EVALUATION OF CREEP COMPLIANCE OF BUTT-BONDED JOINTS UNDER TENSILE LOAD

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This paper aims to evaluate the creep compliance of the adhesively bonded joints by the tensile tests using the time-temperature superposition principle (TTSP). The target specimen is a butt-bonded joint of the hollow cylindrical steel members using the adhesive Konishi E258R. The creep test apparatus of lever beam balance for large-scale experiments were designed with a loading capacity of 150kN. The creep tests were conducted under the applied load of 67 and 51% of the static failure load and the test temperature at 20, 40, and 50 °C. The creep compliance was calculated based on the TTSP by shifting to the reference temperature of 100 °C in order to compare with the creep compliance master curve from the previous study. The result shows that the creep test data from the tensile creep test of butt-bonded joint specimens have high variation when evaluated by the applied constant stress and the creep lifetime. However, the creep test data can be plotted well in the creep compliance master curve of epoxy resin at the reference temperature of 100 °C with a small variation.

Key Words : *creep compliance, master curve, creep lifetime, adhesive joint, adhesive failure*

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 the continuous decrease in the load-carrying capacity of the 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 focused on the creep behavior of adhesively bonded joints analytically and experimentally on various joint specimens, single-lap, double-strap for instance[4~8)].

On the other hand, increasing the test temperature can accelerate the creep life to predict the long-term response. The time-temperature superposition principle (TTSP), identified by Leaderman[9)], can simplify the individual different temperature curves into one single master curve at reference temperature based on creep compliance and time in a logarithmic graph. The performance of the master curve can be seen in several papers which studied various substrates and joint specimens[10~15)].

This paper aims to contribute to a better understanding of the creep behavior and to evaluate the creep compliance of the adhesively bonded joints by the tensile tests using the TTSP. The target specimen is a butt-bonded joint of the hollow cylindrical steel members using the adhesive Konishi E258R.

2. CREEP TESTS

(1) Specimen and material properties

Fig.1 shows the specimen of the adhesively bonded joints used in the creep tests. It is the butt-bonded joints of the hollow cylindrical steel members based on JIS K 6868-1[16]. Specimen C type, 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 height of the specimen is 200 mm (100 mm for each steel substrate). The 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 the assumed values, and the material properties of adhesive Konishi E258R are provided by the material manufacturer[17].

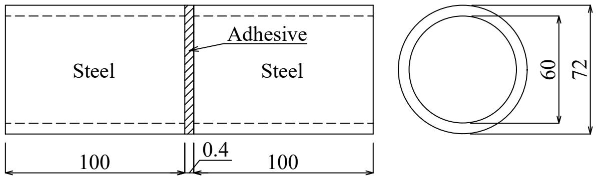


Fig.1 Schematic view of the specimen (JIS K 6868-1)

Table 1 Material properties of steel and adhesive

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

(2) Specimen preparation

The surfaces of steel were prepared by bristle blaster with the steel brush's width of 23 mm and were cleaned by acetone before bonded. The adhesive thickness was controlled to be approximately 0.4 mm using glass beads with a diameter of 0.4 mm. Moreover, to improve the uniform thickness of the adhesive, as shown in **Fig.2**, the fixed magnets (lower and upper) and the quick bar clamp (in the longitudinal direction) were used during the bonding process. After the bonding, the specimens are cured at 40 °C for 24 hours to obtain stable strength of the bonded adhesive. Four strain gauges of 3mm type were attached to the adhesive layer in the longitudinal direction to measure the strain value occurring in the adhesive layer.

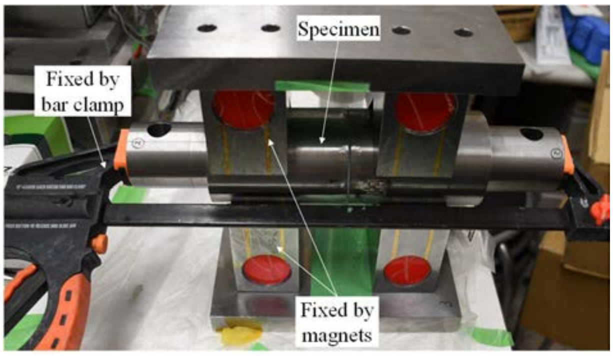


Fig.2 Specimen preparation during bonding process

(3) Design of creep test apparatus

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 tests, 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 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

