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Original Research Article

Expectancy of the lifetime of bonded steel joints due to long-term shear loading

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ABSTRACT

In this paper, the time-dependent behaviour, shear creep behaviour, of double lap galvanized steel joints loaded in shear by tension, is investigated at room temperature. The studied joints are assembled by bonding the galvanized steel adherends by a rigid structural adhesive (epoxy). Two thicknesses of the bondline (0.35 mm and 0.65 mm) are used. The specimens are tested under different shear stress levels. Well-known rheological and empirical models are used to describe the behaviour of the adhesive. The relevant models parameters are experimentally estimated. The time-to-failure of the studied specimens is predicted in accordance with short-term tests (rapid-loading tests) performed on similar specimens. The applied shear stresses for particular lifetimes of the bonded joints are estimated.

1. Introduction

In spite of the encouraging properties, by which the structural adhesives are characterized, the use of these materials in the structural engineering fields needs to be validated. This needs intensive test plans to assess both the short-term and long-term behaviours under defined conditions of mechanical and environmental loading. By demonstrating that bonded joints can carry predefined loads over the lifetime of the joint, the engineering industry would become convinced to use such a technique in its applications.

Long-term assessment is more difficult than the short-term or the accelerated testing because special techniques and equipments are needed for long time; therefore, the costs especially when testing a large number of specimens to accommodate all conditions might increase. However, the long-term testing results, under real conditions, are still more realistic.

The phenomenon of the increase in strain or deformation of a material with time is called creep. This phenomenon occurs when the material is subjected to a constant load over an extended period of time (i.e. time-dependent deformation). The time-dependent deformation increases as the applied load, temperature, and relative humidity increase.

Adhesives, as being polymers, are viscoelastic materials that can deform over a period of time at relatively low stress levels and low temperatures. The durability of these materials, therefore, is expected to be reduced due to the loss of their strength that resulted from the creep phenomenon. This paper presents a contribution to estimate the lifetime of adhesively bonded overlap steel joints loaded for long time and which can be used in lightweight steel constructions.

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2. State-of-the-art

The investigations on the time-dependent behaviour of structural adhesives are still modest. Many researchers have focused on the creep behaviour of one of the available structural adhesives, which is the epoxy, and their investigations were set to study the creep behaviour of it in tension loading. The tension creep of the adhesive was basically described using a particular creep model, Burger's model, whose parameters were found for such loading case [1,2].

The shear creep of an epoxy, used to connect fibre reinforced polymer (FRP) to the concrete, was studied and assessed in [3,4]. Both of them described the long-term behaviour by using rheological models and empirical equations and found the relevant parameters of the used models. It was also recognized by the finite element analysis performed in [3], that the creep of epoxy might result in stress redistribution at the concrete–FRP interfaces.

In stainless steel lap joints bonded by an epoxy adhesive, the time over which the adhesive resisted sustained loads was recorded and evaluated by [5]. Specimens loaded by 20% and 40% of the main static failure load sustained the loads over six months without failure and were showing no apparent damage which might indicate to the existence of the so-called endurance limit.

The behaviour of the bonded metallic single lap joints with epoxy and polyurethane adhesives was evaluated as a function of the load applied by [6]. It was found that joints loaded above 60% of the static strength account for a relatively small lifespan. Epoxy exhibited a higher creep resistance than polyurethane. The safe region for the use of the joints was determined basing on the curve stabilization observed in the load–lifespan curves.

The creep behaviour investigated by the above mentioned researches was obtained by functioning the joint under sustained loads. This kind of long-term tests will also be illustrated here.

3. The principle of creep tests on the bonded joints

The creep of the bonded joint under sustained loads can be done similar to the procedure of (ETAG001-Part five, [7]). The principle of this test method is to maintain the applied load on the joint at a specific level (i.e. at predefined applied stress, usually taken as a ratio of the strength capacity of the same joint under short-term or rapid test). The deformation of the joint, mainly the adhesive, has to be measured until it appears to have stabilized or for at least three months. The frequency of monitoring the deformations (the displacements) has to be high initially in the early stages as the displacements are greatest in these stages and can be reduced with time.

The displacements measured in the tests have to be extrapolated to a specific lifetime according to a known model. The extrapolated displacements shall be less than the average value of the displacements obtained by reference tests (short-term or rapid tests).

4. Modelling of the creep behaviour of the adhesive

The creep behaviour of viscoelastic materials has been modelled by empirical models such as power-law equations like Bailey-Norton and Findley's model and also by mechanical models such as Kelvin–Voigt and Burger's models. However, Bailey-Norton and Kelvin–Voigt models do not consider the instantaneous deformation; therefore, in this work only Findley's and Burger's models are used.

