（14）EXPERIMENTAL STUDY ON TENSILE CREEP BEHAVIOR OF BUTT-BONDED JOINTS

Visal THAY[1], Kumiko KIYONO[2], Hitoshi NAKAMURA[3] and Hisakazu HORII[4]

[1]Member of JSCE, Assistant Professor, Dept. of Civil Eng. and Regional Design, Utsunomiya University
(7-1-2 Yoto, Utsunomiya-shi, Tochigi 321-8585, Japan)
E-mail: vthay@cc.utsunomiya-u.ac.jp
[2]Member of JSCE, Dept. of Civil and Environmental Eng., Tokyo Metropolitan University
(1-1 Minami-Osawa, Hachioji-shi, Tokyo 192-0397, Japan)
E-mail: kiyono-kumiko@ed.tmu.ac.jp
[3]Member of JSCE, Associate Professor, Dept. of Civil and Environmental Eng., Tokyo Metropolitan University
(1-1 Minami-Osawa, Hachioji-shi, Tokyo 192-0397, Japan)
E-mail: hnaka@tmu.ac.jp
[4]Member of JSCE, Research & Development Division No. 4, Osaka Institute, Konishi Co., Ltd.
(4-7-9 Tsurumi, Tsurumi-ku, Osaka 538-0053, Japan)
E-mail: horii-hisakazu@bond.co.jp

This paper aims to contribute to a better understanding of the creep behavior of the adhesively bonded joints by the tensile tests. The test device for static tensile tests and the creep test apparatus for large-scale experiments are designed, and the creep tests are conducted under 67% of the static failure load. As a result, the maximum strain value of the adhesive layer at failure can be considered at approximately 39,000×10^{-6} (about 3.1 times greater than that from static tensile tests, 12,000×10^{-6}), and the lifetime to failure can be confirmed under 67% of the static failure load. Furthermore, the creep data can be plotted in the master curve of creep compliance of epoxy resin.

Key Words : *creep behavior, adhesive joint, adhesive failure, creep lifetime, creep compliance, static strength*

1. INTRODUCTION

Adhesively bonded joints have become more important as an alternative in joining components for repairing and strengthening steel structures instead of conventional methods such as welding, riveting, and bolting[1)]. However, because of the viscoelastic nature of adhesives, adhesively bonded structures exhibit time-dependent behavior when subjected to a constant load, known as the creep phenomenon. The stiffness of the adhesive gradually decreases with time which leads to continuous decrease in the load-carrying capacity of structure[2)]. Therefore, studying the creep behavior of the adhesively bonded joints in the structural application is necessary to increase their durability and reliability[3)].

Several studies have been focused on creep behavior of adhesively bonded joints analytically and experimentally on various joints specimens, single-lap, double-strap for instance[4~8)].

This paper aims to contribute to a better understanding of the creep behavior of the adhesively bonded joints by the tensile tests by experimentally investigate the static tensile strength and creep lifetime of butt-bonded joints of the hollow cylindrical steel members using the adhesive Konishi E258R under ambient temperature.

2. SPECIMEN

(1) Specimen and material properties

Fig.1 shows the specimen of the adhesively bonded joints used in static tensile tests and creep tests. It is the butt-bonded joints of the hollow cylindrical steel members based on JIS K 6868-1[9)]. The largest one amongst three recommendation specimens is selected. The inner and outer diameters are 60 and 72 mm, respectively, giving the width of the bonded area of 6 mm. The creep tests are conducted following the static tensile tests. Material properties of steel (S45C) and epoxy resin adhesive are given in **Table 1**. The epoxy resin adhesive used is Konishi E258R. The material properties of steel are assumed values, and the material properties of adhesive Konishi E258R are provided by the material manufacturer[10).

(2) Specimen preparation

The surfaces of steel are prepared by bristle blaster with the steel brush's width of 23 mm before bonded. After bonding, the specimens are cured at 40 °C for 24 hours. The adhesive thickness is controlled to be approximately 0.4 mm using glass beads with a diameter of 0.4 mm.

3. STATIC TENSILE TESTS

(1) Test device

Fig.2 shows the schematic view of the tensile test device. The device consists of a die set (precisely movable up and down), spacer, center hole hydraulic jack (capacity of 300 kN), nut, and bolt (M24). The die set is to fix and support the specimen. The space between the die set is fixed by inserting the steel plate spacers. The bolt is connected to the specimen, and tensile force is applied by the center hole hydraulic jack.