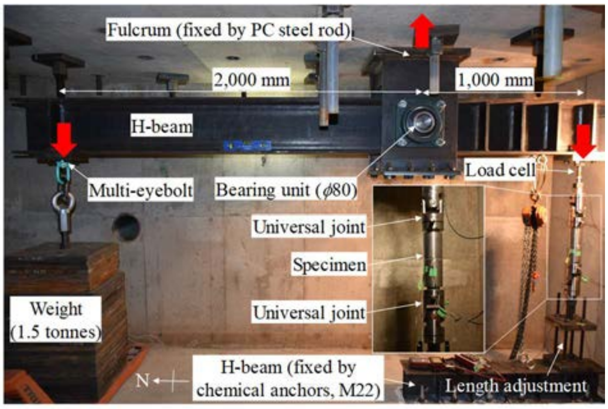


Fig.3 Creep test apparatus and setup of creep test

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.

(4) Temperature control

The experiments were conducted in the basement room where it can maintain a relatively constant temperature. Three cases of temperature tests were conducted, 20, 40, and 50 °C. The oil heater was used to improve and maintain the basement temperature at approximately 20 °C. For high-temperature tests, the mantle heater (wrap around the specimen) and temperature regulator were combinedly used to elevate the temperature of specimens to 40 and 50 °C. **Fig.4** shows the temperature control of the specimen for the high-temperature tests.

(5) Experimental series and conditions

Table 2 shows the experimental series and conditions of the creep tests. 20 specimens of the creep tests were conducted under the applied load of 67 and 51% of the static failure load, equivalent to the stress of 24.3 and 18.7 MPa, and the temperature test at 20, 40, and 50 °C.

It should be noted that the static tensile tests were separately conducted using a special tensile test device for 10 specimens. From the static tensile tests, the average tensile strength was 36.5 MPa. The standar deviation SD is 5.1 MPa, and the coefficient of variation CV is 0.140.[18, 19] This tensile strength is almost the same as the value provided by the adhesive manufacturer as presented in **Table 1** (33 MPa).

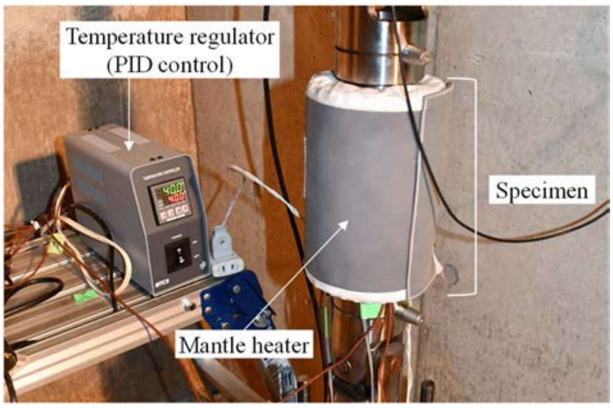


Fig.4 High-temperature test control by mantle heater and temperature regulator

Table 2 Creep test series and conditions

Percentage of applied load (%)	Applied stress (MPa)	Temperature (°C)	Number of specimens
67	24.3	20	12
		40	3
		50	1
51	18.7	40	3
		50	1

Note: the static tensile strength is 36.5 MPa.

