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The Influence of Temperature on the Debonding of Externally Bonded CFRP

by E.L. Klamer, D.A. Hordijk, and H.J.M. Janssen

Synopsis: Fiber Reinforced Polymers have proven to be effective strengthening materials in the construction industry, due to their low weight (easy to apply), non-corrosiveness and high strength. Extensive research has been carried out into the strengthening of concrete structures with externally bonded FRP. It turned out that debonding of the FRP is governing the design of most FRP strengthening applications. One of the parameters, which may affect the bond properties of the FRP-concrete joint, is the ambient temperature. Only little research into the influence of temperature on the bond behavior has been carried out so far. This paper presents the results of an exploratory experimental and numerical investigation in which the influence of temperature on the debonding behavior of externally bonded CFRP was investigated. Two different test setups were applied. Results showed that the failure load of CFRP strengthened concrete structures was affected by the temperature, but depended on the used test setup. Two types of failure were observed. For low to moderate temperatures (-10°C to +40°C), failure occurred in the concrete, leaving 1-3 mm of concrete attached to the adhesive. For elevated temperatures (50°C to 75°C), failure of the adhesive-concrete interface occurred, without leaving any concrete attached to the adhesive.

Keywords: bond; CFRP; debonding; temperature; thermal stresses

Ernst L. Klamer is a PhD-candidate at the structural design group of the faculty of Architecture, Building and Planning of Eindhoven University of Technology. He is an associate member of *fib*-Task Group 9.3, FRP Reinforcement for Concrete Structures.

Dick A. Hordijk is a professor in concrete structures at the structural design group of the faculty of Architecture, Building and Planning of Eindhoven University of Technology and managing director of Adviesbureau ir. J.G. Hageman B.V. (consultancy office) in the Netherlands. He is a member of *fib*-Task Group 9.3, FRP Reinforcement for Concrete Structures and member of the board of the Dutch Concrete Society.

Harrie J.M. Janssen is an assistant professor in mechanics at the structural design group of the faculty of Architecture, Building and Planning of Eindhoven University of Technology.

INTRODUCTION

Strengthening of concrete structures with externally bonded Fiber Reinforced Polymers (FRP) has become increasingly popular in the construction industry. Strengthening with FRP laminates has many advantages over strengthening with steel strips, like the high strength, the non-corrosiveness, the low weight and consequently the easiness of application and maintenance. The last two decades, extensive research has been carried out into the behavior of FRP as a strengthening material. In 2001, *fib*-Bulletin 14 (*fib* TG 9.3 2001) has been published, in which available information was gathered and design guidelines for the calculation and application of FRP were given. Guidelines in this field will most probably be updated in the near future, as the various related topics are subject of ongoing research and development. The main issue governing the design of a FRP strengthening application is the debonding of the FRP. Debonding is initiated before the ultimate tensile strength of FRP can be reached. Research into the debonding behavior of externally bonded FRP is rather difficult, due to the explosive and sudden way of failure. Despite the various investigations that have been carried out so far, still several questions have to be answered.

RESEARCH SIGNIFICANCE

One of the research needs, which so far received only little attention, is the influence of temperature on the debonding capacity of externally bonded Carbon Fiber Reinforced Polymers (CFRP). Temperature changes will induce additional thermal stresses, due to the significant difference in coefficient of thermal expansion between concrete ($\alpha_c \approx 10 \times 10^{-6}$ / °C) and CFRP ($\alpha_f \approx 0 \times 10^{-6}$ / °C) (in the longitudinal direction). Furthermore, differential temperature in a strengthened structure causes imposed deformations. Both influences will induce additional stresses in the CFRP and the concrete and may affect the load level at which debonding occurs. The material properties of concrete, CFRP and the adhesive are also affected by changes in temperature. This especially counts for the adhesive, as the strength and stiffness will drop significantly when the glass-transition temperature is reached ($T_g \approx 45$°C – 80°C for most epoxies).

REVIEW OF PREVIOUS WORK

Only limited research into the influence of temperature on the debonding of externally bonded laminates has been carried so far. Tadeu and Branco carried out several double-lap shear tests on steel laminates externally bonded to concrete specimens (Fig. 1) (Tadeu and Branco 2000). Three different concrete grades were tested. The specimens were produced at 20°C and tested at 20°C, 30°C, 60°C, 90°C and 120°C. Thermal stresses were small in this case, because steel and concrete have almost the same coefficient of thermal expansion.

For comparison, all available experimental result, which are treated in this chapter, were plotted in Fig. 2. The results from Tadeu and Branco showed a reduction of the failure load with an increase of temperature starting from 20°C. Especially for high strength concrete ($f_{cm,cube}$ = 74.1 MPa), there was a significant reduction of the failure load, when the temperature was just above room temperature. Increasing the temperature from 20°C to 30°C resulted in a decrease by 32%.

For specimens at 60°C, the failure load was reduced to 45 - 51% of the initial failure load, whereas for 90°C only 24 - 29% of the initial capacity was left. At 120°C, hardly any capacity was left (7 - 9%). The type of failure was also affected by the temperature. For 20°C and 30°C failure occurred in the concrete, whereas for higher temperatures, failure of the adhesive occurred.

Blontrock carried out double-lap shear tests on concrete specimens strengthened with externally bonded CFRP (Blontrock 2003). Two concrete blocks were connected by two CFRP strips and the entire specimen was loaded in a tensile testing machine (Fig. 3). The specimens were tested at 20°C, 40°C, 55°C and 70°C. Anchorage sheets were applied at one side to make sure debonding occurs at the other side, where the strain distribution was recorded by means of strain gauges.