Findley's approach has been developed since 1956 [8] and many equations were derived from it till this time. The Simplified Findley's model is given for the shear case as:

$$\gamma(t) = \gamma_0 + At^B \tag{1}$$

where $\gamma(t)$ is the shear strain over the time t, γ_0 is the instantaneous shear strain when $t = 0$ (measured directly after applying the load), and A and B are constants (tuning factors in the shear case evaluated by a regression analysis of the deformations measured during the creep test).

Due to the difficulties in measuring the exact instantaneous strain γ_0, it can be determined separately by the short-term or rapid-loading test on a specimen of material identical to that used in the creep test being evaluated [8]. The instantaneous strain γ_0 by this way is defined by Eq. (2):

$$\gamma_0 = \frac{\tau}{G_{t(0)}} \tag{2}$$

where τ is the applied shear stress and $G_{t(0)}$ is the initial shear elasticity modulus taken from rapid-loading test.

The most common mechanical model in literature being used to describe the creep behaviour of the adhesives (as being polymers) is Burger's model which consists of two simple models, Maxwell and Kelvin–Voigt models, attached together in series.

The Burger's model in shear (Fig. 1) is given in Eq. (3):

$$\gamma(t) = \frac{\tau}{G_M} + \frac{\tau}{\lambda_M} \cdot t + \frac{\tau}{G_K}\left(1 - e^{-(G_K/\lambda_K)t}\right) \tag{3}$$

In which, τ is the constant applied shear stress; G_M, G_K, λ_M and λ_K represent the shear elasticity and the shear viscosity of Maxwell and Kelvin elements respectively. It is obvious that the first term in Eq. (3) represents γ_0, the instantaneous shear strain when $t = 0$.

5. Creep tests of adhesively bonded steel joints

5.1. Studied joint

Double lap shear joints, whose geometry is shown in Fig. 2, were selected. The common hot-dip galvanized steel D × 51D

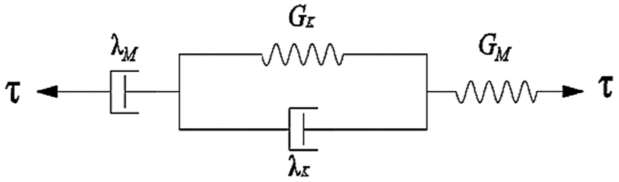


Fig. 1 – Mechanical Burger's model.

+ Z (275) as classified in DIN EN 10327 with thicknesses of 1 and 2 mm was selected to be the external and internal adherends respectively. The investigated adhesive is the two-component cold-cure epoxy DP 490. The bonded area 16 mm × 16 mm for each side was used. The thickness of the adhesive layer is 0.35 and 0.65 mm which was achieved by the use of one-sided adhesive strips, as shown in Fig. 2. Preventing the squeeze-out adhesive from participating in carrying a part of the shear stresses was also achieved with the use of transparent tapes after the overlap region on each side.

The specimens have two advantages, the applied force will be centrally transferred from one side to the other and every specimen has four bonded areas to be tested instead of two. The adhesive was applied according to the recommendations of the manufacturer 3 M Scotch-Weld^{TM}. After bonding, the specimens were left 7 days at room temperature to be cured.

5.2. *Test procedure*

The specimens were installed into a creep machine which consists of six cantilever steel beams designed to amplify 5 times a given static load. The beams were placed by rollers on a truss steel structure which is fixed to the ground of the laboratory. The beams were designed to be rigid enough to avoid any possible deflection that may occur at the free ends of the shorter parts.

Three constant shear stresses were used and applied to the specimens and they were chosen to be equal to or less than 50% of the short-term maximum-shear strength [5] at 20 °C. The creep machine is shown in Fig. 3. To guarantee that the received forces at the shorter sides are accurate as possible, the used weights and all equipments were weighed and calibrated before the tests by using a tension sensor, Fig. 4, connected to a digital screen installed where each specimen should be installed.

The temperature and the relative humidity were observed over the test period at different time intervals and found to be around 20 ± 3 °C and 40–50% of R.H. respectively.

The shear deformation was measured by observing the displacement of six gauge points (DEMECs predrilled gauge points) fixed at front and back faces on the specimens as shown in Fig. 5(a). The distances between the points were measured using a movable digital strain device with 0.001 mm resolution, Fig. 5(b). This procedure was followed by many researchers, e.g. [3,4,9].

The test was repeated twice for a period of 2641 h for each time. In every test, two groups of EP-0.35 mm and EP-0.65 mm were investigated together. Each of them has three specimens loaded by three different shear stresses (5.74, 7.66, 9.57 MPa). It should be noted that EP represents the epoxy adhesive, while 0.35/0.65 indicates the thicknesses of the adhesive layer tested.