Table 3 Creep test series and results

Specimens	Applied constant stress σ_0 (MPa)	Temperature T (°C)	Shift factor a_T (at T=100 °C)	Creep lifetime t (hours)	Total strain $\varepsilon(t, T)$ (×10^{-6})	Creep compliance $D_c(t, T)$ (GPa^{-1})	Creep lifetime before shifting t (min)	Creep lifetime after shifting t' (min)
C1	24.3	16.4	1.07×10^{7}	199.50	9,092	0.37	1.20×10^{4}	1.12×10^{-3}
C2	24.2	20.4	4.01×10^{6}	13.40	8,088	0.33	8.04×10^{2}	2.01×10^{-4}
C3	24.2	21.5	3.09×10^{6}	606.90	7,830	0.32	3.64×10^{4}	1.18×10^{-2}
C4	24.5	20.9	3.55×10^{6}	7.30	7,779	0.32	4.38×10^{2}	1.24×10^{-4}
C5	24.6	20.2	4.20×10^{6}	0.90	7,032	0.29	5.40×10^{1}	1.29×10^{-5}
C6	24.1	20.5	3.97×10^{6}	0.50	7,740	0.32	3.00×10^{1}	7.55×10^{-6}
C7	23.7	20.3	4.17×10^{6}	0.10	5,913	0.25	6.00×10^{0}	1.44×10^{-6}
C8	24.6	20.5	3.93×10^{6}	0.60	7,565	0.31	3.60×10^{1}	9.17×10^{-6}
C9	24.7	20.6	3.87×10^{6}	5.10	7,560	0.31	3.06×10^{2}	7.91×10^{-5}
C10	24.6	20.5	3.91×10^{6}	218.40	8,481	0.34	1.31×10^{4}	3.35×10^{-3}
C11	24.7	20.0	4.46×10^{6}	137.62	7,294	0.30	8.26×10^{3}	1.85×10^{-3}
C12	22.9	20.0	4.46×10^{6}	0.07	6,312	0.28	4.12×10^{0}	9.24×10^{-7}
Average	**24.3**	**20.2**	$\mathbf{4.53\times10^{6}}$	**99.2**	**7,557**	**0.31**	$\mathbf{5.95\times10^{3}}$	$\mathbf{1.55\times10^{-3}}$
SD	0.5	1.2	1.90×10^{6}	172.5	829	0.03	1.03×10^{4}	3.25×10^{-3}
CV	0.020	0.059	0.421	1.739	0.110	0.101	1.739	2.099
C13	24.4	39.6	5.06×10^{4}	3.87	7,473	0.31	2.32×10^{2}	4.59×10^{-3}
C14	24.5	40.2	4.46×10^{4}	0.41	8,112	0.33	2.47×10^{1}	5.53×10^{-4}
C15	24.7	40.3	4.34×10^{4}	9.80	8,225	0.33	5.88×10^{2}	1.36×10^{-2}
Average	**24.5**	**40.0**	$\mathbf{4.62\times10^{4}}$	**4.7**	**7,937**	**0.32**	$\mathbf{2.82\times10^{2}}$	$\mathbf{6.23\times10^{-3}}$
SD	0.1	0.3	3.15×10^{3}	3.9	331	0.01	2.33×10^{2}	5.43×10^{-3}
CV	0.005	0.008	0.068	0.826	0.042	0.039	0.826	0.872
C16	**24.2**	**50.0**	$\mathbf{5.88\times10^{3}}$	**0.04**	**9,312**	**0.38**	$\mathbf{2.10\times10^{0}}$	$\mathbf{3.57\times10^{-4}}$
C17	18.8	39.7	4.97×10^{4}	28.88	8,649	0.46	1.73×10^{3}	3.49×10^{-2}
C18	18.7	37.4	8.12×10^{4}	1.58	5,918	0.32	9.49×10^{1}	1.17×10^{-3}
C19	18.7	39.5	5.21×10^{4}	41.36	7,314	0.39	2.48×10^{3}	4.77×10^{-2}
Average	**18.7**	**38.9**	$\mathbf{6.10\times10^{4}}$	**23.9**	**7,294**	**0.39**	$\mathbf{1.44\times10^{3}}$	$\mathbf{2.79\times10^{-2}}$
SD	0.1	1.0	1.43×10^{4}	16.6	1,115	0.06	9.97×10^{2}	1.96×10^{-2}
CV	0.003	0.026	0.235	0.694	0.153	0.150	0.694	0.703
C20	**18.7**	**46.8**	$\mathbf{1.12\times10^{4}}$	**31.02**	**8,788**	**0.47**	$\mathbf{1.86\times10^{3}}$	$\mathbf{1.67\times10^{-1}}$

Note: the temperature of C11, C12, and C16 are assumed values.

3. CREEP TEST RESULTS

(1) Creep test results

Table 3 shows the creep tensile test series and results of the 20 specimens. In the case of test temperature at 50 °C for the applied load of 67 and 51%, there is only one specimen for each case conducted. So that the average, SD, and CV are abbreviated.

