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Estimation of Strength of Tubular Joints

Estimation de la résistance des noeuds de profilés circulaires

Abschätzung der Festigkeit von Rohrstössen

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1 INTRODUCTION

This paper presents the method of evaluation of the strength of tubular joints of the off-shore structures for drilling the seabed, in connection with the construction of Honshu-Shikoku Connecting Bridge over the Seto inland sea. The structures under consideration are of tubular type. In the trusses with the tubular members, tubular joints with directly connected web tube and chord tube are often used, but only a few systematic informations are available of the strength of the tubular joints, especially for the case where D/T is large. In this case, the appropriate stiffening methods must be investigated to construct the reliable structures. In this study, the authors attempt to present the systematic informations about the strength of the tubular joints, based on the investigation of the data obtained so far, where D/T is less than 40. At the same time, we shall outline the results on the understanding and evaluating of the low cycle fatigue strength of the basic tubular joints.

2 OBJECTS OF TESTS

Both static and fatigue tests were performed. The objects of the static tests are; a) to investigate whether the results obtained so far can be extrapolated up to the case where D/T=100 or not, b) to understand the influences of the geometrical parameters, D/T, d/D, and so on, upon the strength of the tubular joints, and c) to evaluate the rigidity of the tubular joints. Low cycle fatigue tests are performed to obtain the S-N curves for various types of tubular joints under large repeated loads up to 10,000 cycles. The loads and number of cycles are determined taking the actions of waves and tides for an assumed service period of three years for off-shore structures into account.

3 SPECIMENS AND TEST PROGRAM

The specimens are fabricated with Japanese Industrial Standard STK 50 steel (for chord tube) and STK 41 (for web tube), of which breaking strengths are 50 and 41 kg/mm^2, respectively. The geometrical parameters of the specimens are; 40, 70, 100 for D/T; and 0.2, 0.4, 0.6 for d/D. Intersecting angles were 90 degrees for most of the tests with a few tests with 45 degrees. In order to see the effects of reinforcing members which are indispensable for actual structures, both directly and indirectly load-transmitted joints were tested. Series I and II are the former type and Series III through V are the latter type. The total number of specimens amount to some 150 pieces. The stress levels for low cycle fatigue tests are selected in four steps, which are 0.8, 0.5, 0.4 and 0.3 for P/P_{max}. The S-N curves were drawn based on four test points, which may subject to variation. Special attention has been paid to the welding condition in order to have specimens of the same quality and to minimize the variation in the test results. The test specimens amount to 30.

4 MATERIAL TESTS

The material test results for chord tube are tabulated as follows:

Coupon Test for Material (Tension) (TAB. 1)

Tension tests for the circumferential direction for D/T=40 are omitted.

Loading Tests for Tube (TAB. 2)

The definitions of the experimental yield strength are given by FIG. 1(a) and 1(b).

TAB.1

OUTER DIA. (mm)	σ_{yL} (t/cm²)	σ_{yc} (t/cm²)	σ_{yc}/σ_{yL}	σ_B (t/cm²)	ε_B (%)
165.2	4.4~5.0	—	—	5.35~5.6	27~31.5
318.5	4.1~4.5	3.6 ~3.8	0.78~0.89	5.3 ~5.6	28~32
457.2	4.0~4.6	3.45~4.05	0.81~0.92	5.4 ~5.8	29~33

TAB.2

LOADING	SPECIMEN	DIA. (mm)	THICK. (mm)	σ_{yL} (t/cm²)	P_{ye} (t)	σ_{ye} (t/cm²)	P_{max} (t)	σ_{max} (t/cm²)	P_y (t)	σ_y (t/cm²)	P_{ye}/P_y or σ_{ye}/σ_y
AXIAL THRUST	CTP – 40	165.2	4.65	4.21	–	4.45	–	4.84	–	4.21	1.06
	CTP – 70	318.5	4.55	4.21	–	4.32	–	4.32	–	4.21	1.02
	CTP –100	457.2	4.5	4.2	–	4.3	–	4.3	–	4.2	1.02
TRANS-VERSE SHEAR	STP – 40	165.2	4.5	4.69	65	–	72.3	–	50	–	1.3
	STP – 70	318.5	4.5	4.37	115	–	118	–	93	–	1.23
	STP –100	457.2	4.5	4.2	175	–	175	–	134	–	1.3
TRANS-VERSE BENDING	BTP – 40	165,2	4.7	4.69	34.0	–	35.8	–	33.6	–	1.01
	BTP – 70	318.5	4.4	4.37	54.7	–	54.7	–	58.7	–	0.93
	BTP –100	457.2	5.0	4.2	73.5	–	81.3	–	93.0	–	0.79