The experimental results of Blontrock were significantly different from the results of Tadeu and Branco for steel laminates (see Fig. 2). Increasing the temperature from 20°C to 40°C resulted in a significant increase of the failure load (41%) in stead of a decrease ($f_{cm,cube}$ = 40 MPa). Blontrock mentioned two possible causes for the different results compared to Tadeu and Branco:

1. The dimensions of the specimens: A significant difference in bonded surface resulted in a different failure mode. Failure occurred in the concrete near the bonded surface (depth approximately 0-1 mm), whereas Tadeu and Branco found failure of the concrete at a depth of 30 mm from the bonded surface.
2. The difference in coefficients of thermal expansion. For steel and concrete, the coefficient of thermal expansion was approximately the same, whereas it differed significantly in case of CFRP laminates. This induced additional interfacial stresses between CFRP and concrete. These stresses obviously had a positive effect on the capacity. Further increasing the temperature to, respectively, 55°C and 70°C resulted in a decrease of the failure load, although at 55°C still higher than the initial failure load at 20°C. The decrease of the failure load was caused by the softening of the adhesive.

Di Tommaso et al. carried out several three point bending tests on small scale concrete specimens without internal reinforcement (Di Tommaso et al. 2001). The specimens were strengthened at room temperature with two different types of CFRP (high and normal E-modulus laminates) and tested at four different temperatures, -100°C, -30°C, 20°C and 40°C.

The results showed that increasing the temperature to 40°C decreased the load capacity (see Fig 2.). This was explained by the additional thermal stresses and softening of the adhesive. This result was opposite to the results obtained by Blontrock. As a result of the decreased temperature to respectively -30°C and -100°C, the load-deflection relation became linear up to a higher load level. However, the ultimate failure load was in most tests lower than the failure load at 20°C (see Fig. 2). At low temperatures, the specimens showed less ductile behavior. In the experiments, three different types of failure were observed, mainly governed by the applied temperature (see Fig. 4). For specimens at 40°C cohesive failure in the adhesive layer was found, due to the softening of the adhesive. For moderate temperatures, concrete shear failure was found and for low temperatures delamination within the CFRP was found.

The presented experimental results from literature have shown that the influence of temperature can be significant. However, based on the reported failure loads as function of the temperatures no distinctive conclusions could be drawn. In this respect it was also not known to what extent the applied test-setup had influenced the results. Further research is needed to gain a better insight into the influence of temperature on the bonding capacity of CFRP.

EXPERIMENTS

To investigate the influence of temperature on the debonding behavior, two different types of experiments, as reported in the literature, were used in an exploratory investigation at Eindhoven University of Technology. Twelve double-lap shear tests, similar to that used by Blontrock, were carried out. Compared to the experiments of Blontrock there was a difference in the CFRP laminate dimensions and only one threaded rod was used to make the connection of the specimen to the loading device.

Furthermore, seven three point bending tests were carried out on concrete specimens, strengthened in flexure with externally bonded CFRP at the soffit of the beam. Although it was initially intended to use the same dimensions for the CFRP laminate as in the double-lap shear tests, it was decided to use a CFRP laminate which was half the original width, based on experiences in preliminary tests. Besides the effect of temperature increase also the effect of freezing (-10°C) was investigated in both test setups.

Preparation of the test specimens

The specimens for the double-lap shear tests were produced in three series of four concrete specimens each (150 × 150 × 800 mm^3). To be able to connect the specimen to the tensile testing machine, one steel threaded rod (M24) of about 1 m length was placed into the center of the specimen (see Fig. 5 Left). The specimens, including the rod, were cut in half after curing of the concrete for about seven days (at 20°C and 60% relative humidity). By doing this, the two parts had exactly the same width and height. After about 28 days, the concrete surfaces were sandblasted and two CFRP laminates ($50 \times 1.2 \times 650$ mm^3) were bonded to the two side faces of the concrete specimens. The adhesive had a thickness of about 1.5 mm. 50 mm of cardboard was placed in between the CFRP and concrete at the location of the saw cut. In this way, 50 mm in the middle of the CFRP (25 mm at each side of the saw cut) remained unbonded (see Fig. 5 Left), which was done to avoid local stress concentrations at the saw cut.

The specimens for the three point bending tests were produced in two series of four concrete specimens. The concrete specimens measured $150 \times 250 \times 800$ mm^3 and were cut in at midspan till half the height of the beam (see Fig. 5 Right), to create an initial bending "crack". One CFRP laminate ($25 \times 1.2 \times 650$ mm^3) was applied to the soffit of the specimens, after curing 28 days (at 20°C and 60% relative humidity) and sandblasting of the concrete surface. No internal reinforcement was applied and 50 mm of cardboard has been placed in between the CFRP and the concrete at the location of the saw cut (25 mm at each side), to avoid local stress concentrations.

Material properties

The concrete compressive strength and tensile splitting strength were determined using $150 \times 150 \times 150$ mm^3 cubes. The bond strength was determined according to CUR Recommendation 20 (CUR 1990) by bonding steel cylinders (∅ 50 mm) on the sand-blasted concrete surface and pulling them off by a hydraulic jack. The measured average concrete properties at 20°C are given in Table 1. The bond strength of the concrete depends on the ambient temperature and was therefore also determined for different temperatures for series B (see Fig. 6). Concrete of series A, B and C were used for the double-lap shear tests, concrete of series B and D for the three point bending tests. Especially the concrete of series C had a much lower strength than intended. Probably there was a mistake in the mixing. Nevertheless, these specimens were used in this exploratory investigation. The CFRP (SIKA CarboDur S512) had a tensile strength of 2800 MPa, an elastic modulus of 165,000 MPa and a coefficient of thermal expansion of 0.3×10^{-6} / °C in the longitudinal direction and is temperature resistant till at least 150°C (all according to the manufacturer). The adhesive (SikaDur-30) had an elastic modulus is 12,800 MPa, a coefficient of thermal expansion of 90×10^{-6} / °C and a glass transition temperature (T_g) of 62°C.