The applied constant stress and test temperature are measurement values from the experiment. The creep lifetime is the time until the failure of the specimen The calculation of shift factor, total strain, and creep compliance will be explained in **section (4)**.

(2) Strain behavior

Fig.5 shows the strain behaviors obtained from the strain gauge attached to the adhesive layer (S1-S4). 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 increase again in the last stage to failure. **Fig.5** also plotted the applied load (solid black line) and temperature (solid yellow line) measured in the basement. Constant values of applied load (approximately 30.3 kN) and temperature (approximately 20 °C) can be confirmed.

(3) Creep lifetime

Fig.6 plots all of the experimental data and the average data of static tensile tests and creep tests under applied load and lifetime to the failure of test temperature at 20 °C. 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 average lifetime of creep under the applied load of 67% of the maximum static load is 99.2 hours (SD=172.5 hours, CV=1.739).

Fig.7 plots all cases of the average load and average lifetime until failure. From the figure, the lifetime until failure of test temperature at 40 and 50 °C are shorter than that of 20 °C. However, the variation can be seen in cases of 40 and 50 °C under applied stress of 51%.

(4) Creep compliance

The creep compliance $D_c\,(t,\ T)$ (GPa^{-1}) in **Table 3** is calculated by **Eq. (1)**[20]. It is the ratio of the total strain $\varepsilon\,(t,\ T)$ to the applied constant stress σ_0 (GPa). Here, t is the creep lifetime to failure (min), and T is the temperature (°C).

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

The total strain is calculated by **Eq. (2a)**. The values of elastic modulus E_1 and E_2, and viscosity coefficients η_1 and η_2 are described in **Fig.8** and **Eq. (2b)~Eq. (2e)**[11]. The red line shows the strain behavior of the average strain value obtained from the four strain gauges attached to the adhesive layer in the longitudinal direction.

$$\varepsilon(t,T) = \sigma_0\left[\frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2}\left(1 - \exp\left(-E_2 t / \eta_2\right)\right)\right] \tag{2a}$$

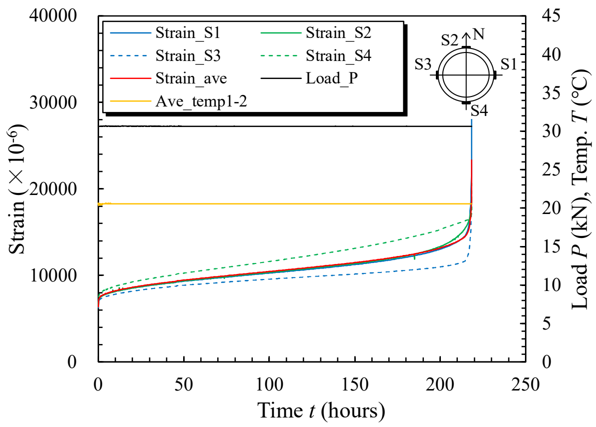


Fig.5 Average load versus lifetime until failure

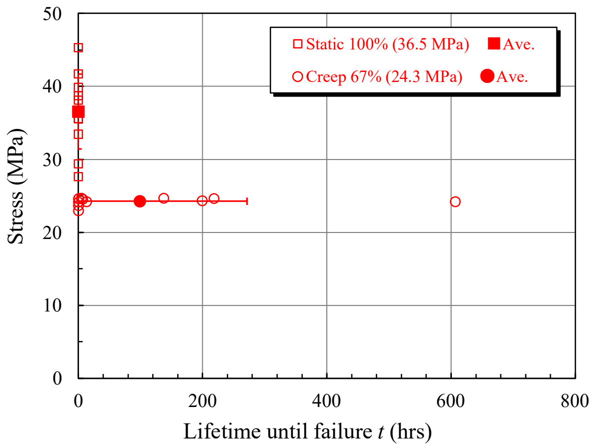


Fig.6 Load versus lifetime until failure (temperature at 20 °C)