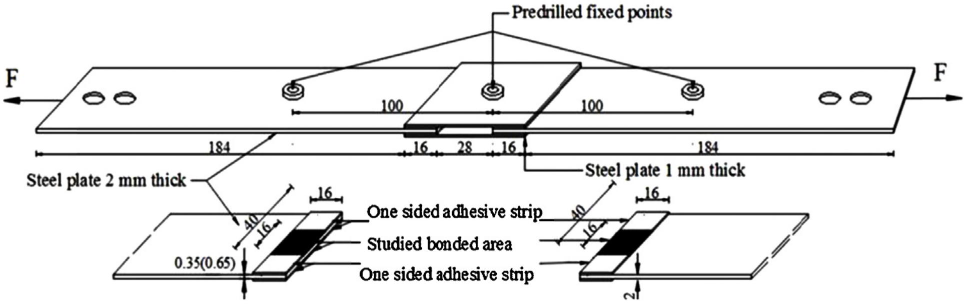


Fig. 2 – Double lap shear joint, black areas represent the bonded areas.

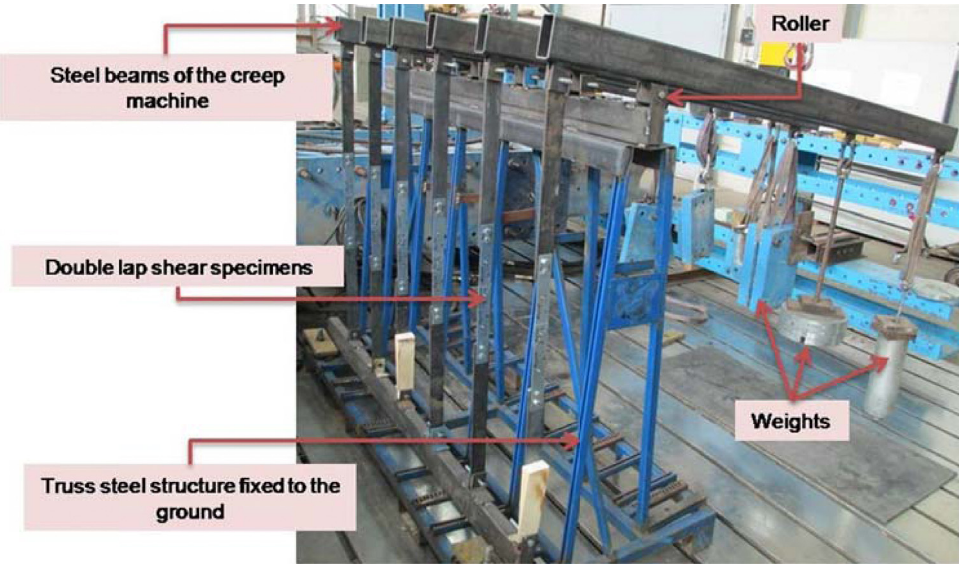


Fig. 3 – Creep machine.

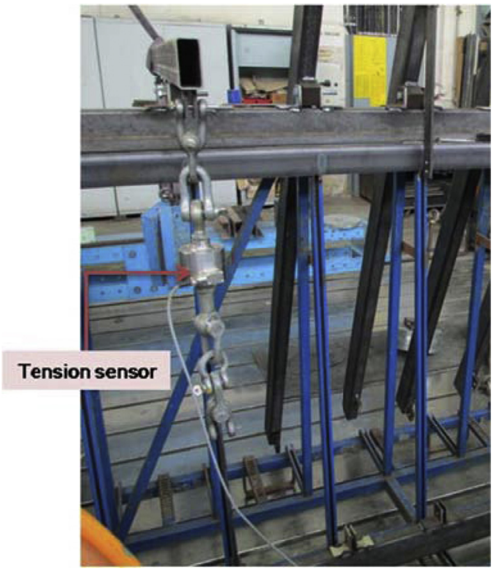


Fig. 4 – Tension sensor used to calibrate the applied loads.

The shear stress was considered regularly distributed over the bondline and calculated by dividing the applied force by the two-sided bonded areas, i.e. $2 \times 16 \times 16 = 512\ \text{mm}^2$.

It was noted that the displacements measured were scattered; therefore, the shear strain was calculated by taking the average value of the displacements (after subtracting the normal strain of the steel adherends) and dividing it by the relevant adhesive layer thickness. The shear strain–time curves were plotted.