Double-lap shear test setup

The double-lap shear test specimens were tested in a 250 kN tensile testing machine. Steel clamps were used at the bottom side of the specimen, to make sure that debonding of the CFRP was initiated at the upper side (see Fig. 7). This had the benefit that strain gauges only had to be used at the upper side. Series A and B were used to investigate the influence of elevated temperatures (see Table 2). The specimens were heated in an oven for at least 12 hours before testing.

Series C was used to investigate the influence of low temperature (-10°C). Two specimens of series C were frozen for at least 24 hours. Reference specimens were tested at 20°C for series A and C. A reference specimen for series B was not tested, because all specimens were initially intended to have the same concrete quality. Unfortunately, this turned out not to be true. All heated and frozen specimens were packed with isolation during the tests. Only 2.5 hours were needed to bring the core of a specimen (100 × 100 × 700 mm^3) to the desired temperature (Di Tommaso et al. 2001). Though not measured, it was expected that for the slightly bigger specimens in this investigation, 12 hours of heating was enough to reach a uniform temperature and entirely warm up the specimen. The surface temperature was measured during the experiment and changed with a maximum of 2°C.

Two Linear Variable Differential Transformers (LVDTs), placed diametrically to the center of the specimen, were used to measure the displacement over the saw cut (see Fig. 7). To determine the strain development over the length of the CFRP laminate, five strain gauges were applied per laminate (only one specimen per investigated temperature). The strain gauges (measuring length was 10 mm) were applied at 10, 80, 150, 220 and 290 mm from the end of the laminate with the last one at a distance of 10 mm from the start of the bonded area. The measured strains were temperature corrected.

Three point bending tests

The three point bending test specimens were tested in a 100 kN testing machine. The specimens had a 750 mm span and were supported at one fixed hinge support and one roller support and loaded at midspan. Specimens from series B were tested at -10°C, 20°C and 50°C, specimens from series D at -10°C, 20°C, 50°C and 65°C (see Table 3).

The specimens were not isolated during the tests, to have a clear sight on the specimen during the test. The surface temperature was measured during the tests and changed with a maximum of 5°C. Five strain gauges were applied on the CFRP at the same location as in the double lap shear tests (10, 80, 150, 220 and 290 mm from the end of the laminate). This was only done for one specimen per investigated temperature. Steel clamps were used to make sure debonding occurs at one side, which reduced the number of needed strain gauges. The deformation was measured at midspan, directly next to the saw cut.

THEORETICAL ANCHORAGE FORCE

It turned out that the CFRP was not able to reach its maximum strength, because the CFRP debonded at the end anchorage zone, due to high shear stresses. The maximum CFRP anchorage force at 20°C can be calculated with the model of Holzenkämpfer, modified by Neubauer and Rostásy. The maximum CFRP anchorage force ($N_{fa,max}$) is related to the fracture energy (G_F) of concrete, assumes a bilinear bond-slip relation (Holzenkämpfer 1994) and can be determined using Eq. (1).

$$N_{fa,max} = \alpha \cdot k_c \cdot k_b \cdot b_f \sqrt{2 \cdot c_F \cdot E_f \cdot t_f \cdot f_{cbm}} \qquad (1)$$

where α = reduction factor to account for the influence of inclined cracks on the bond strength; k_c = factor to account the state of compaction of the concrete; k_b = geometry factor; c_F = calibration factor, b_f = width of FRP; E_f = elastic modulus of FRP; t_f = thickness of FRP; f_{cbm} = mean value of concrete bond strength. The corresponding maximum anchorage length ($\ell_{b,max}$) can be determined using Eq. (2). A higher anchorage length does not result in a higher anchorage force because the anchorage force is limited due to the fracture energy of concrete (Neubauer and Rostásy 1999).

$$\ell_{b,max} = 1.57 \cdot \alpha \cdot \sqrt{\frac{c_F \cdot E_f \cdot t_f}{f_{cbm}}} \qquad (2)$$

The maximum anchorage force (per laminate, at 20°C) ($N_{fa,max}$) and corresponding anchorage length ($\ell_{b,max}$) for the applied concrete mixes are given in Table 4. The available anchorage length (ℓ_b) was 300 mm, which was longer than the maximum anchorage length. The analytical failure load for the double-lap shear tests with two laminates can therefore be taken twice the maximum anchorage force. The analytical failure load for the three point bending test can be calculated by taking the CFRP force equal to $N_{fa,max}$ and determining the strain distribution in the cross section at midspan. Based on this strain distribution, the place of the neutral axis can be determined (± 22 mm from the top for both series). With these values, the moment in the mid span cross section can be determined, which can be converted to the external (failure) load (F_{max}).

DOUBLE-LAP SHEAR TEST RESULTS

Elevated temperatures

The measured failure loads as function of the applied temperature were plotted in Fig. 8. The two specimens from series A, tested at 20°C, failed in an explosive way by debonding of the concrete at the interface with the adhesive, leaving 1-3 mm of concrete attached to the CFRP laminate and adhesive The average failure load of 61.4 kN corresponds well with the theoretical failure load (63 kN).