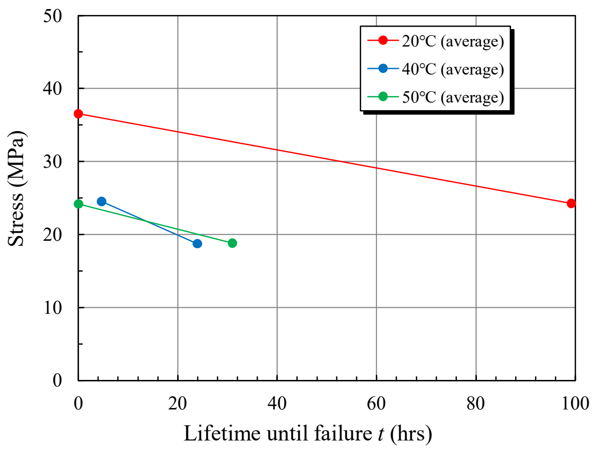


Fig.7 Average load versus lifetime until failure

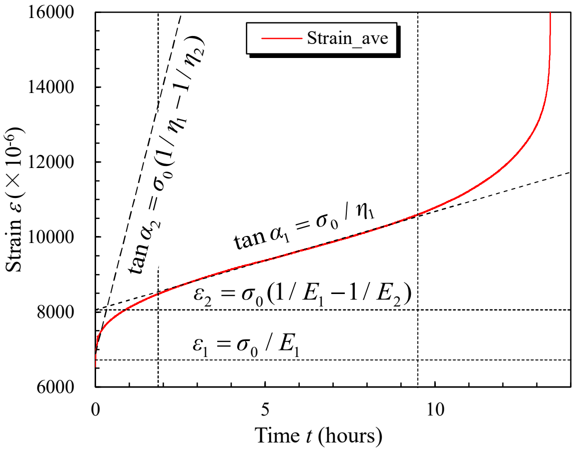


Fig.8 Strain behavior and parameter determination (C2)

