-direction tensile minimum strength of 400 tf/m has been satisfactorily obtained except the plug welding type with a leg length of 5 mm and part of the plug welding type with a leg length of 10 mm.

The SM50A (material of the rivet and welding com-

Table 5 Test results of "T" connection sheet piles for straight web sheet piles with high interlock tension (KSP-FR)

Connecting method			Combination of riveting and welding Fig. 8(a)		Plug welding Fig. 8(b)		Welding with wavy-edged splice Fig. 8(c)	
Material			SY30	SM50A	SY30		SY30	
Loading direction	Arc cell direction	1	600 tf/m	563 tf/m	1) 415 tf/m	2) 349 tf/m	3) 530 tf/m	4) 476 tf/m
		2	711	568	408	344	497	480
		3	674	595	386	342	481	461
		4	671	676	426	360	—	497
		Av.	664	601	409	349	503	479
	Circular cell direction	1	775 tf/m	752 tf/m	1) Plug welding with leg length of 10 mm 2) With leg length of 5 mm		3) Wave length of splice plate : 200 mm 4) Wave length of splice plate : 250 mm	
		2	772	783				
		3	764					
		Av.	770	768				

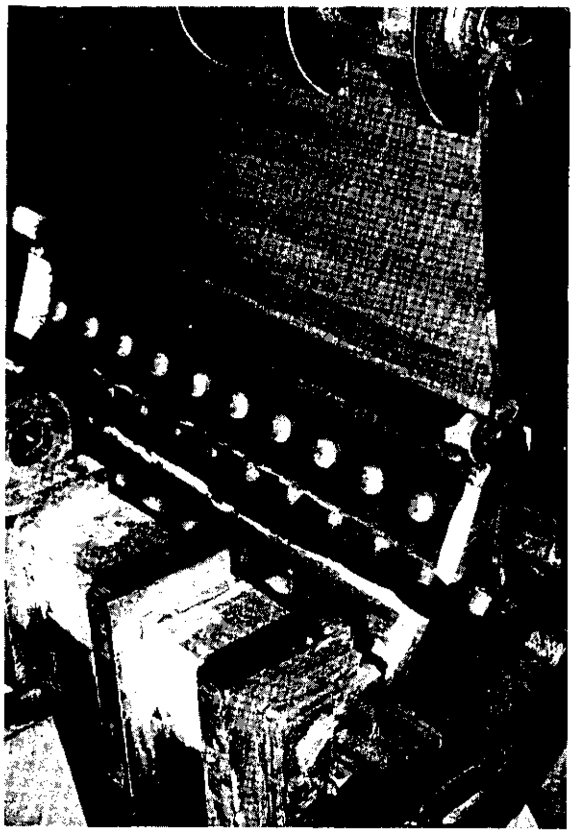


Photo 7 Typical failure mode of "T" connection sheet piles connected by a combination of riveting and welding

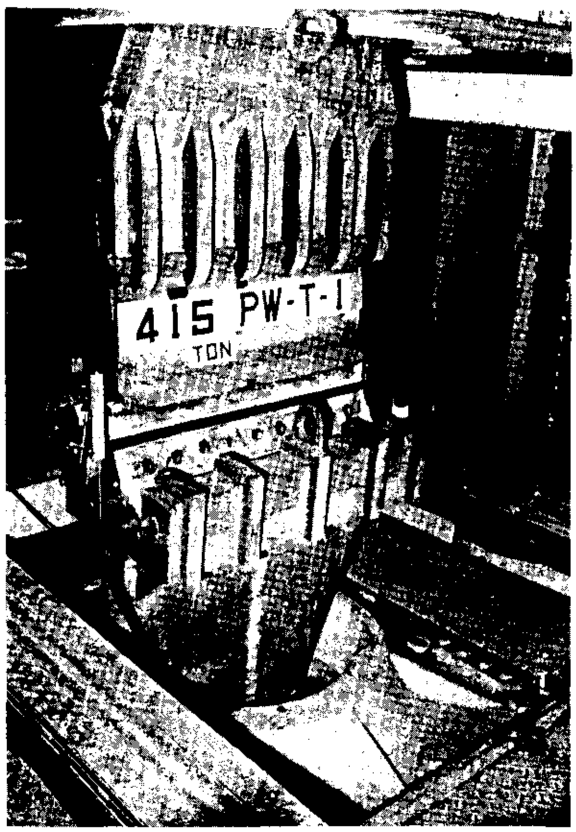


Photo 8 Typical failure mode of "T" connection sheet piles connected by a combination of fillet welding and plug welding