TAB.3

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	$\bar{\sigma}_{yL}$ (t/cm²)	t (mm)	$\bar{\sigma}_{yL}\cdot A$ (t)	d (mm)	d/D	P_{ye} (t)	P_{max} (t)	P_y (t)	P_{ye}/P_y
I-CB-100-0.4	4.0	0.9	4.9	93	4.5	4.7	106.6	165.2	0.361	10.0	10.0	12.5	0.80
I-CB'-100-0.4	4.0	0.87	4.9	93	4.5	4.7	106.6	165.2	0.361	15.7	15.7	17.7	0.89

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	$\bar{\sigma}_{yL}$ (t/cm²)	t (mm)	$\bar{M}_y$ (t·cm)	d (mm)	d/D	M_{ye} (t·cm)	M_{max} (t·cm)	M_y (t·cm)	M_{ye}/M_y
I-B - 100-0.4	4.1	0.85	4.8	95	4.8	4.7	581.1	165.2	0.361	184	184	187.5	0.97
I-BL-100-0.4	4.1	0.86	4.8	95	4.8	4.7	581.1	165.2	0.361	54	68	50.6	1.06

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	$\bar{\sigma}_{yL}$ (t/cm²)	t (mm)	$\bar{\sigma}_{yL}\cdot A$ (t)	d (mm)	d/D	g (mm)	P_{ye} (t)	P_{max} (t)	P_y (t)	P_{ye}/P_y
I-CS-100-0.4	4.0	0.90	4.8	95	—	4.5	—	165.2	0.361		8.2	8.2	7.0	1.17
II-CK-100-0.2	4.1	0.83	4.9	93	3.7	3.0	30.1	89.1	0.195	121	9.0	9.0	8.6	1.05
II-KK- 70-0.2	4.2	0.87	4.4	73	3.4	3.0	18.4	60.5	0.190	233	11.0	11.0	10.0	1.10

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	H (mm)	H/D	P_{ye} (t·m)	P_{max} (t·m)	P_y (t)	P_{ye}/P_y
III-B -100-1.0	4.3	0.85	4.8	95	450	0.98	2.8	3.3	3.12	1.05
IV-C -100-0.3	4.5	0.78	4.9	93	150	0.328	6.0	14.5	6.5	0.92

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	σ_y (t/cm²)	t (mm)	$bt\sigma_y$ (t)	R (mm)	R/D	b (mm)	b/D	P_{ye} (t)	P_{max} (t)	P_y (t)	P_{ye}/P_y
V-TG-100-30	4.4	0.92	5.0	91	—	—	—	—	—	228.6	0.5	10.9	25.6	11.6	0.95
V-SB-100-0.25-0.25	4.0	0.90	4.9	93	2.78	9.0	27.5	110	0.241	110	0.241	34.0	—	31.8	1.06
V-SR-100-0.25-0.5	4.0	0.90	4.9	93	2.78	9.0	55.0	110	0.241	220	0.481	43.0	—	31.8	1.35
V-TR-100-0.25-0.5	4.4	0.85	4.9	93	2.7	9.0	53.5	110	0.241	220	0.481	26.5	65.9	27.3	0.97
V-CR-100-0.25-0.5	4.2	0.81	4.7	97	2.7	9.0	53.5	110	0.241	220	0.481	33.0	44.1	27.3	1.21

SPECIMEN	σ_{yL} (t/cm²)	σ_{yc}/σ_{yL}	T (mm)	D/T	σ_y (t/cm²)	t (mm)	R (mm)	R/r	d (mm)	$\cos\phi_u$	P_{ye} (t)	P_{max} (t)	P_r (t)	P_y/P_r	P_y (t)	P_{ye}/P_y
VI-CS 1	3.9	0.87	4.9	93	4.4	9.0	150	0.663	165.2	0.314	58.0	72.7	63.0	1.0	63.0	0.92
VI-CS 2	3.9	0.87	4.9	93	4.4	9.0	120	0.531	165.2	0.322	45.0	63.1	46.0	1.0	46.0	0.98
VI-CS 3	3.9	0.87	4.9	93	3.9	12.0	120	0.531	165.2	0.322	53.0	72.5	54.5	1.0	54.5	0.97
VI-CS 4	3.85	0.92	4.95	92	4.2	16.0	120	0.531	165.2	0.322	73.0	93.8	78.0	1.0	78.0	0.97
VI-CS 5	3.85	0.92	4.95	92	4.4	9.0	90	0.398	165.2	0.332	35.0	49.7	30.6	1.0	30.6	1.14

5 OUTLINES OF TEST RESULTS

Some typical test results are given in TAB. 3, and FIG. 2, 3.