For series A and B the same tendency can be observed. When increasing the temperature for series A to 50°C, first the failure load increased about 10%. Unfortunately, the initial increase in failure load could not be verified for series B, as mentioned before. However, it can be seen that the failure load stays at a constant level between 40°C and 50°C. Further increasing the temperature to 65°C and 75°C resulted in a 41% and 27% lower failure load than at 50°C for respectively series A and B.

This was similar to what Blontrock (2003) had found, though he reported a much larger increase in failure load when increasing the temperature from 20°C to 40°C. The reduction in strength for the higher temperatures can be understood when it is realized that the glass transition temperature of the applied adhesive was 62 °C.

The strain distributions in the two CFRP laminates (average values for the two sides that showed similar results) were compared at different temperatures for an arbitrarily chosen load level of 35 kN (see Fig. 9) and at the failure load (see Fig. 10). It appeared that at 35 kN and at 20°C, there was a concentration of strains in the first approximately 70 mm of the bonded strip adjacent to the saw cut, whereas it was spread over a longer length at 40°C and 50°C. At 75°C there was an almost linear strain distribution from the beginning to the end of the strip. The strain in the unbonded part of the FRP laminate (300 mm from CFRP end) can be calculated with $F / (A_f \times E_f)$. At a load of 35 kN, the strain in the FRP is 17,500 / (50 × 1.2 × 165.000) = 1768 μm/m, which corresponded rather well with the strain distributions in Fig. 9. In this respect it should be realized that strains were measured at discrete points and that in Fig. 9 and 10, these points were connected by straight lines. The real strain distribution will probably be non-linear.

It can also be seen that just before failure, the strains were almost linear distributed along the length of the CFRP. It can therefore be concluded that the specimen, which was tested at 75°C, was almost at its failure load in Fig. 9. Two different types of failure were found in the experiments (see Fig. 11). At moderate temperatures (20°C and 40°C) failure occurred in the concrete, leaving about 1-3 mm of concrete attached to the unbonded CFRP strip. At higher temperatures (50°C, 65°C and 75°C) debonding occurred in between the adhesive and concrete, leaving hardly any concrete attached to the CFRP strip. For both failure modes debonding occurred in a rather explosive way.

Based on the presented results it was expected that the behavior at elevated temperatures could be explained as follows. Due to a higher temperature the stiffness of the adhesive was reduced. As a result the strain and bond stresses along the length of the laminate became more equally distributed. For temperatures up to at least 50°C most probably the bond strength will not significantly be reduced so that the more uniform bond stress distribution yielded the higher failure load. Or put in other words, the influence of the temperature on the stiffness, resulting in a more uniform bond stress distribution, governed over a possible negative influence on the bond strength. For temperatures 65°C and 75°C (> T_g of the adhesive (62°C)), the strain distribution along the laminate was even more linear and resulted in an almost uniform bond stress distribution. However, at these temperatures, a reduction of the (bond) strength of the adhesive was governing and resulted in a significant lower failure load and other failure mode.

Low temperatures

Because of the rather poor concrete quality of the concrete used in series C, it was not combined with the tests for the other series and used separately to investigate the effect of low temperatures. Two reference specimens were tested at 20°C and failed at 56.7 kN and 60.1 kN respectively (see Fig. 12), which was about 10% higher than the analytical calculated failure load (see Table 4). Decreasing the temperature to -10°C resulted for one specimen in a 38% lower failure load (39.8 kN), whereas for the other the failure load did not differ much (56.0 kN) from the reference tests. For the specimen at -10°C that resulted in an almost equal failure load as for the specimens tested at 20°C, the measured load-displacement curve was also similar. Based on these two experiments no conclusions could be drawn on the influence of low temperatures on the bond behavior.

THREE POINT BENDING TEST RESULTS

The results of the three point bending tests were plotted in Fig. 13. For both series, the same tendency can be observed. The two specimens tested at 20°C failed by debonding of the CFRP, due to failure of the concrete at the joint with the adhesive, followed by flexural failure of the concrete at the cross-section at midspan. The observed failure loads (at 20°C) were 37% and 22% higher than the analytical calculated failure loads for respectively series B and D (see Table 4). A possible explanation could be the fact that the adhesive joint was not only loaded in shear, as in the double-lap shear tests, but also in compression, perpendicular to the adhesive, due to bending of the specimen. Compression perpendicular to the adhesive joint will result in a higher shear capacity of the adhesive joint and thus in a higher failure load.

When decreasing the temperature from the initial 20°C to -10°C, a reduced failure load was found for both series (respectively 17 and 24% lower). When increasing the temperature, first a small reduction of the failure load was found (respectively 4 and 7% lower). However, further increasing the temperature to 65°C seems to result in a 9% higher failure load for series D. Unfortunately, this could not be verified for series B, because one specimen of this series was lost.

The results of the tests at elevated temperatures seem to be contradictory to the result of the double-lap shear test, which showed an initial increase of the failure load, followed by a large decrease of the failure load, when increasing the temperature. The question was whether a possible explanation for this different behavior could be the difference in used test setups. To further investigate this, first, the strain development along the length of the CFRP at an arbitrary chosen external load level of 15 kN (see Fig 14) and at the failure load (see Fig. 15) were investigated.