5.3. *Shear creep results of adhesive-bonded joints*

The plots of the obtained shear strains versus the time are presented in Figs. 6 and 7 for EP-0.35 and EP-0.65 respectively. The average shear strains were best-fitted using Findley's and Burger's models (Eqs. (1) and (3)) by a regression analysis. The instantaneous shear strain γ_0 for both models was determined from Eq. (2) using the shear moduli (G) taken from the rapid-loading tests, Table 1. After that, the parameters (G_M, λ_M, G_K and λ_K) of Burger's model and those of Findley's model (A and B) were found.

The models parameters and the coefficient of determination R^2 of them are listed in Tables 2 and 3. It is obvious, that both models well represent the shear creep of the used adhesive. However, R^2 values generally indicate that Findley's model fits the data points better than Burger's model over the test period.

5.4. *The lifetime expectancy of the bonded joints*

The time-to-failure was estimated using the fitted models, Findley's and Burger's models, by assuming that the specimens will fail at the corresponding shear strain obtained from the rapid-loading tests (Table 1). However, as it is expected, the time-to-failure by these approaches estimated with a noticeable variation.

Due to the fact that the data points are stabilized at the last stages of the curves, it was further suggested that the steady-state creep rate of the test results is to be used together with the two models.

This is for the sake of comparing the predicted (time-to-failure) obtained by the models with the corresponding one predicted using the steady-state creep rate method.

The principle of the last method is that the creep rate has to be calculated over the stage of the creep curve where the data points are stabilized, and then the creep rate over this stage can be described by expression (4):

$$\gamma_s = \gamma^* \cdot t + a \tag{4}$$

in which γ_s is the shear strain of the adhesive at the steady-state stage, γ^* is the creep rate at this stage, and a is a parameter that expresses the intersection point at the shear strain axis.

The parameters of this expression can be estimated using the linear regression analysis of the points which are within the steady stage; therefore, the last three points of the shear creep plots have been taken in order to guarantee that they belong to this stage.

It should be noted that an approximate estimation using the three methods was being made during the last month of the test. According to the steady-state creep rate and Burger's model, the second specimen of EP-0.65 loaded by the highest level was supposed to fail at the end of intended test period, however, Findley's model gave much longer time to the failure.