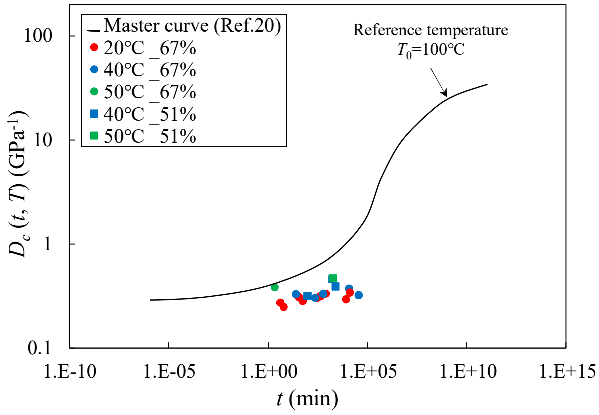


Fig.9 Relation between creep compliance and creep lifetime before shifting

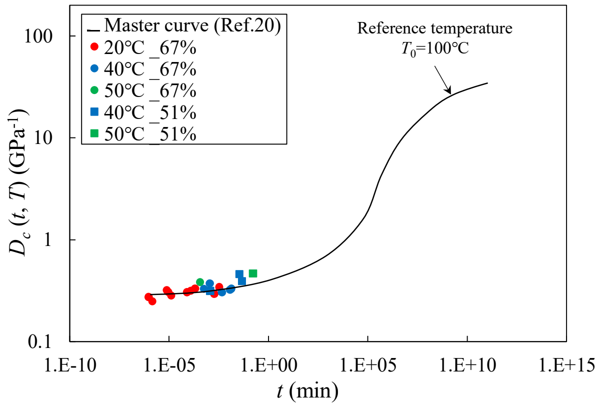


Fig.10 Relation between creep compliance and creep lifetime after shifting

$$E_1 = \frac{\sigma_0}{\varepsilon_1} \tag{2b}$$

$$\eta_1 = \frac{\sigma_0}{\tan\alpha_1} \tag{2c}$$

$$E_2 = \frac{E_1\sigma_0}{E_1\varepsilon(0) - \sigma_0} \tag{2d}$$

$$\eta_2 = \frac{\eta_1\sigma_0}{\eta_1\tan\alpha_2 - \sigma_0} \tag{2e}$$

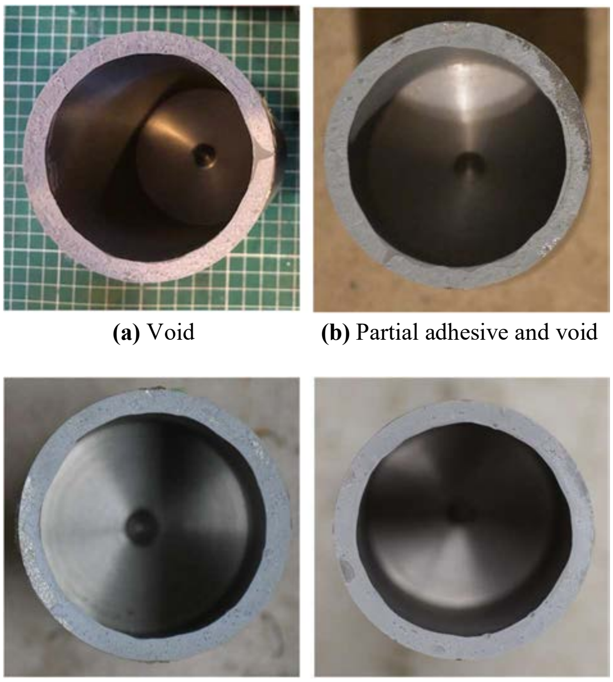
The creep master curve at the reference temperature T_0 can be constructed from the creep tests from different temperatures using the temperature-dependent shift factor a_T based on the TTSP, and a_T is defined by **Eq. (3)**, an approach based on Arrhenius law. Here, ΔH is the activation energy (ΔH=41 kcalmol^{-1}), and R is the universal gas constant (R=1.96×10^{-3} kcalK^{-1}mol^{-1})[10].

$$\log(a_T) = \frac{\Delta H}{2.303 \times R}\left(\frac{1}{T} - \frac{1}{T_0}\right) \tag{3}$$

The creep lifetime after shifting t' (min) is expressed by **Eq. (4)**, the creep lifetime before shifting t (min) divided by shifting factor a_T.

$$t' = \frac{t}{a_T} \tag{4}$$

Fig.9 and **Fig.10** plot the current creep test data in the creep compliance master curve of epoxy resin[20]. **Fig.9** plots the creep lifetime before shifting, and **Fig.10** plots the creep lifetime after shifting to the reference temperature T_0 of 100 °C. The horizontal axis is the creep lifetime before and after shifting, and the vertical axis is the creep compliance. The circles are applied load of 67% and the squares are applied load of 51%. The red, blue, and green are for 20, 40, and 50 °C data, respectively. The creep compliance master curve was drawn at the reference temperature T_0 of 100 °C based on the TTSP by shifting the creep compliance curves at various temperatures T. From the figures, the creep lifetime after shifting fits well with the creep compliance master curve. However, it requires further creep test data of temperature tests higher than 50 °C to confirm the whole master curve.


(a) Void **(b)** Partial adhesive and void

(c) Partial adhesive **(d)** Cohesive and smooth

Fig.11 Failure modes

(5) Failure modes

Fig.11 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. 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.

4. 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 lifetime of creep under the applied load of 67% of tensile failure load at the temperature tests of 20 °C can be confirmed and it is 99.2 hours.
(2) The lifetime until failure of test temperature at 40 and 50 °C are confirmed to be shorter than that of 20 °C. However, the variation can be seen in cases of 40 and 50 °C under applied stress of 51%. This is due to the current limited number of data.
(3) The creep tensile test data have high variation when evaluated by the applied constant stress and the creep lifetime.
(4) The creep tensile test data can be plotted well in the creep compliance master curve of epoxy resin at the reference temperature T_0 of 100 °C 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 the creep lifetime.

Future work will deal with the creep test parameters of test temperature and applied stress and the data collection from the creep tests to further understand and construct the creep compliance master curve.