(2) Experimental series and results

Table 2 shows the experimental series and results of tensile tests. 13 specimens are prepared for the static tensile tests. The average adhesive thickness is 0.49 mm. The average maximum load measured by the load cell is 45.5 kN (tensile strength σ_{tu}=36.5 MPa). The tensile strength is almost the same as the value provided by the adhesive manufacturer as presented in **Table 2** (33 MPa). The standard deviation is 6.4 kN, and the coefficient of variation is 0.140. The average maximum strain value of the adhesive layer obtained from the strain gauge is 12,647×10^{-6} (SD=3,729×10^{-6}, CV=0.295). The failure modes of all 10 specimens are cohesive failures. It should be noted that three specimens with adhesive failure mode are not included and considered in this result.

4. CREEP TESTS

(1) Design and setup of creep test

Fig.3 shows the design and setup of the creep test apparatus for large-scale experiments in the basement. A lever beam balance, a well-known technique for creep test, is designed. The fulcrum is fixed to the basement roof by a PC steel rod (M36, tension by 377 kN). The length of the steel H-beam (300×300×10×15 mm) is 3,300 mm (2,000 mm to the weight side and up to 1,000 mm to the loading side). Six bearing units of square flange shape refueling

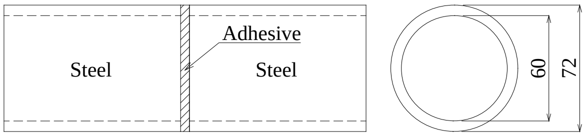


Fig.1 Schematic view of the specimen (JIS K 6868-1)

Table 1 Material properties

Materials	Elastic modulus E (GPa)	Poisson's ratio ν	Tensile Strength σ_{tu} (MPa)
Steel (S45C)	205	0.30	–
Adhesive (Konishi E258R)	3.6	0.34	33

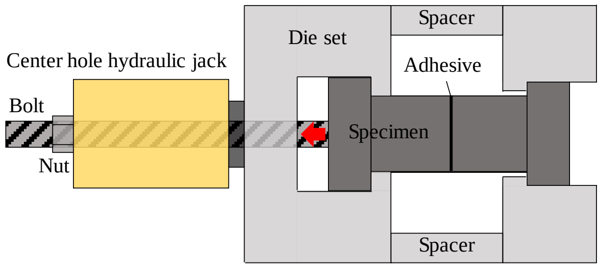


Fig.2 Schematic view of the tensile test device

Table 2 Experimental series and results

Specimen No.	Adhesive thickness t_e (mm)	Maximum load P_{max} (kN)	Tensile strength σ_{tu} (MPa)	Maximum strain (×10^{-6})
1	–	56.4	45.3	–
2	–	48.2	38.7	–
3	0.48	49.6	39.8	14,307
4	0.52	44.3	35.6	17,781
5	0.47	34.4	27.7	6,623
6	0.47	41.6	33.4	10,111
7	0.49	51.9	41.7	11,823
8	0.53	47.4	38.1	18,205
9	0.48	44.3	35.6	9,856
10	0.50	36.6	29.4	12,467
Average	**0.49**	**45.5**	**36.5**	**12,647**
SD	0.02	6.4	5.1	3,729
CV	0.043	0.140	0.140	0.295

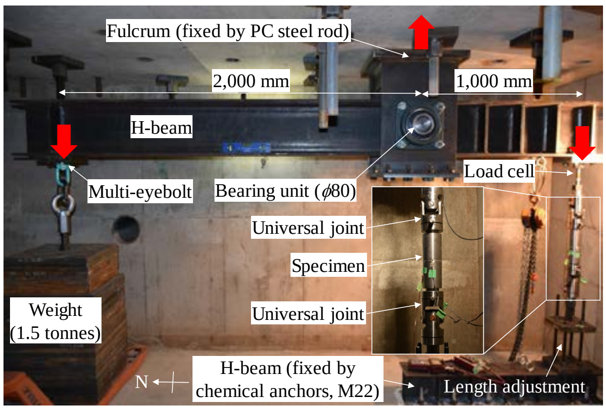


Fig.3 Setup of creep test

type (ϕ80×6 units, the capacity of static load per unit: 86.5 kN). The weight of approximately 1.5 tonnes (15.2 kN) is attached to one side of the steel H-beam. Multi-eyebolt (M24) is used as a hinge on the weight side. On another side, the specimen is attached to the upper part through the universal joint (Kyowa, SC-50-00A) and load cell (capacity of 50 kN), and to the lower part of another steel H-beam (200×200×8×12 mm) through another universal joint and length adjustment of 4 bolts (M16). Steel H-beam is fixed to the concrete floor slab by chemical anchors (R-type, M22×10 bolts). The capacity of each anchor bolt is 47.4 kN (long term). The attachment distance from the fulcrum is designed at 200, 400, 600, 800, and 1,000 mm, which provide the maximum applied load of 10 times (10, 5, 3.3, 2.5, 2 times accordingly). It should be noted that the end of the steel rod to fix the weight is extended to the hole of the concrete floor slab as a stopper for a countermeasure during the earthquake.