It could be seen that for a constant load level (15 kN), the peak in the strain near the saw cut (at 300 mm) was decreased, when the temperature was increased. This was different from what could be seen in the double-lap shear tests, where this peak stayed at a constant level. This means that, for the same external load on the beam, the force in the CFRP laminate at midspan decreased, when the temperature was increased. It could also be seen that the strain was distributed more equally along the length of the strip, which was in agreement with what was seen in the double-lap shear tests. At the failure load, the strain distribution was almost linear, which also was in agreement with the results of the double-lap shear tests.

The type of failure was also affected by the temperature, in the same way as for the double-lap shear tests. At -10°C and 20°C, failure occurred in the concrete, leaving 1-3 mm of concrete attached to the adhesive (see Fig. 16a). At higher temperatures (50°C and 65°C) failure occurred at the concrete-adhesive joint, leaving hardly any concrete attached to the adhesive (see Fig. 16b).

It was expected that also in the bending tests two effects played an important role, when increasing the temperature. Firstly, the reduction of the stiffness of the adhesive resulted in more linear distribution of strains along the length of the strip, and thus a lower peak in shear stresses at the same external load level. Second effect was the reduction of the strength properties of the adhesive at high temperatures.

In the results of the three point bending tests, the results of the strain distribution at high temperatures raised several questions, especially why the strain peak in the CFRP laminate in the unbonded part near the saw cut decreased, when the temperature was increased. To be able to get a better insight in the possible differences between the behavior in the two different tests, some linear elastic Finite Element Analyses were performed, in which the stiffness of the adhesive was varied.

FINITE ELEMENT ANALYSES

Linear elastic Finite Element Analyses were carried out with the Finite Element Method program DIANA. Fig. 17 shows the used FEM model for the double-lap shear test, Fig. 18 for the three point bending test.

Both models were made with eight-node iso-parametric plain stress elements for all elements. The applied material properties are given in Table 5. Only linear elastic analyses were performed to study the effect of the stiffness of the adhesive and the applied test-setup on the strain distribution, so strength values were not required.

Three different values for the stiffness of the adhesive were applied to be able to simulate the effect of a temperature increase, which was assumed to result in a decrease of stiffness. In Fig. 19 and 20, the strain development along the length of the laminate is plotted for three different arbitrary chosen stiffnesses of the adhesive (100%, 50% and 10% of the initial E-modulus) for respectively the double-lap shear test and the three point bending test. An external load of 2 kN was applied on the double lap shear test and 1 kN on the three point bending test.

The strain in the unbonded part of the CFRP laminate (at 300 mm) was calculated with $F / (A_f \times E_f)$ for the double-lap shear test. At an external load of 2 kN, the strain in the CFRP is $1000 / (50 \times 1.2 \times 165.000) = 101$ μm/m (see Fig. 19). The tendencies in the results seem to correspond well with the experimental results. The peak strain was more or less constant in the double-lap shear tests, whereas it decreased for the three point bending tests. Both figures show that the strains became more equally distributed along the length of the CFRP, when the stiffness of the adhesive was decreased. Despite this agreement in tendencies, the results can as yet qualitatively not be explained. For instance even with the very low stiffness of the adhesive in the FE-analyses the more or less linear strain distribution along the length of the strip was not found. This means that more (material) parameters in the FE analyses played a role.

To be able to investigate whether the strain in the CFRP was differently distributed along the length of the strip for the two used test setups, the strain development was compared for the same tensile stress in the CFRP strip. Fig. 21 shows the strain development at a CFRP stress of 16.7 MPa for both test setups. This corresponds with 1 kN in the CFRP for the double-lap shear test and 0.5 kN in the CFRP under the saw cut for the three point bending test, because of the half width of the CFRP. There was no significant difference in strain development between the two used test setups. Keeping the tensile force in the strip constant, made that the applied external force was the same in the double-lap shear test for each stiffness of the adhesive, where it had to be increased for the three point bending test, when decreasing the stiffness.

The strain at the cross section at midspan of the three point bending test specimen is plotted in Fig. 22 for the different stiffnesses of the adhesive, to investigate whether a decreased stiffness of the adhesive had any influence on the height of the neutral axis. It could be seen that the neutral axis stayed at the same height, but it could also been seen that the strain in the concrete became higher, whereas the CFRP strain became lower, when decreasing the stiffness. This meant that decreasing the stiffness resulted in higher stresses in the concrete and lower stresses in the CFRP. There was a redistribution in the contributions to the bending moment. At higher temperatures the contribution of the uncracked part of the concrete cross-section increased, whereas the contribution of the tensile force in the CFRP strip decreased. As a result the load and so also the maximum strain in the middle part of the specimen decreased for the same external load at a higher temperature. This also meant that the deformation increased, when the stiffness of the adhesive was reduced. This was confirmed by both the results of the Finite Element Analysis as well as the experiments.

CONCLUSIONS AND RECOMMENDATIONS

For the influence of temperature on the bond behavior of externally bonded CFRP contradictory results were reported in literature. To increase insight in the significance of the parameter temperature, a research program was started at Eindhoven University of Technology. In the preliminary experiments with double-lap shear tests and three point bending tests, it was found that the bending capacity was not much influenced as long as the glass transition temperature was not reached. It was concluded that the bond capacity was affected by three important effects, when the temperature was increased. First of all, the stiffness of the adhesive was reduced, which resulted in a more equally distributed strain along the length of the anchorage zone, and thus lower peak shear stresses between concrete and CFRP. Second, the strength of the adhesive was reduced, especially for temperatures above the glass-transition temperature. The third effect only occurs in the three point bending tests. The CFRP force appeared to be lower for higher temperatures at a given external load, which resulted in a higher capacity of the structure. This was caused by the reduced stiffness of the adhesive. As a consequence, the stress in the concrete and the deformation increased. This third effect was not a material property, but a structural effect due to the test-setup.

