TEMPERATURE EFFECT ON MECHANICAL BEHAVIOUR OF ADHESIVE-BONDED STEEL JOINTS UNDER SHORT AND LONG-TERM LOADING

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Abstract: *This paper briefly presents the results of experimental and analytical investigations on the effect of the temperature on the short and long-term behaviour of two different kinds of structural adhesives used in metal assemblies.*
Double shear by tension tests were performed on specimens composed of galvanized steel sheets assembled by using epoxy and acrylic adhesives. Two thicknesses of adhesive bondline at four temperatures (-20^o,0^o, 20^o, and 40^{o}C) were used for the short-term tests, while one thickness at 40^{o}C used for the long-term tests.
The investigations showed that increasing temperature adversely affects the used adhesives behaviour, mechanical shear properties, and failure modes. In addition to that, long-term tests showed that a higher temperature can lead to failure in shorter period, even when a joint loaded by constant shear stresses much less than the short-term ultimate shear strength. Also, it was confirmed that the less the thickness of the adhesive layer, the stiffer the adhesive and the greater the shear strength.

Key words*: Structural adhesives, temperature, mechanical shear properties, steel joints.*

1. Introduction

With the continued aging of infrastructure, the need of strengthening the existing steel structures is increasing. Moreover, strengthening may be needed to upgrade the structural capacity to accommodate increasing loads due to modified uses.

Adhesive-bonded steel connections might be considered as an efficient alternative solution used for strengthening steel members due to not only the advantages of structural adhesive itself with its improving properties, but also the advantages of using such connections as whole. In light-weight steel structures, which used, for instance in façades, if bigger bonded areas are used, the shear capacity of a structural adhesive could be more than the tensile capacity of the steel member itself, i.e. the steel material might yield in tension earlier than the adhesive does in shear provided that of using relatively large bonded areas [1].

Although all the advantages that the adhesive-bonded connections have, adhesives, as being polymeric materials, have also disadvantages as their capability to be affected by environmental factors such as temperature, humidity, and hostile environments. Moreover,

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adhesive materials can be considered as sensitive to the so-called rheological phenomena such as creep and shrinkage which may result in shortening of their durability [2].

The study of the effects of these factors on a bonded connection may be done together or separately. However, taking the effect of the factors individually may facilitate the investigation procedure and lead to acceptable results.

It is well known that as the temperature increases, the mechanical properties of the adhesive such as ultimate strength, elasticity modulus, and stiffness decrease. Moreover, the increase of temperature would result in change of the behaviour of the adhesive from brittle into ductile; furthermore, increasing temperature can also change the failure modes of a bonded connection from cohesive into adhesive failure [3].

In this paper the effect of temperature on the mechanical behaviour of galvanized steel shear joints, bonded by rigid and toughened structural adhesives (epoxy and acrylic, respectively) was illustrated to get good understanding of their behaviour.

Only the creep behaviour under sustained loads, i.e. constant shear stresses, at 40^oC was focused on here for the sake of predicting the durability of the acrylic adhesive.

2. Tests

2.1. Materials

- Adherends:

The common hot-dip galvanized steel D×51D+Z (275) as classified in DIN EN 10327 with thicknesses of 1 and 2 mm was selected. To determine the mechanical properties of it, a tensile test according to DIN EN ISO 6892-1:2009-12, was conducted on 40 specimens cut from all steel sheets. Dimensions and type of test pieces were selected according to DIN 50125. The value of yield strength was found not less than 412 MPa, while the elasticity modulus was about 210000 MPa.

- Adhesives:

Two systems of adhesives epoxy and acrylic were chosen for bonding the joints. The criterion preliminarily adopted for the selection of the adhesive was the highest shear strength with cohesive failure at room conditions, i.e. (20^oC and 50% R.H.); therefore, polyurethane adhesive was completely excluded due to its little shear strength [4]. Another candidate acrylic adhesive SkiaFast® 5241, tested by the author, was also excluded because it failed adhesively.

The succeeded two kinds were:

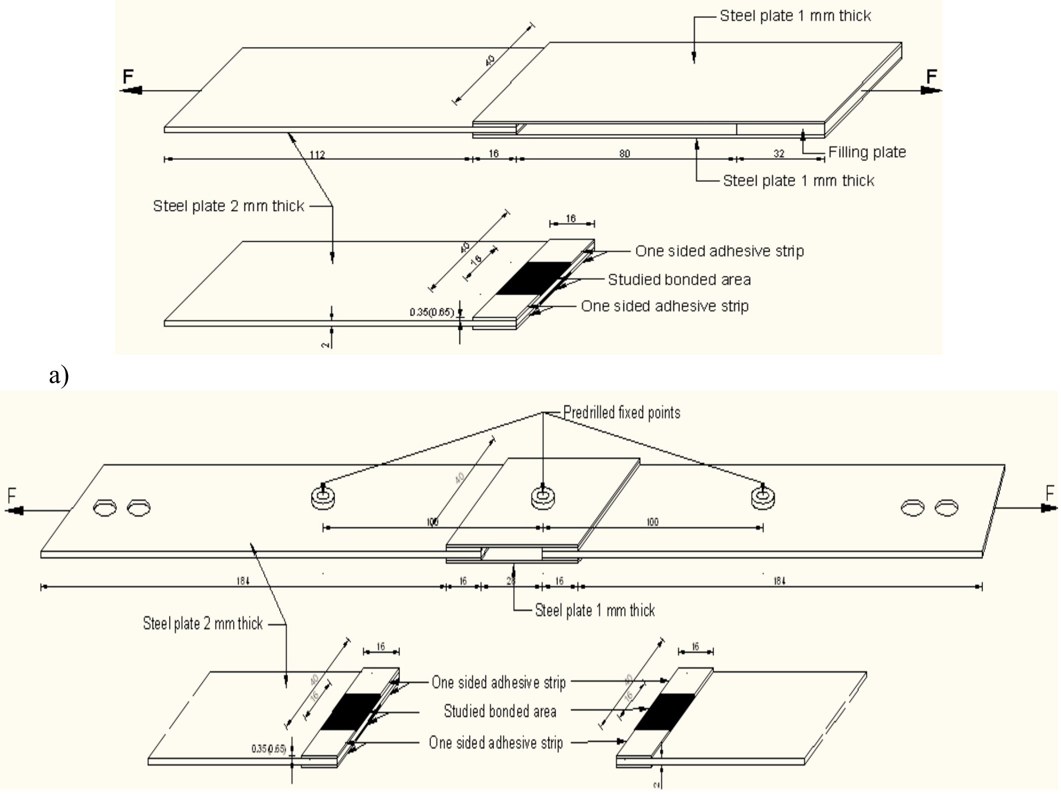
- **DP 490:** Two-component, cold-cure epoxy (needs 7 days to full curing at room temperature), denoted later by EP.
- **DP 810:** Two-component, cold-cure toughened acrylic (needs 24 hours to full curing at room temperature), denoted later by AC.

Both the DP 490 and DP 810 adhesives were supplied in double-tube cartridges, incorporating the adhesive and the hardener. The adhesives were applied using a special gun applicator which forces the two components, in the correct proportions, through a pre-mixing nozzle attached to the cartridge (3M EPX applicator).

2.2. Studied Joints

Double lap shear joints, whose geometry shown in fig. 1, were selected. External and internal steel plates are 1 mm and 2 mm thick respectively. For all conditions, the same bonded area 16x16 mm for each side was used. Only the thickness of the adhesive layer was 0.35 and 0.65 mm for short-term test and 0.65 mm for long-term test. The thickness of adhesive layer was achieved by the use of one-sided adhesive strips, as shown in fig.1.

Specimens used for long-term test have an advantage: each of them have four bonded areas to be tested instead of two.



a)

b)

Fig. 1. Double lap shear joints, black areas represent bonded areas
: a) For short-term test; b) For long-term test

The surfaces to be bonded were prepared according to the manufacturer recommendations. After bonding, the specimens were left (7 days for EP and 5 days for AC) at room temperature to be cured as recommended by the manufacturer.

2.3. Short-Term Test Procedure

Full cured bonded specimens, fig. 1a, were put in a climate chamber at desired temperature for 24 hours. The relative humidity was set to be 10 % to avoid the effect of the humidity on the adhesive; nevertheless, the relative humidity reached up to 40%. in tests with negative temperatures. After 24 hours of conditioning, specimens were tested by means of tensile testing machine, fig. 2. The installation of a specimen up to the end of the test was done within 3 minutes. Seven specimens for each temperature were tested.