(2) Creep test series and results

Table 3 shows the creep test series and results. 14 specimens are prepared for the creep tests (C1-C14). All specimen are conducted under the same applied load of 30.3 kN (approximately 67% of the maximum load), equivalent to 24.3 MPa. Four strain gauges are attached to the adhesive layer in the longitudinal direction for all specimens (two strain gauges for C1). The data is recorded at the minimum of 1-second intervals and the maximum of 10-minute intervals. The oil heater is used to maintain the temperature at approximately 20 °C. Noted that there is no change of specimen size and method of specimen preparation from static tensile tests.

The average of the maximum strain value of the adhesive layer at failure obtained from strain gauge is 39,703×10^{-6} (SD=13,184×10^{-6}, CV=0.332). This value is approximate 3.1 times greater than the maximum strain value from static tensile tests (12,647×10^{-6}).

(3) Strain behavior

Fig.4 shows the strain behaviors obtained from the strain gauge attached at the adhesive layer (S1-S4). From all specimens, it can be grouped into four categories of behaviors (**Table 4**). Category 1, the perfect one, has good strain behavior with a small influence of bending (**Fig.4(a)**). The change of strain value can be seen in 3 stages: quick increase in the early stage, gradual increase in the middle stage, and quick increasing again in the last stage to failure. Category 2 has a good strain behavior with a large influence of bending (**Fig.4(b)**). A large difference between each strain gauge can be observed. Category 3 has a small influence on bending but is not good in strain behavior (**Fig.4(c)**). The strain values are almost stable until a quick increase to failure at the end. The last category has a large influence on bending and is not good in strain behaviors (**Fig.4(d)**).

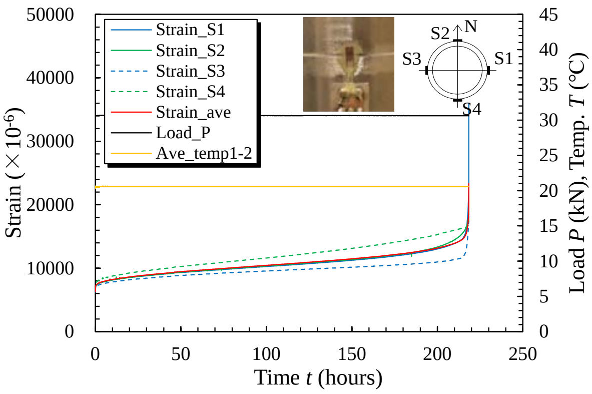
Fig.4 plotted the applied load (solid black line) and temperature (solid yellow line) measured in the basement. Stable values of applied load (approximately 30.3 kN) and temperature (approximately 20 °C) can be confirmed.

(4) Creep lifetime

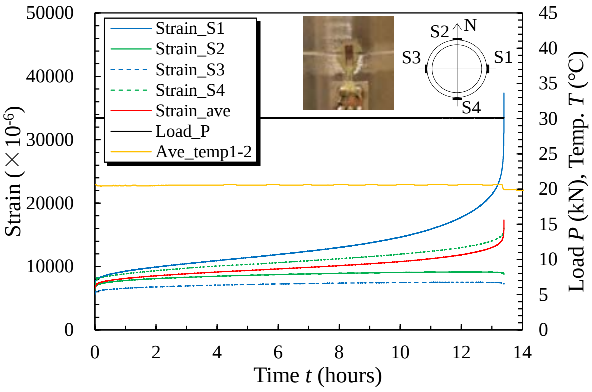
Fig.5 plots all of the experimental data and the average data of static tensile tests and creep tests under applied load and lifetime to failure. The square red dots are static tensile test data, and the red circle dots are creep test data. From the figure, the creep lifetime can be obtained, although with a high variation. The