Which of the three effects had the most effect on the failure load, seemed to be depended on the ambient temperature, the used test setup and the properties of the adhesive. For the capacity above 65°C, the big difference found between the two test-setups could so far not be explained. The failure mode was also affected by the temperature. The failure mode was changed from failure in the concrete to failure in the contact plane between concrete and adhesive for temperatures above 50°C. Based on the results of these experiments, it is expected that for normal temperature regimes (below the glass-transition temperature of the adhesive) the effect of the temperature on the bond behavior of externally bonded CFRP for strengthening in bending is limited. However, further research into the influence of temperature is recommended.

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Table 1 — Properties of the applied concrete (at 20°C).

Material properties	Series A	Series B	Series C	Series D
	MPa	MPa	MPa	MPa
Compressive strength ($f_{cm,cube}$)	37.7	31.5	18.6	24.4
Tensile splitting strength ($f_{ctm,sp}$)	2.7	2.4	1.7	2.3
Bond strength (f_{cbm})	3.7	3.1	2.6	3.2

Table 2 — Tested double-lap shear test specimens and corresponding temperatures.

Series A	Temperature	Series B	Temperature	Series C	Temperature
	°C		°C		°C
DLST-A1	20	DLST-B1	40	DLST-C1	20
DLST-A2	20	DLST-B2	40	DLST-C2	20
DLST-A3	50	DLST-B3	50	DLST-C3	-10
DLST-A4	75	DLST-B4	65	DLST-C4	-10

Table 3 — Tested three point bending test specimens and corresponding temperatures

Series B	Temperature	Series D	Temperature
	°C		°C
TPBT-B1	-10	TPST-D1	-10
TPST-B2	20	TPST-D2	20
TPST-B3	50	TPST-D3	50
		TPST-D4	65

Table 4 — Theoretical values for the anchorage force, anchorage length and failure load.

Experiment	Series	$N_{fa,max}$	$\ell_{b,max}$	ℓ_b	F_{max}
		kN	mm	mm	kN
Double-lap shear test	A	31.5	148	300	63.0
	B	28.9	160	300	57.8
	C	26.6	174	300	53.2
3-point bending test	B	15.6	160	300	19.6
	D	15.7	159	300	20.3

Table 5 — FEM material properties.

Material properties	E-modulus	Poisson's ratio	Mass density
	(MPa)	(-)	(kg/m^3)
Concrete	32,350	0.20	2500
CFRP	165,000	0.35	1200
Adhesive	12,800	0.30	1500

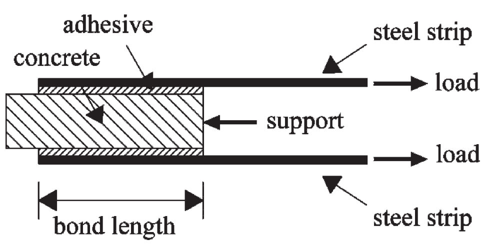

Figure 1 — Double-lap shear test (Tadeu and Branco 2000).

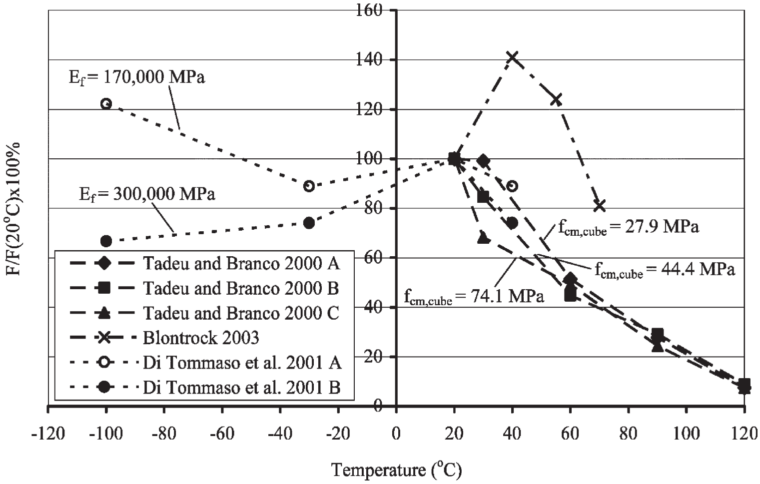

Figure 2 — Summary of the test results.

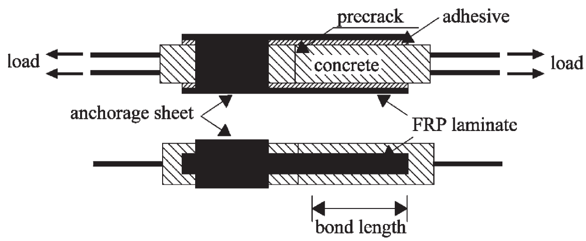

Figure 3 — Double-lap shear test (Blontrock 2003).

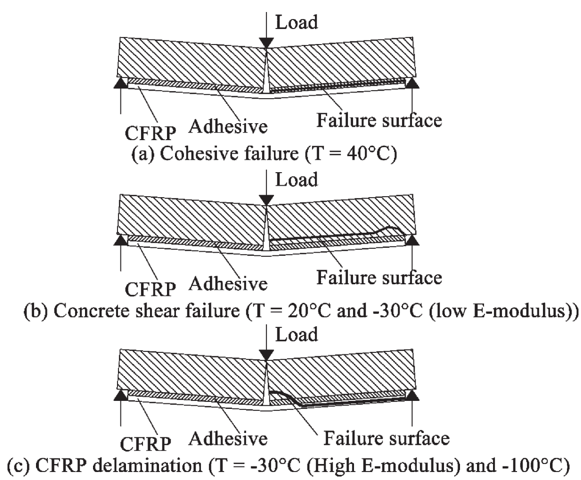

Figure 4 — Failure modes (Di Tommaso et al. 2001).