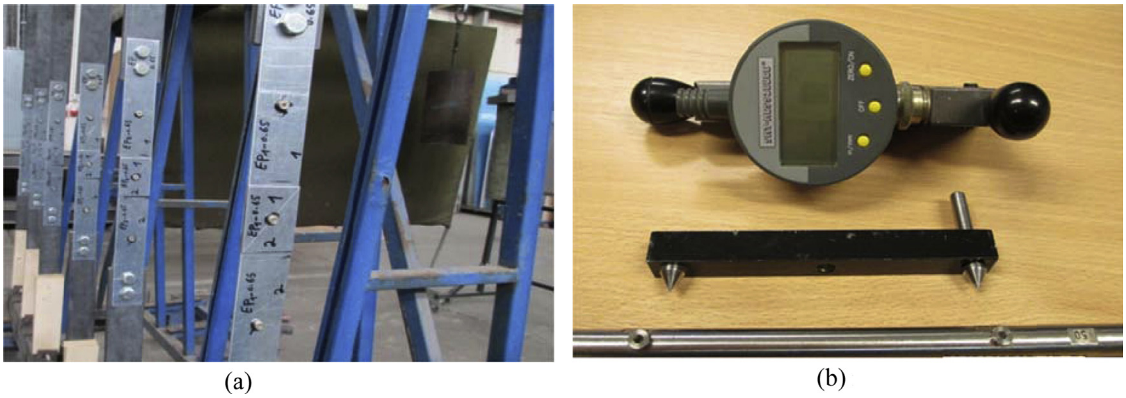
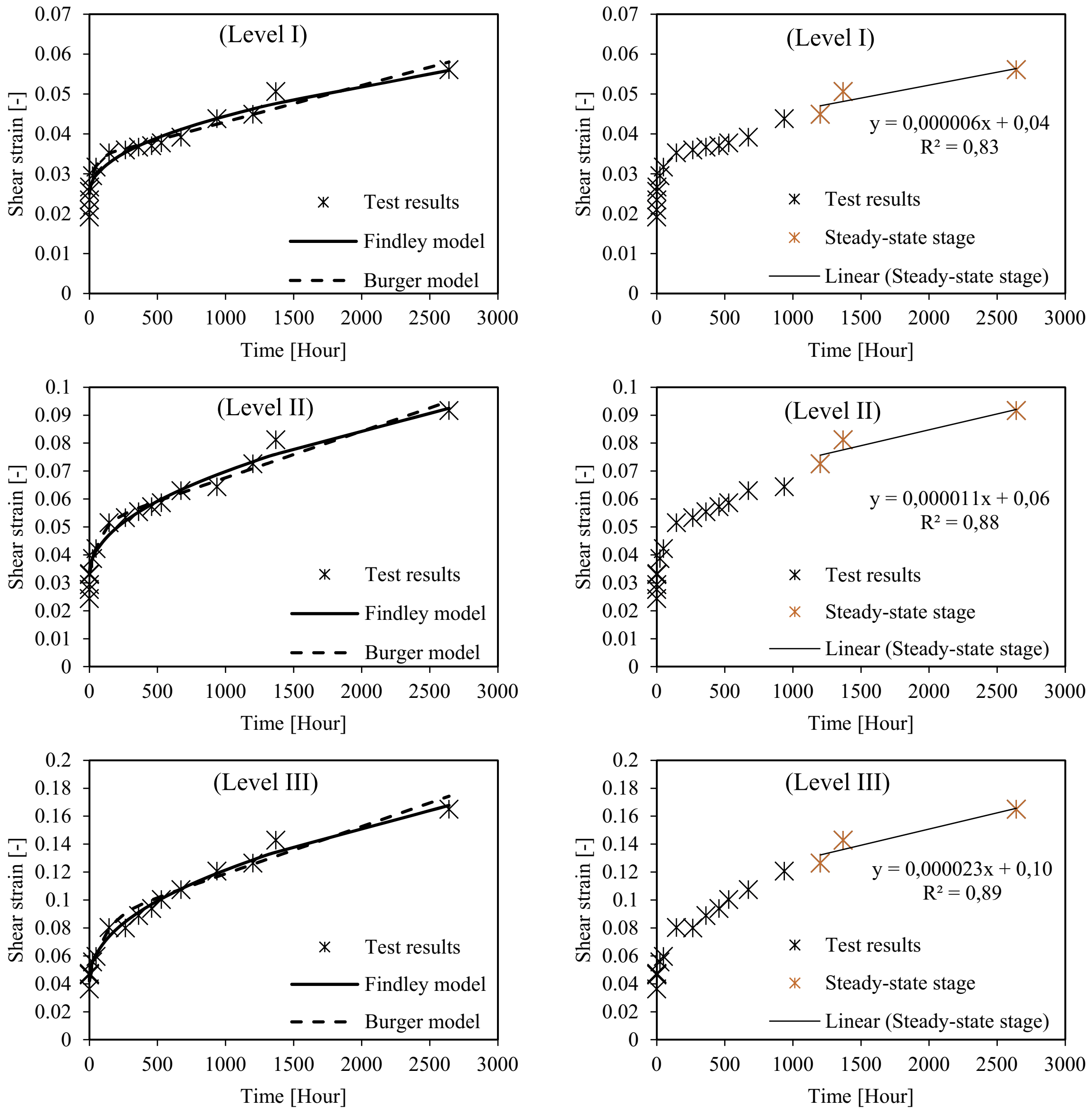

(a) (b)

Fig. 5 – Long-term shear strain measurement. (a) Six gauge points fixed on front and back surfaces and (b) movable device for measuring the displacements.



(a) (b)

Fig. 6 – Shear creep strains of EP-0.35. (a) Fitted Findley's and Burger's models and (b) determination of the steady-state creep rate.

Therefore, this specimen was left till the failure happened, which was almost eight days after the last data point recorded. This might verify the estimation by Burger's model and, also, might be evidence of the disability of Findley's model to describe the creep behaviour for longer time due to the unlimited retardation spectrum of this model [11].

Table 1 – Some of the short-term mechanical shear properties of DP 490.

	Short-term tests, rapid-loading tests[a] [10]		
	G (MPa)	τ_{max} (MPa)	$\gamma_{at\ break}$
EP-0.35	233.97	26.68	0.4
EP-0.65	317.60	23.89	0.24