Table 3 Creep test series and results

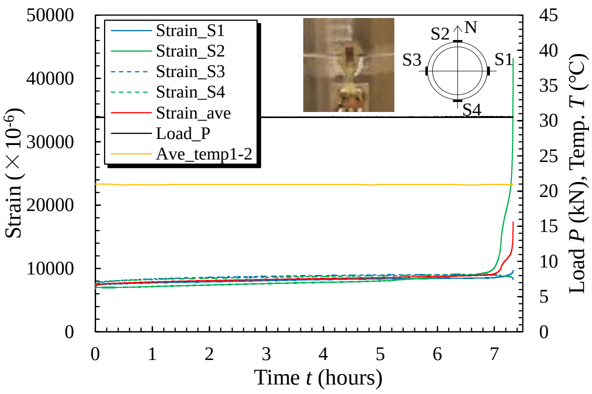
Specimens	Applied load P (kN)	Ave. strain at failure (×10^{-6})	Max. strain at failure (×10^{-6})	Comparison with static strength (times)	Creep lifetime (hours)	Creep compliance (GPa^{-1})	Failure modes and conditions (all are cohesive)	Evaluations (quantitative judgment)
C1	30.3 (67% of static strength)	21,146	32,520	2.6	199.7	0.86	Void	◎
C2		17,541	37,395	3.0	13.4	0.71	Void	○
C3		21,462	45,285	3.6	606.9	0.87	Partial adhesive	○
C4		17,713	43,110	3.4	7.3	0.72	Partial adhesive and void	○
C5		34,581	75,105	5.9	0.9	1.40	Partial adhesive	−
C6		17,871	48,098	3.8	0.5	0.72	Void	−
C7		−	−	−	−		Cohesive and smooth	−
C8		13,262	32,610	2.6	0.1	0.54	Cohesive and smooth	−
C9		13,382	29,303	2.3	0.6	0.54	Void	−
C10		12,446	17,573	1.4	5.1	0.50	Partial adhesive	−
C11		23,342	36,015	2.9	218.4	0.95	Partial adhesive	◎
C12		−	−	−	−		Cohesive and smooth	−
C13		19,196	40,178	3.2	137.6	0.78	Void	◎
C14		15,396	39,240	3.1	0.1	0.62	Cohesive and smooth	−
Average		**18,945**	**39,703**	**3.1**	**99.2**	**0.77**	−	−
SD		5,757	13,184	1.0	172.5	0.23	−	−
CV		0.304	0.332	0.332	1.738	0.304	−	−



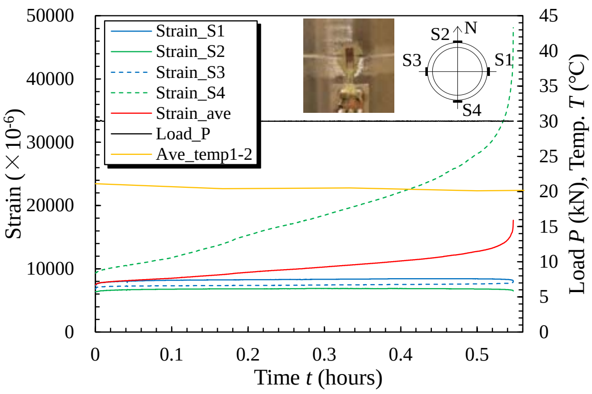
(a) Category 1 (C11)



(b) Category 2 (C2)



(c) Category 3 (C4)



(d) Category 4 (C6)

Fig.4 Four categories of strain behaviors

Table 4 Four categories of strain behaviors

Categories	1 (C11)	2 (C2)	3 (C4)	4 (C6)
Strain behavior	Good	Good	Not good	Not good
Bending influence	Good	Not good	Good	Not good