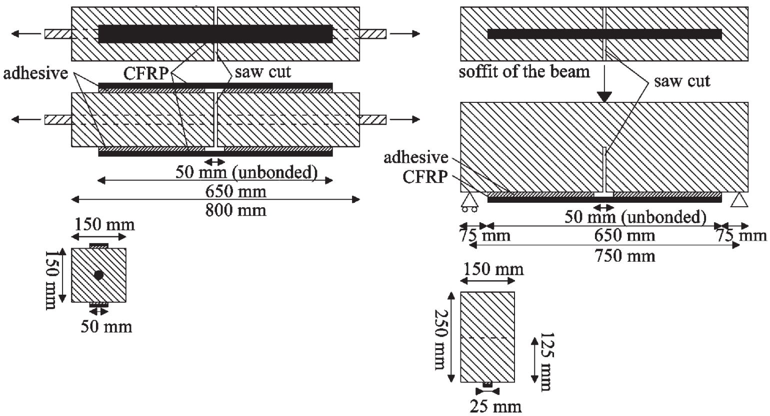

Figure 5 — Left: Double-lap shear test setup. Right: Three point bending test setup.

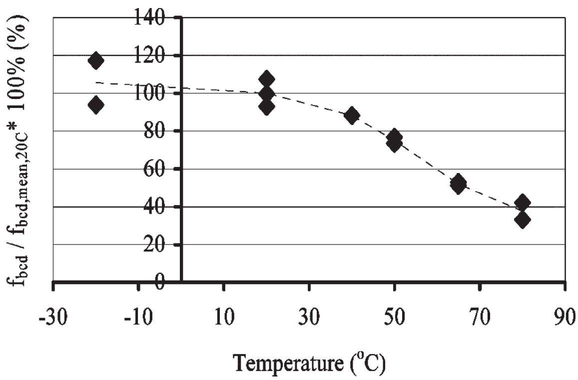

Figure 6 — Relation between the bond strength of the adhesive on concrete and the temperature.

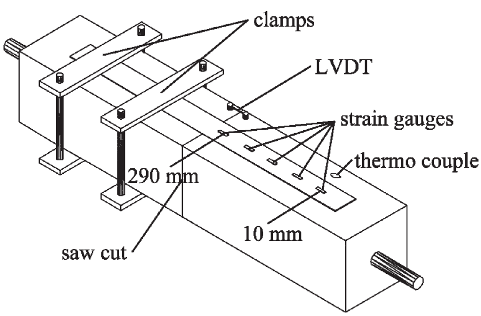

Figure 7 — Double-lap shear test setup including the measurement devices.

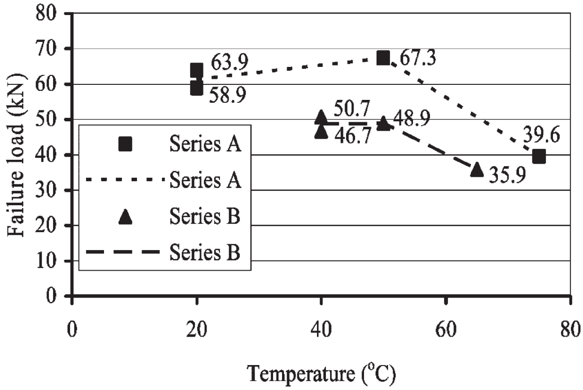

Figure 8 — Failure loads of the double-lap shear test specimens (series A and B).

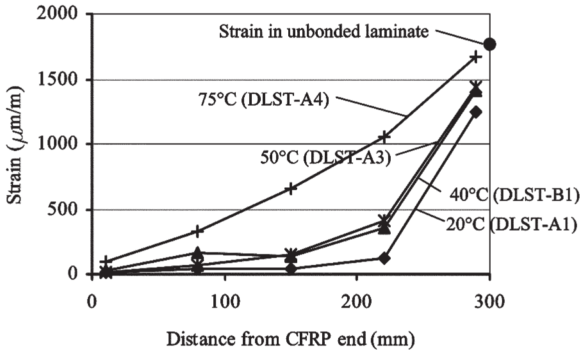

Figure 9 — Strain development in CFRP (35 kN).

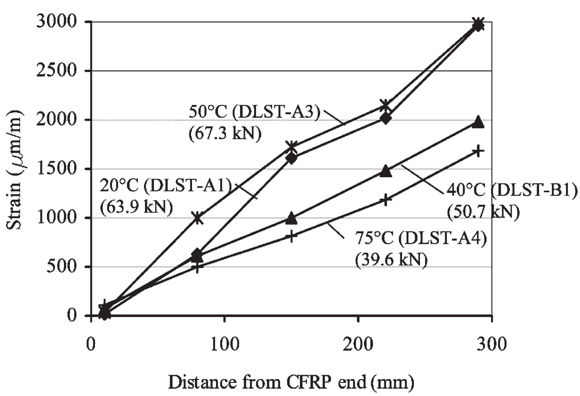

Figure 10 — Strain development in CFRP (at the failure load).

Figure 11 — (a) Failure in the concrete and (b) in the adhesive.