6 DISCUSSION AND CONCLUSIONS OF TEST RESULTS

Main test results are summarized as follows:

a) Static test

1) The formulas obtained so far for D/T less than 40 for the strength of tubular joints can be applied for D/T=40~100 with slight modifications of the formulas.

2) It would suffice to consider the normal component of the load acting to the chord tube for estimating the strength of tubular joints in the case of obliquely intersecting ones.

3) The appropriate stiffening methods are indispensable for the case where the value of D/T is large. The following two methods may be important; increasing the thickness of the chord tube, or reinforcement by the stiffening ring.

4) Since the strength of the ring can be estimated theoretcally, and the load from the web tube are transmitted smoothly to the chord tube, the ring-stiffened tubular joints are preferable to other stiffened types from the standpoint of strength. The most appropriate stiffening method, however, must be decided from the careful judgement in close relation to fabrication and erection.

b) Low cycle fatigue test

1) Both initiation and development of the fatigue crack took place in the mother material, and the strength of the welds had little influence upon the joint strength.

2) Fatigue crack started at an early stge, namely, $N'/N \fallingdotseq 0.1$; where N'=Number of cycles when crack starts, and N=Number of cycles when fatigue rupture occurs. However, even after the initiation of fatigue crack stable loading continued almost up to the end at which fatigue rupture took place.

3) Linear S-N curve on the semilog scale closely fits the test results for each series. It was observed that the fatigue strength increased with increasing values of D/T, but this increment was insignificant.

4) S-N curve for each series can be expressed by the following equations:

I-RT	:	$S=1.13-0.19\log N$	$(340 \leqq N \leqq 30000)$
II-RK	:	$S=1.19-0.21\log N$	$(360 \leqq N \leqq 49000)$
III-R	:	$S=1.04-0.19\log N$	$(470 \leqq N \leqq 14000)$
IV-R	:	$S=1.23-0.20\log N$	$(630 \leqq N \leqq 66000)$
V-RG	:	$S=1.02-0.16\log N$	$(630 \leqq N \leqq 21000)$
VI-RS	:	$S=1.47-0.23\log N$	$(370 \leqq N \leqq 420000)$

These relations show that the fatigue strength is the minimum for series III, while series VI show the maximum fatigue strength. This means stiffening ring is effective for increasing the fatigue strength of tubular joints.

7 DESIGN FORMULAS

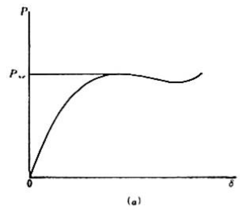
The design formulas might be proposed, based upon this experimental study. The yield strength P_y of the tubular joints for static loading is fundamental. The design load P_{all} for repeated loading is given, when the safety factor for the low cycle fatigue ν is specified.

$$P_{all} = SP_y/\nu$$

P_y is predicted by the formulas given in TAB. 4 and 5.