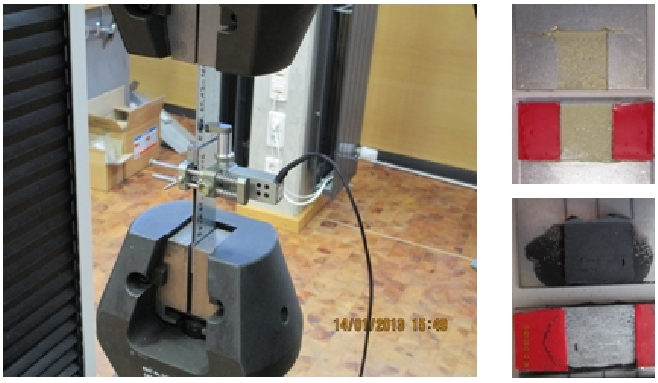


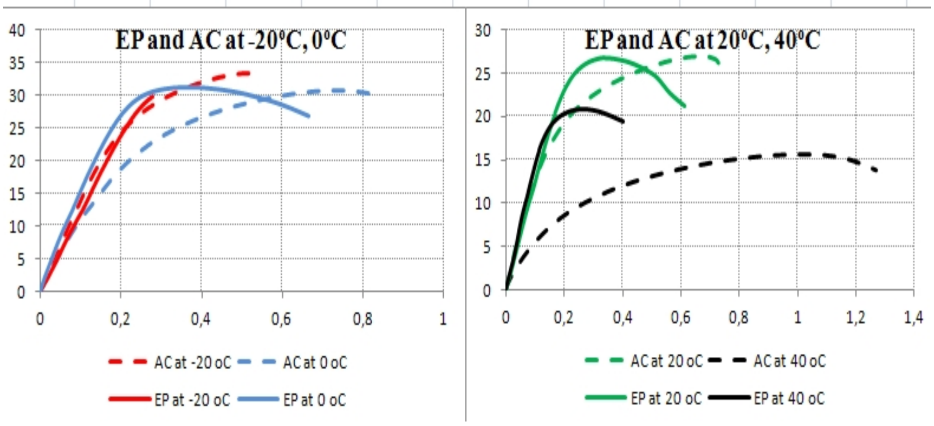
Fig. 2. Left: Short-term test set up
Right: Failure modes of AC (above) and EP (below)

The speed rate of the crosshead was set to 1.27 mm/min. The longitudinal strain was recorded by the use of an extensometer which has a range of measurement of 1.8 mm. This recorded strain was used to calculate the shear strain by dividing it by the bondline thickness. The shear stress was considered regularly distributed over the bondline and calculated by dividing the recorded applied force by the two-sided bonded areas, i.e. 2x16x16= 512 mm^2.

The shear stress-strain curves were plotted; the shear modulus G was estimated by taking the slope of the linear portion of the curve at the shear strain interval up to 0.05.

The maximum shear strength and its corresponding strain, as well as shear stress at break with its corresponding strain were recorded. Table 1 presents the mean values and standard deviations (values in brackets) of the above mentioned parameters for specimens bonded by epoxy at studied temperatures. Table 2 shows the matching values of specimens bonded by acrylic. It is worthwhile to mention that all specimens failed either cohesively (CF) or special cohesively (SCF), see [5]. In both tables, above and below values indicate values of specimens with two adhesive layers: 0.35 mm and 0.65 mm respectively.

Fig. 3 illustrates the comparison between mechanical behaviour of both epoxy and acrylic at -20°C, 0°C and at 20°C, 40°C respectively. The thickness of the adhesive layer was 0.35 mm. It is clear that epoxy adhesive is rigid and mostly fails in brittle at different temperatures, while acrylic adhesive, even it is toughened, can be considered as more ductile than the epoxy. Also, one can see that when the temperature increases, both adhesives become more ductile.



a) b)

Fig. 3. Shear stress-strain curves for a specimen of EP and AC at various temperatures: a) at -20°C, 0°C; b) at 20°C, 40°C

Table 1. Mean and standard deviations of mechanical shear properties and failure modes of EP-specimens at various temperatures

T (°C)	G (MPa)	τ_{max} (MPa)	γ at τ_{max} (-)	τ at Break (MPa)	γ at Break (-)	Failure mode
-20	138.29(9.42) 230.55(16.32)	29.36(2.04) 22.21(2.45)	0.25(0.04) 0.11(0.02)	29.36(2.04) 22.21(2.45)	0.25(0.04) 0.11(0.02)	SCF
0	147.12(14.79) 230.50(19.63)	29.29(2.09) 24.45(1.81)	0.32(0.09) 0.12(0.01)	28.30(1.88) 24.45(1.81)	0.41(0.17) 0.12(0.01)	SCF
20	144.50(16.17) 212.52(9.42)	26.68(0.60) 23.89(0.76)	0.32(0.04) 0.18(0.02)	24.72(2.12) 21.32(1.28)	0.47(0.16) 0.29(0.06)	SCF
40	129.91(19.31) 190.25(10.16)	20.88(0.69) 18.90(1.01)	0.29(0.04) 0.14(0.02)	19.95(0.59) 18.79(0.96)	0.39(0.03) 0.15(0.02)	SCF

Table 2. Mean and standard deviations of mechanical shear properties and failure modes of AC-specimens at various temperatures