bination type) which ought to have better weldability shpws lower ultimate length than that of SY30 which has been considered inferior in weldability. This may be attributable to the following reason: For the specimen consisted of SY30, a standard of visual inspection for weld configurations was set up and inspection was carried out carefully, whereas for SM50A, only inspection for cracks was performed in view of its good weldability, and no standard for visual inspection was given. Thus the weld toe shape of SM50A specimens became inferior to that of SY30. In case that the weld toe of SM50A specimen was further smoothened in shape, higher "T" connection ultimate strength could be obtained.

The reason for lower ultimate strength of the plug welding type with leg lengths of 5 and 10 mm is that the round hole diameter of the plug weld was as small as 30 mm, that sound welding was difficult to maintain and was unable to be held until coacting between the splice angles and steel sheet piles could reach the higher load region.

In the wavy-edged splice welding, even the wider wave pitch of 125 mm (wave length, 250 mm) has achieved the required ultimate strength of 400 tf/m and over and proved that the lightest high-strength "T" connection sheet piles for the high interlock straight web steel sheet piles can be obtained.

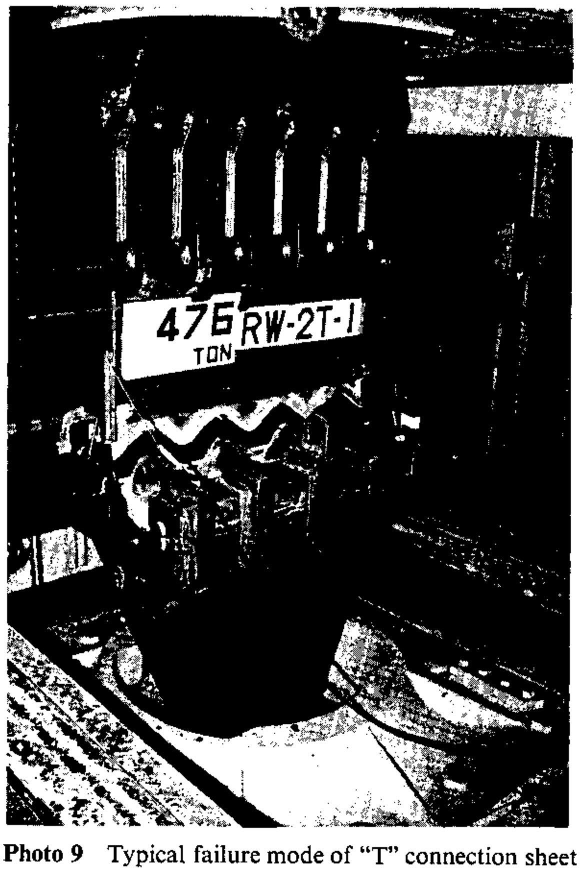


Photo 9 Typical failure mode of "T" connection sheet piles connected by fillet welding with wavy-edged splice plates

4 Conclusion

For the purpose of studying the ultimate strength of "T" connection sheet piles, which are used for almost all types of cellular cofferdams in Japan, and also to develop new types of connection sheet piles with higher strength, a series of two-directional simultaneous tensile tests was conducted by using several types of about one meter long proto-type "T" connection sheet piles.

As a result, the following conclusions were obtained:

(1) Concerning riveted connection sheet piles with specified minimum rivet pitch arrangement, where failure occurs, it is always a result of shear failures on the arc-cell-side. Moreover, the ultimate strength of the connections for the material combination of SY30, SY40 (steel sheet piles) and SV34, SV41 (rivet) depends upon the strength at which shear failures of arc-cell-side rivets occur. The arc-cell-direction ultimate strength, T_{max}, can be well calculated by estimating the shear strength of rivet material at $1/\sqrt{3}$ of its tensile strength, and it does not depend on the magnitude of circular-cell-direction tensile force, P, virtually.