TAB.4

BASIC TYPE	YIELD FORCE	β	APPLICATION OF BASIC TYPE		
A: P_{yo} (T, d, D) I-CB	$\frac{P_{yo}}{\sigma_y T^2}=\frac{7.3}{1-0.833d/D}$ WHEN $15\le D/T\le 100$, $0.2\le d/D\le 1.0$	$\frac{P_{yo}}{\sin\theta}$; P_{yo}; $\frac{P_{yo}}{\sin\theta}$; $\frac{P_{yo}}{\sin\theta}$ *	I-CB (P, θ); II-CK (P); II-TK (P, θ); II-KK (P, P, θ)	$T\to T'$, $D\to D'$, $\theta\to\theta'$, $\sigma_y\to\sigma_y'$ WHEN $T'/T\le 2$, $B\ge D\left(\frac{1}{\tan\theta}+1.2\right)$ OR $B\ge D$	VII (D, T, T', D', θ, $\sigma_y=\sigma_y$, $\sigma_y=\sigma_y'$, B)
B: P_{yo} I-CS	$\frac{P_{yo}}{\sigma_y T^2}=\frac{5.3}{1-0.833d/D}$ WHEN $15\le D/T\le 100$, $0.2\le d/D\le 1.0$	$\frac{P_{yo}}{\sin\theta}$; $\frac{P_{yo}}{2\sin\theta}$	(P, θ); (P, P, θ)	$T\to T'$, $D\to D'$, $\theta\to\theta'$, $\sigma_y\to\sigma_y'$ WHEN $T'/T=2$, $D'/D=1.4$, $B/D=1.7$	VI-TK (D, T, T', D', θ, θ', $\sigma_y=\sigma_y$, $\sigma_y=\sigma_y'$, B)
C: M_{yo}	$\frac{M_{yo}}{\sigma_y T^2}=\left(0.3\frac{D}{T}+5\right)\left(\frac{d}{D}\right)^2 D$ WHEN $15\le D/T\le 100$, $0.2\le d/D\le 0.5$				
D:	$\frac{M_{yo}}{\sigma_y T^2}=\left(-0.03\frac{D}{T}+6.1\right)\left(\frac{d}{D}\right) D$ WHEN $15\le D/T\le 100$, $0.2\le d/D\le 0.5$				
E: III M_{yo} (B)	$\frac{M_{yo}}{\sigma_y T^2}=7B$ WHEN $15\le D/T\le 100$, $0.6\le B/D\le 2.5$	$\frac{M_{yo}}{D\cos\theta}$; $\frac{2\tan\theta\cdot M_{yo}}{D}$; M_{yo}; M_{yo}	(P, θ); (P); III (M); III (M, M)		
F: IV P_{yo}, B	$\frac{P_{yo}}{\sigma_y T^2}=5.3+2.23\frac{B}{D}$ WHEN $15\le D/T\le 100$, $0.3\le b/D\le 2.0$	P_{yo}; $\frac{P_{yo}}{2\sin\theta}$	IV-C (P); (P, P, θ)		
G: V-RG (B, D)	$\frac{P_{yo}}{\sigma_y T^2}=21\frac{B}{D}$ WHEN $15\le D/T\le 100$, $0.25\le B/D\le 0.8$	P_{yo}; $\frac{P_{yo}}{\sin\theta}$	VI-CB (P); (P, θ)	$\frac{P_{yo}}{2\sin\theta}$; $\frac{P_{yo}}{\sin\theta}$	(P, P, θ); (P, P, θ)



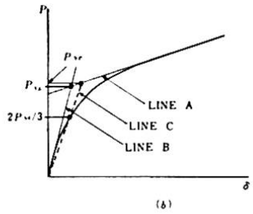


FIG.1(a) FIG.1(b)

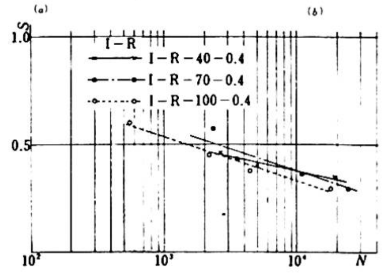


FIG.2

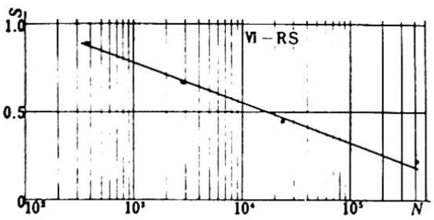
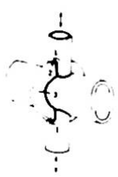
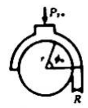
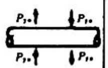
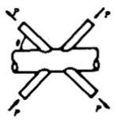
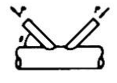
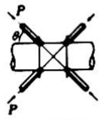
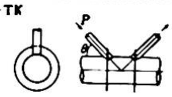
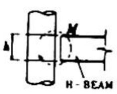
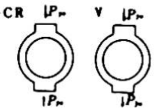