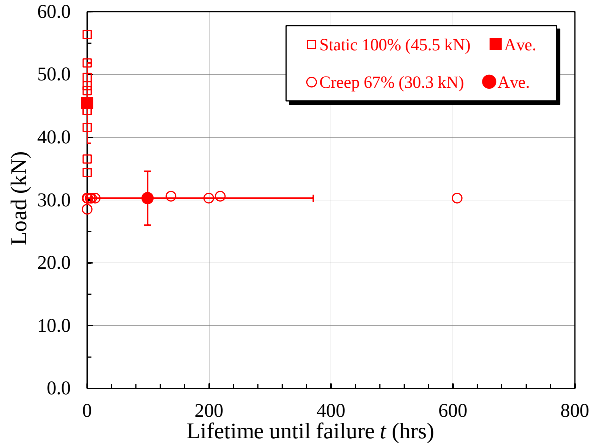


Fig.5 Load versus lifetime until failure

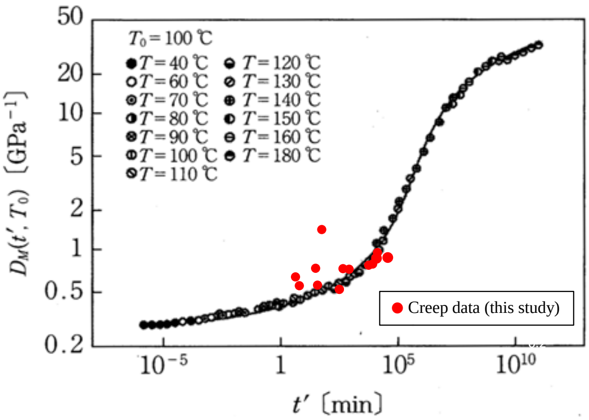


Fig.6 Creep compliance[11)]

average lifetime of creep under the applied load of 67% of the maximum static load is 99.2 hours (SD=172.5 hours, CV=1.738). Some specimens are confirmed to be failed at the very early stage of loading.

(5) Creep compliance

Fig.6 plots the current creep data in the master curve of creep compliance of epoxy resin from Ref 11). The red circles are the current creep data. Although some data are not properly plotted on the curve, small variation can be confirmed compared to the load versus lifetime to failure presented in **Fig. 5**. It should be noted the creep compliance is calculated by **Eq.(1)** below[11)].

$$D_c(t,T) = \frac{\varepsilon(t,T)}{\sigma_0} \quad (1)$$

Here,

$D_c(t, T)$: Creep compliance (GPa^{-1})

$\varepsilon(t, T)$: Average strain value at failure

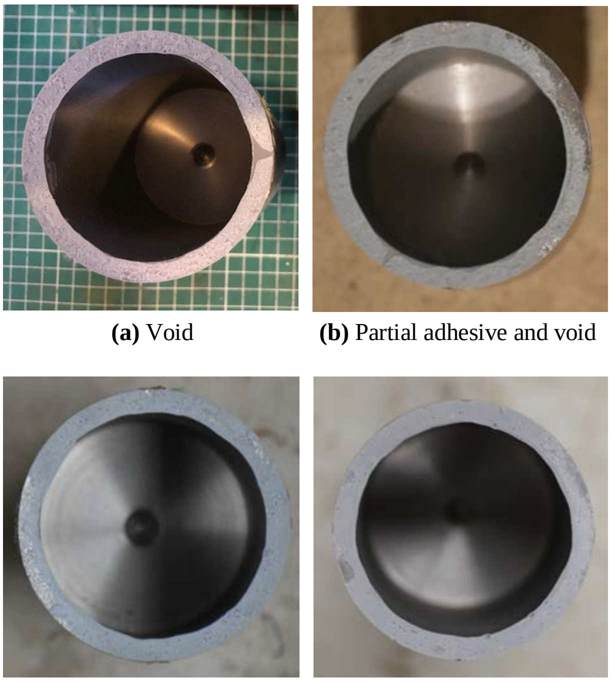
σ_0 : Sustained stress (GPa)

t : Creep lifetime to failure (min)

T : Temperature (°C)

(6) Failure modes

Fig.7 shows the four types of failure modes and conditions found after the failure of the specimen: (1) void, (2) partial adhesive failure and void, (3) partial adhesive failure, and (4) cohesive failure and smooth surface. From **Table 3**, it is difficult to find the relationship between failure modes and conditions from type (1)-(3) and the creep lifetime. However, failure mode and condition type (4) provide a short creep lifetime.



(a) Void **(b)** Partial adhesive and void **(c)** Partial adhesive **(d)** Cohesive and smooth

Fig.7 Failure modes

5. CONCLUSIONS

In conclusion, the findings in the experimental study on tensile creep behavior of butt-bonded joints can be summarized as follows:

(1) The average static tensile strength and the average maximum strain value are 36.5 MPa and $12{,}647\times10^{-6}$.
(2) The average maximum strain value at failure is $39{,}703\times10^{-6}$, approximately 3.1 times greater than the average maximum strain value from static tensile tests.
(3) The average lifetime of creep under the applied load of 67% of maximum static load can be confirmed and it is 99.2 hours.
(4) The creep data can be plotted and confirmed in the master curve of creep compliance of epoxy resin with a small variation.
(5) Four types of failure modes and conditions can be found after failure of specimen: (a) void, (b) partial adhesive failure and void, (c) partial adhesive failure, and (d) cohesive failure and smooth surface. The cohesive failure and smooth surface has found to be influenced to the creep lifetime.

Future work will deal with the data collection from the creep tests and the improvement of test apparatus to reduce the bending effect.

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