(2) In welded connection sheet piles, with and without splice angles independently, connections fail due to cracks initiated at circular-cell-side toes of fillet welds. Such failures are caused by the out-of-plane bending of the circular-cell-side steel sheet piles induced by tensile force in the arc-cell direction, and so this failure mode will not change even if the connection is groove-welded with full-penetration instead of fillet weld. In this type of connection sheet pile, the material properties of the steel sheet pile, particularly its local elongation, and the shape of the weld toe affect the ultimate strength. And so, careful attention should be paid to giving a smooth shape to the weld toe on the circular-cell-side.

(3) The high strength bolted "T" connection can be treated as a kind of riveted "T" connection with high strength rivets. The shear strength of the bolt material, however, should be estimated at 1/2 of its tensile strength. A trial calculation based on the nominal tensile strength (guaranteed strength) shows that the number of bolts in the high strength bolted "T" connection can be reduced 40% (F-type sheet piles) to 30% (FA) for F8T high strength bolts and 55% (F) to 50% (FA) for F10T from the number that would be required for riveted "T" connections.

(4) In addition to the standard cross section design-

ated in the design specification of the Japan Port and Harbour Association[3], the F-type riveted "T" connection type (rivet dia.: 25 mm, pitch: 85 mm) was proved to have sufficient ultimate strength of connection to satisfy the specified minimum strength for the maximum cell radius ratio (=arc cell radius/circular cell radius) of 2/3.

(5) For straight web steel sheet piles with high interlock strength (minimum interlock strength of 600 tf/m), either piles fabricated by a combination of riveting and welding or piles welded with a wavy-edged splice (newly developed), can be recommended.

References

1) Architectural Institute of Japan: "AIJ Standard for Design of Steel Structure", (1970)
2) Japan Road Association: "Specifications for Highway Bridges", (1973)
3) The Japan Port and Harbour Association: "Technical Standard for Port and Harbour Facilities and Commentaries", (1979)
4) Steel Material Club and Japan Steel Structure Association: "Compendium of Steel Structure Connection Data—Riveted Tee Connection and High Strength Bolt Tee Connection", (Mar. 1977)
5) S. Kikukawa, K. Murata and A. Nishimura: "Secular Changes of Slip Resistance of Friction-type Bolted Joints in Structural Members", *Kawasaki Steel Technical Report*, **11** (1979) 4, pp. 127–135 (in Japanese)
6) T. Yagyu: *Kowan*, **57** (1980), 8, pp. 55–66
7) JIS-A5528: "Steel Sheet Piles", (1967)
8) N. Ishizawa, T. Narumiya, F. Shima, and M. Ishiwata: *The Bridge and Foundation Engineering*, **4** (1970) 2, pp. 28–34
9) Y. Kuriyama, T. Kawano, et al.: "Tee Connection Studies on Bending Deformability of Tee-connection Fillet Welds (Parts 1 and 2)", *Preprints of National Meeting of Japan Welding Society*, No. 20, (1977), pp. 22–25
10) Material Sub-committee, Sectional Meeting for Safety, Society of Steel Construction of Japan-Technical Comittee: "Fracture and Deformation Capacity of Tee Welded Joints by Pull-bend Test", *JSSC*, **11** (1975) 110. pp. 23–46
11) M. Uchida et al.: "Effects of Bead Shapes on Bending Deformability of Tee Fillet Welded Joints (Parts 1 and 2)". *Preprints of the National Meeting of Japan Welding Society*, No. 22 (1978), pp. 160–163
12) Y. Lacroix, M. I. Esrig and U. Luscher: "Design, Construction, and Performance of Cellular Cofferdams", Proc. of Soil Mech. & Found. Div., Specialty Conf. on Lateral Stresses in the Ground & Earth Retaining Structure, ASCE (Jun. 1970), pp. 271–328
13) E. P. Swatek: "Cellular Cofferdam Design and Fracture", *Proc. of ASCE*, WW 3, (Aug. 1967), pp. 109–132