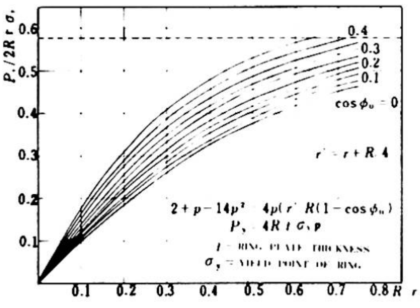
FIG.3

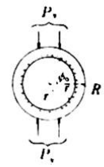


TAB. 5

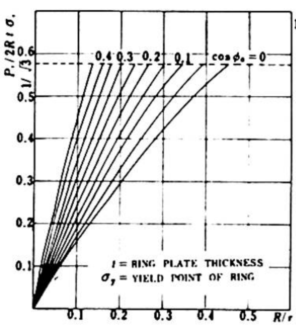
BASIC TYPE	YIELD FORCE	P_y	APPLICATION OF BASIC TYPE
H :  $r' = r + R/4$	$P_{y0} = 4Rt\sigma_y p$ OR $= \frac{2Rt\sigma_y}{\sqrt{3}}$ GRAPH 1 $2 + p - 14p^2 = 4p\left(\frac{r'}{R}\right)(1 - \cos\phi_0)$ t : RING PLATE THICKNESS σ_y : YIELD POINT OF RING WHEN $t/T \leq 3.0$ $\sigma_y/\sigma_{yL} \leq 1.0$, $R/r \leq 0.7$		
I : 	$P_{y0} = 4Rt\sigma_y p$ OR $= \frac{2Rt\sigma_y}{\sqrt{3}}$ GRAPH 2 $1 - 2\alpha^2 p^2 = p\left(\frac{2r}{R}\right)\frac{\phi_0}{\sin\phi_0}\left(\frac{1}{\cos\frac{\phi_0}{2}} - 1\right)$ $\alpha = \frac{1}{2\cos^2\phi_0}$ WHEN $t/T \leq 3.0$ $\sigma_y/\sigma_{yL} \leq 1.0$, $R/r \leq 0.7$	$P_y = P_{y0}$	
J : 	$P_{y0} = 4Rt\sigma_y p$ GRAPH 3 $1 - 12p^2 = p\left(\frac{4r}{R}\right)\frac{1}{\sin\phi_0}(\phi_0 - \sin\phi_0)$ WHEN $t/T \leq 3.0$ $\sigma_y/\sigma_{yL} \leq 1.0$ $R/r \leq 0.7$		
K : 	$P_{y0} = \frac{D}{\sqrt{3}} T\sigma_{yL}$	$P_y = \frac{P_{y0}}{\sin\theta}$ $P_y = \frac{P_{y0}}{\sin\theta}$	 

APPLICATION OF BASIC TYPE		
	GRAPH 1 $P_y = \frac{P_{y0}}{\sin\theta}$	M−KK 
	GRAPH 2 * $P_y = \frac{P_{y0}}{\sin\theta}$	M−TK 
	GRAPH 2 $P_y = \frac{P_{y0}}{\sin\theta}$ GRAPH 2 $M_y = P_{y0} h$	M−KK   * V−CR V 



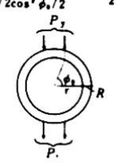


GRAPH 1

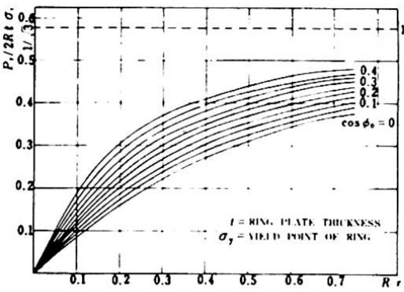


$1 - 2\alpha^2 p^2 = p(2r/R)\frac{\phi_0}{\sin\phi_0}\left(\frac{1}{\cos\frac{\phi_0}{2}} - 1\right)$

$\alpha = 1/2\cos^2\phi_0/2$

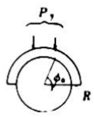


GRAPH 2



$1 - 12p^2 = p\left(\frac{4r}{R}\right)\frac{1}{\sin\phi_0}(\phi_0 - \sin\phi_0)$

$P_y = 4Rt\sigma_y p$



GRAPH 3

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SUMMARY

Experimental studies have lead to systematic information on the static strength and low cycle fatigue behaviour of tubular joints. Design formulas have been proposed. The formulas for yield strength of basic stiffening method of ring type have been developed from test results. The stiffening method of partially increasing thickness of chord tube has been investigated for practical application.

RESUME

Une série d'études expérimentales a fourni une information sur la résistance et le comportement à la fatigue, à bas cycle de noeuds de profilés circulaires. Une formule dans le domaine plastique pour le renforcement du tube avec des anneaux a été obtenue d'après essais. Le renforcement du tube de grand diamètre, par augmentation de l'épaisseur, a été examiné pour une application pratique.

ZUSAMMENFASSUNG

Aus experimentellen Untersuchungen wurden systematische Informationen über die statische Traglast und die "Low-cycle" Ermüdungsfestigkeit der Anschlüsse von zylindrischen Röhren gezogen. Eine Bemessungsformel wird vorgeschlagen. Die Formeln für die statische Traglast der mit Ringen ausgesteiften Anschlüsse wurden aus Versuchsergebnissen hergeleitet. Ausgesteifte Anschlüsse mit örtlich zunehmender Wanddicke wurden hinsichtlich ihrer praktischen Anwendbarkeit untersucht.