T (^{o}C)	G (MPa)	τ_{max} (MPa)	$\gamma_{at\ \tau max}$ (-)	$\tau_{at\ Break}$ (MPa)	$\gamma_{at\ Break}$ (-)	Failure mode
-20	162.59(7.99) 214.33(7.56)	34.17(0.72) 29.51(0.44)	0.51(0.04) 0.36(0.03)	33.97(0.91) 29.36(0.48)	0.55(0.06) 0.39(0.04)	SCF
0	137.04(16.02) 236.58(22.93)	29.70(1.00) 27.13(1.21)	0.60(0.07) 0.41(0.07)	29.09(1.22) 26.16(1.20)	0.69(0.09) 0.50(0.10)	CF
20	126.95(11.85) 149.89(23.76)	26.58(0.54) 21.34(1.08)	0.69(0.04) 0.67(0.09)	25.37(0.59) 15.42(3.30)	0.80(0.05) 1.03(0.18)	CF
40	65.15(3.61) 89.94(6.71)	16.31(1.75) 16.72(0.58)	0.91(0.13) 1.07(0.12)	12.02(3.97) 10.18(1.46)	1.34(0.13) 1.44(0.09)	CF

2.4. Long-Term Test Procedure

Specimens with four bonded areas, fig. 1b, were installed into a creep machine designed to amplify 5 times a given static load. Three constant shear stresses, as listed in table 3, applied to three specimens, were chosen to be less than 40% of the short-term maximum shear strength [6] at 40°C.

This machine was put inside a huge climate chamber existing in the laboratory of materials testing in BTU. The temperature was set to 40°C with 10% of R.H. for 101 hours.

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, see fig. 1,b. The distance between these points was measured with 0.001 mm resolution. This procedure followed by many researchers, e.g. [7].

Shear strain-time curves were plotted for each stress level and best fitted to Findley model which is valid for tests under sustained loads [8] and given as the following:

$$S(t) = s_0 + a * t^b$$

S_0 is the initial strain at t=0, and a b constants (tuning factors) evaluated by a regression analysis.

Fig. 4 shows the recorded creep curves, mean values of the four areas, and best fitted curves according to Findley model for the joints bonded by AC of 0.65 mm.

The initial strain, evaluated Findley constants resulted by regression analysis, and the determination coefficient (R^2) of each fitted curve listed in table 3.

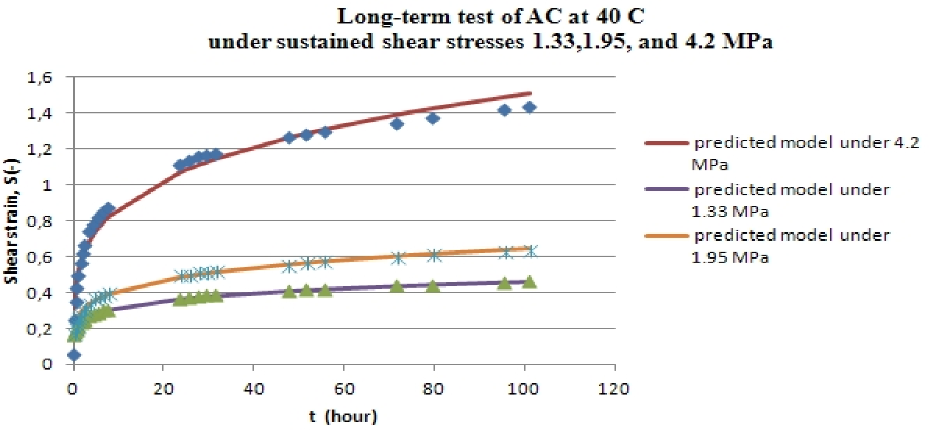


Fig. 4. Creep curves and best fitted curves according to Findley model for the joints bonded by AC of 0.65 mm at 40°C
(points represent test results and lines represent predicted curves)

Table 3. Evaluated values of the initial strain, Findley constants, and coefficient determination of AC-bonded specimens subjected to three different shear stress levels at 40°C.

Shear stress (MPa)	S_0	a	b	R^2
1.33	0.0147	0.205	0.170	0.998
1.95	0.0216	0.242	0.205	0.996
4.20	0.0470	0.470	0.246	0.964

It is shown by extrapolating the shear strain, according to Findley approach, for the largest applied stress, that the joint was about to reach the failure after 101 hours, while the other joints need about one year to reach it, of course supposing the same conditions applied here, i.e. a combination of a constant shear stress and 40°C of temperature.

3. Conclusions

Short and long-term double shear tests were performed on specimens composed of galvanized steel sheets assembled by using epoxy and acrylic adhesives. Tests carried out at four temperatures (-20°, 0°, 20°, and 40°C) for the short-term tests, only 40°C was used for the long-term tests. The investigations showed that increasing temperature changes the mechanical behaviour, from brittle into ductile, and decreases both the shear modulus and shear strength. Furthermore, failure modes may change as temperature increases. In addition to that, long-term tests showed that a higher temperature can lead to failure in shorter period, even when a joint loaded by constant shear stresses much less than the short-term ultimate shear strength.

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