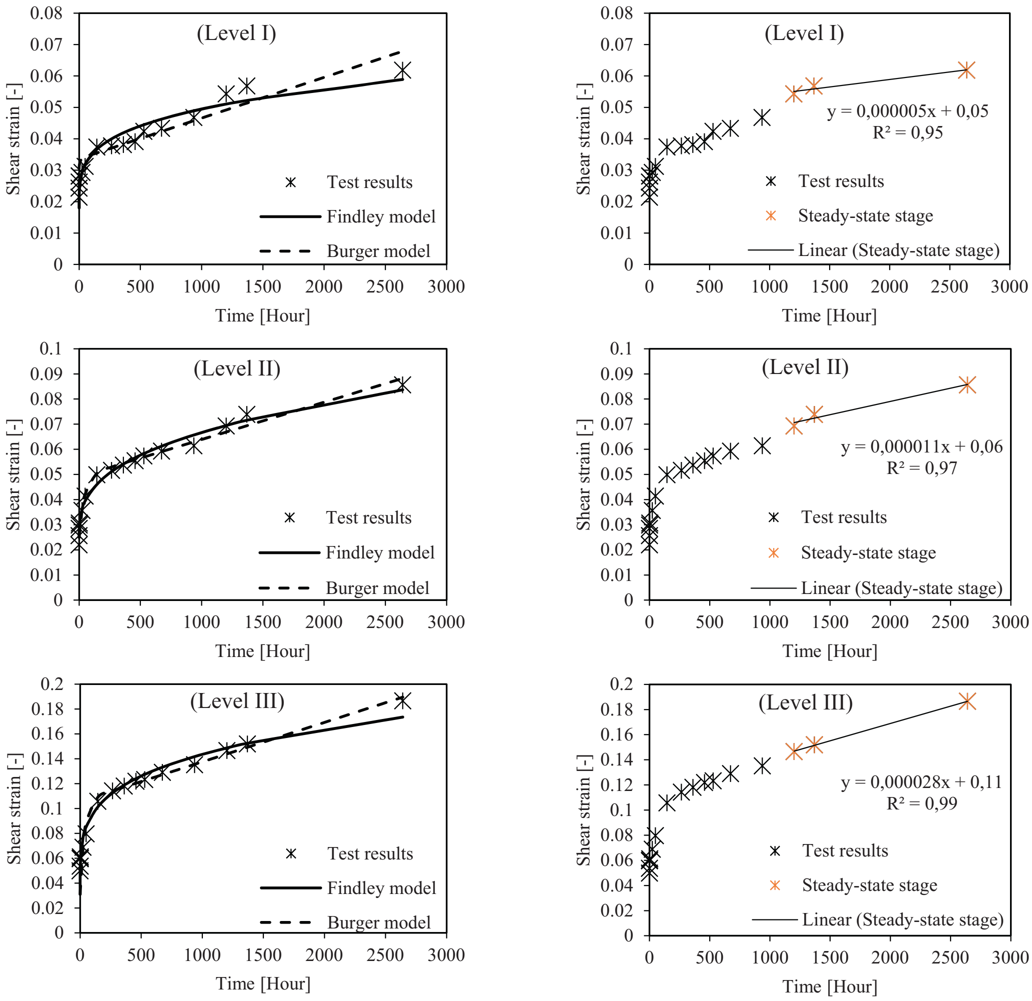
[a] G is the shear elasticity modulus, τ_{max} is the maximum shear stress, and $\gamma_{at\ Break}$ is the shear strain at break.

Table 4 lists the parameters of the steady-state creep rate approach. The predicted time-to-failure of the studied joints according to all mentioned methods is shown in Table 5 in which values denoted by (a) refer to the average value between the real failure time recorded for one specimen and the failure time estimated by the relevant model for the other specimen.

The relative errors committed by using Burger's and Findley's models when compared with the steady-state creep rate approach are presented in Table 6. It is obvious that Findley's model gives very excessive time values.

5.5. *Estimation of the applied shear stress for particular lifetime of the bonded joints*

The normalized shear stresses (see Table 5) are plotted as functions of the natural logarithm of the time-to-failure in Fig. 8(a) for the Burger's estimations and in Fig. 8(b) for those of



(a) (b)

Fig. 7 – Shear creep strains of EP-0.65. (a) Fitted Findley's and Burger's models and (b) determination of the steady-state creep rate.

Table 2 – Summary of Burger's model parameters of the shear creep strains.

Applied shear stress	Burger's model parameters				
	G_M (MPa)	λ_M (MPa h)	G_K (MPa)	λ_K (MPa h)	R^2
EP-0.35					
Level I	229.60	6.283E+05	646.33	2.418E+04	0.951
Level II	232.12	4.595E+05	427.75	3.283E+04	0.967
Level III	227.86	2.832E+05	222.53	2.340E+04	0.976
EP-0.65					
Level I	318.89	4.426E+05	367.63	433.36	0.921
Level II	306.40	5.170E+05	317.98	13,641.12	0.983
Level III	308.71	3.019E+05	127.89	4593.32	0.887

the steady-state creep rate, while the Findley's predictions were excluded due to its overestimation of the lifetime, as shown in Tables 5 and 6. It is obvious, that the plots can be approximated by a straight line fit [6,12,13] as follows:

$$\frac{\tau_{app}}{\tau_{max}} = -K \cdot \ln(t_f) + b \tag{5}$$

where τ_{app} is the applied shear stress, τ_{max} is the maximum short-term shear strength, K is the slope, t_f is the time-to-failure in hours, and b is a parameter that expresses the intersection point at the vertical axis. The parameters K and b are found by a linear regression analysis and are shown in Table 7.