REFERENCES

1) Japan Society of Civil Engineers (JSCE) : Advanced technology of joining for FRP structures and FRP bonding for steel structures, *Hybrid Structure Reports 09*, 2013.11 [in Japanese]
2) Nuwayer, H. M. and Newaz, G. M. : Flexural creep behavior of adhesively bonded metal and composite laminates, *International Journal of Adhesion and Adhesives*, Vol. 84, pp.220-226, 2018.8
3) Su, N. and Mackie, R. I. : Two-dimensional creep analysis of structural adhesive joints, *International Journal of Adhesion and Adhesives*, Vol. 13, No. 1, pp.33-40, 1993.1
4) Queiroz, R. A., Sampaio, E. M., Cortines, V. J., Rohem, N. R. F. : Study on the creep behavior of bonded metallic joints, *Applied Adhesion Science*, Vol. 2, No. 8, pp.1-12, 2014.3
5) Saeimi Sadigh, M. A., Paygozar, B., da Silva L. F. M., Vakili Tahami, F. : Creep deformation simulation of adhesively bonded joints at different temperature levels using a modified power-law model, *Polymer Testing*, Vol. 79, No. 1, pp1-6, 2019.10
6) Saeimi Sadigh, M. A., Paygozar, B., da Silva L. F. M., Matinez-Paneda, E. : Creep behaviour and tensile response of adhesively bonded polyethylene joints: Single-Lap and Double-Strap, *International Journal of Adhesion and Adhesives*, Vol. 102, pp.1-10, 2020.10
7) Saeimi Sadigh, M. A. : Creep simulation of adhesively bonded joints using modified generalized time hardening model, *Journal of Mechanical Science and Technology*, Vol. 30, No. 4, pp.1555-1561, 2016.4
8) Costa, I. and Barros, J. : Tensile creep of a structural epoxy adhesive: Experimental and analytical characterization, *International Journal of Adhesion and Adhesives*, Vol. 59, pp.115-124, 2015.1
9) Leaderman, H. : Elastic and creep properties of filamentous materials and other high polymers., *Washington, D.C., Textile Foundation*, 1943.
10) Miyano, Y., Kanemitsu, M., Kunio, T. : Time and temperature dependence of mechanical behaviors in transversal direction of fibers in CFRP, *Journal of the Society of Materials Science*, Vol.28, pp.1098-1103, 1979.11 [in Japanese]
11) Houhou, N., Benzarti, K., Quiertant, M., Chataigner, S., Fléty, A., Marty, C. : Analysis of the nonlinear creep behavior of concrete/FRP-bonded assemblies, *Journal of Adhesion Science and Technology*, Vol.28, No.14-15, pp.1345-1366, 2014.8
12) Sheng, X., Akinc, M., Kessler, M. R. : Creep behavior of bisphenol E cyanate ester/alumina nanocomposites, *Materials Science and Engineering A*, Vol.527, pp.5892-5899, 2010.8
13) Dasappa, P., Lee-Sullivan, P., Xiao, X. : Temperature effects on creep behavior of continuous fiber GMT composites, *Composites Part A*, Vol.40, pp.1071-1081, 2009.8
14) Vaidyanathan, T. K., Vaidyanathan, J., Cherian, Z. : Extended creep behavior of dental composites using time-temperature superposition principle, *Dental Materials*, Vol.19, pp.46-53, 2003.1
15) Majda, P. and Skrodzewicz, J. : A modified creep model of epoxy adhesive at ambient temperature, *International Journal of Adhesion Adhesives*, Vol.29, pp.396-404, 2009.6
16) JIS K 6868-1 : Adhesives−Determination of shear behaviour of structural bonds−Part 1: Torsion test method using butt-bonded hollow cylinders, 1999.
17) Konishi : Product guide & technical data, Bond E258R, 2019. [in Japanese]
18) Thay, V., Kiyono, K., Nakamura, H., Horii, H. : Experimental study on tensile creep behavior of butt-bonded joints, *JSCE, Proceedings of the 14th Symposium on Research and Application of Hybrid and Composite Structures*, pp.14-1-14-5, 2021.11
19) Kiyono, K., Thay, V., Nakamura, H., Horii, H. : Experimental study on evaluation of static bonding strength under combined stress, *JSCE, Proceedings of the 14th Symposium on Research and Application of Hybrid and Composite Structures*, pp.5-1-5-8, 2021.11 [in Japanese]
20) The Japan Reinforced Plastics Society (JRPS) : FRP Basics−From basics to applications of fiber reinforced plastics−, *Corona Publishing*, pp.123-127, 2016.4 [in Japanese]

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