Using Eq. (5) with the estimated parameters (K, b), the lifetime of the studied adhesive and the applied shear stress

Table 3 – Summary of Findley's model parameters of the shear creep strains.

Applied shear stress	Findley's model parameters			
	γ_0	A	B	R^2
EP-0.35				
Level I	0.025	0.001	0.476	0.947
Level II	0.033	0.001	0.493	0.966
Level III	0.042	0.003	0.472	0.991
EP-0.65				
Level I	0.018	0.005	0.270	0.923
Level II	0.025	0.004	0.352	0.988
Level III	0.031	0.021	0.243	0.964

Table 4 – Parameters of the steady-state creep rate approach.

Applied shear stress	Steady-state creep rate approach parameters		
	γ^* (1/h)	a	R^2
EP-0.35			
Level I	0.000006	0.04	0.83
Level II	0.000011	0.06	0.88
Level III	0.000023	0.01	0.89
EP-0.65			
Level I	0.000005	0.05	0.95
Level II	0.000011	0.06	0.97
Level III	0.000028	0.11	0.99

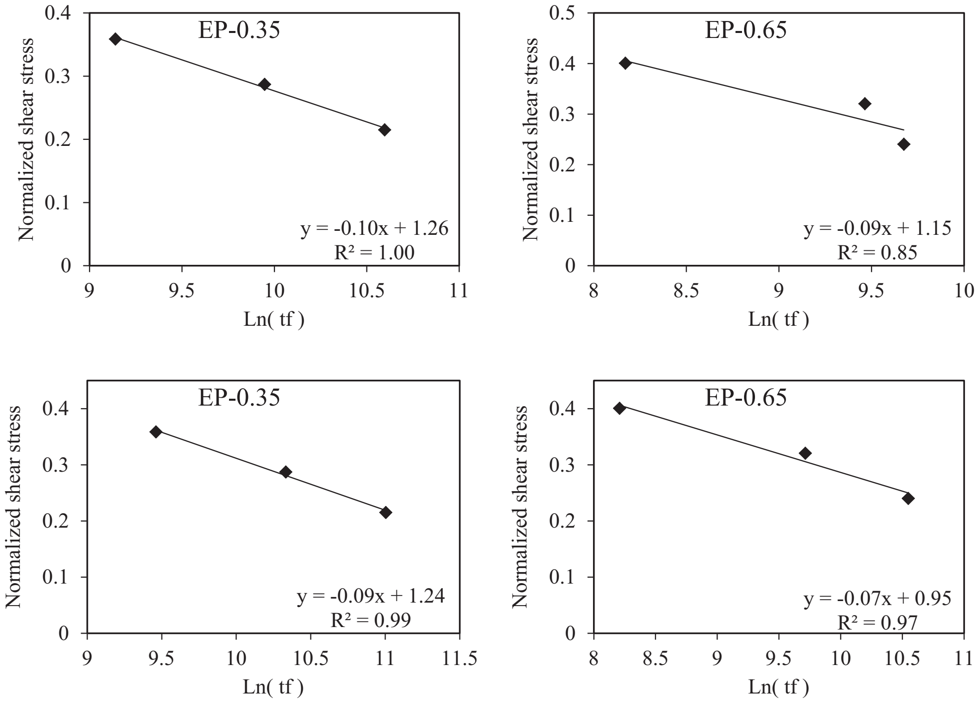
Table 5 – Predicted time-to-failure.

Stress level	Stress ratio (%)	Time-to-failure acc. to[a]		
		Findley (h)	Burger (h)	Creep rate (h)
EP-0.35				
I	21.5	5.00E+5	4.0E+4	60,120
II	28.7	1.06E+5	2.1E+4	30,722
III	35.9	2.42E+4	9321	12,857
EP-0.65				
I	24	1.39E+6	1.6E+4	38,128
II	32.1	1.05E+5	1.3E+4	16,551
III	40.1	7.80E+3(a)	3.5E+3(a)	3.7E+3(a)

[a] Values denoted by (a) refer to the average value between the real failure time recorded for one specimen and the failure time estimated by the relevant model for the other specimen.

Table 6 – Relative errors of time-to-failure comparing with steady-state creep rate approach.

Stress level	Relative error of the time-to-failure (%)	
	Findley	Burger
EP-0.35		
I	731.67	33.46
II	245.02	31.64
III	88.22	27.50
EP-0.65		
I	3545.61	58.03
II	534.40	21.45
III	110.81	5.40



(a) (b)

Fig. 8 – Normalized shear stress vs. ln(t_f). Estimation of (a) Burger and (b) steady-state creep rate.

Table 7 – Parameters of normalized shear stress–ln(t_f) correlation.

	Findley		Burger		Steady-state	
	K (1/ln(h))	b	K (1/ln(h))	b	K (1/ln(h))	b
EP-0.35	–	–	0.1	1.26	0.09	1.24
EP-0.65	–	–	0.09	1.15	0.07	0.95

Table 8 – Normalized shear stress for 1, 5, 10, and 25 years.

	τ_{app}/τ_{max} (%)			
	1 year	5 years	10 years	25 years
EP-0.35	35.2	19.1	12.2	3.0
EP-0.65	31.5	18.8	12.6	4.3

can be estimated when one of them is given or assumed. Table 8 gives the normalized shear stress (τ_{app}/τ_{max}) the minimum value according to all models used, which can be applied for 1, 5, 10, and 25 years. It was found that none of the joints are expected to remain for a lifetime of 50 years. The values of normalized shear stress, in fact, represent the conversion factors to be considered for the long-term loading of the studied joints.

6. Discussion and conclusion

Shear creep experiments were performed to investigate the creep behaviour of a structural epoxy adhesive used to join overlapped galvanized steel plates. Specimens were subjected to sustained loads for up to more than three and a half months at room temperature. Based on the experimental observations and measurements, the shear creep of epoxy was modelled by means of known models used for viscoelastic materials, Findley's and Burger's models. Consequently, the applied shear stress for particular lifetimes of the bonded joints was proposed.

Over the test period (110 days), both Findley's and Burger's models well represent the shear creep for the used adhesives. However, Findley's model generally fits the shear creep data better than Burger's model.

Longer lifetime of adhesives should be predicted by Burger's model. Findley's model, which indicated by huge relative errors, is not useful for predicting long lifetimes due to the unlimited retardation spectrum of that model [11].

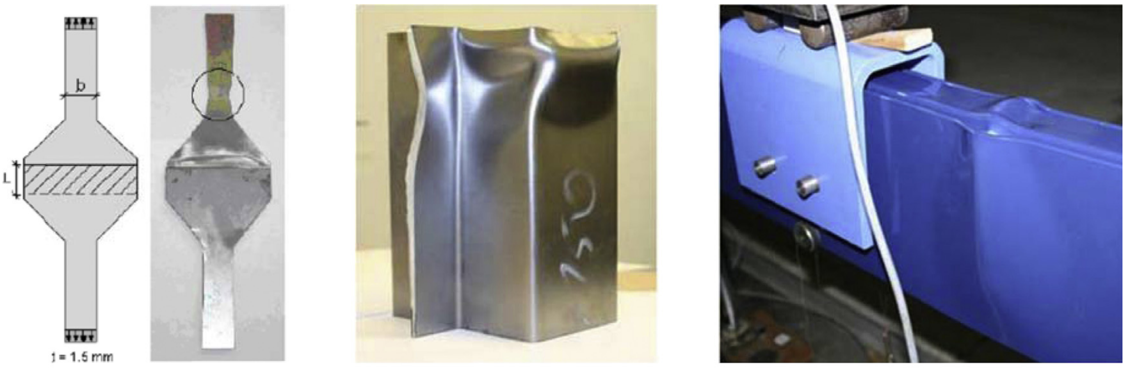
The scatterband of the strain measurements, which was also reported by [2,4], points out the need of a larger number of specimens to be tested in order to satisfy the statistical considerations. The test results showed that the shear creep behaviour is dependent on the magnitude of the applied stress which is consistent with the findings of [1–5]. The estimation of the lifetime of the adhesive studied was shown to be in agreement with the results of [5] whose specimens tested under 20% and 40% of the mean static strength did not exhibit failure at the end of the testing period (after nearly six months).

It has been shown several times, that if thin adherends are used in lap shear bonded steel joints, then they will yield (Fig. 9 (a), [14]) or buckle (Fig. 9(b), [14] and Fig. 9(c), [15]) prior to failing adhesively.

In these joints whose bonded areas are relatively large, the stresses developing over the adhesive layer will be very small; therefore, depending on the size of the bonded areas, the proposed applied shear stresses given in Table 8 can be found in such joints.

The results showed that epoxy adhesive exhibits a creep strength that is suitable for structural applications designed for up to 10, 5 and 1 year if the applied shear stresses are 12%, 19% and 31–35% of the maximum shear strength of the adhesive respectively. Longer lifetimes (more than 10 years) need more investigation.

Hence, bonded joints might be used in facades [15], temporary structures or in strengthening structural members [14–16] to take over additional short-term loads which have not been considered in the design process.



(a) (b) (c)

Fig. 9 – (a) Yielding of the adherend in a steel bonded joint under tension. (b) Local buckling in a bonded lightweight steel column under compression. (c) Local buckling in RP 1806-beam strengthened by bonding an internal steel plate (bending test).

Conflict of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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