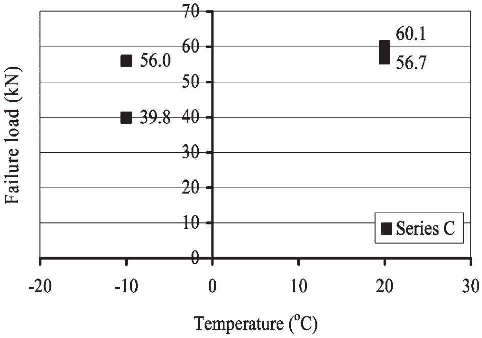

Figure 12 — Failure load of the double-lap shear test specimens (series C).

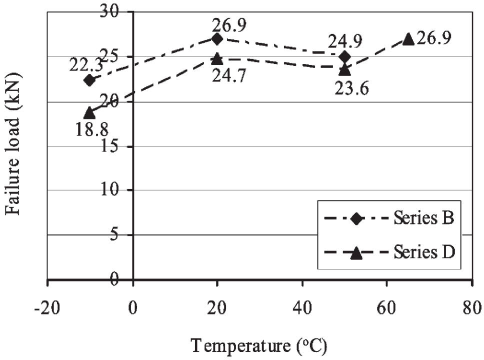

Figure 13 — Failure load of the three point bending test specimens.

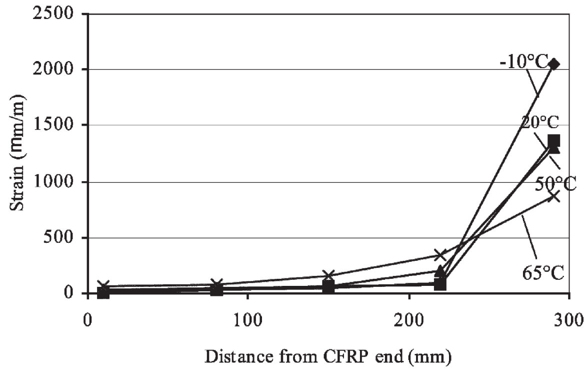

Figure 14 — Strain development in CFRP (15 kN, series D).

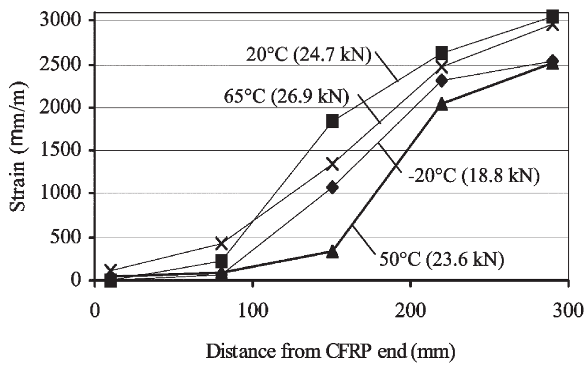

Figure 15 — Strain development in CFRP (at the failure load, series D).

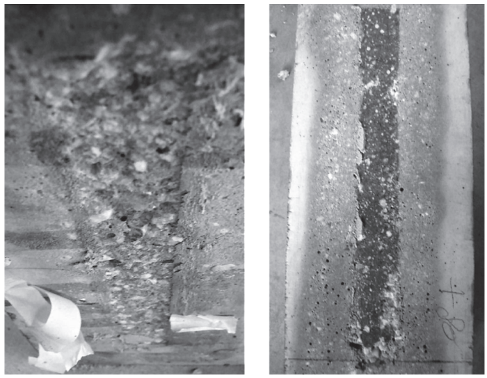

Figure 16 — (a) Failure in the concrete and (b) in the adhesive.

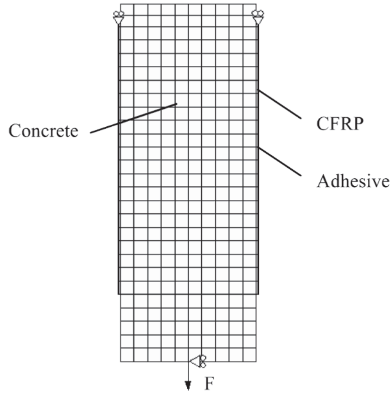

Figure 17 — FEM model of the double-lap shear test.

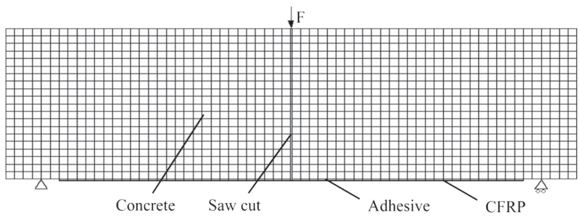

Figure 18 — FEM model of the three point bending test with saw cut till half of the height.

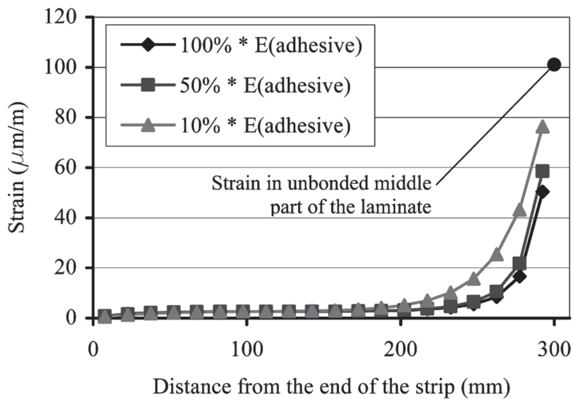

Figure 19 — Average strain in the CFRP for the double-lap shear test (2 kN tensile load).

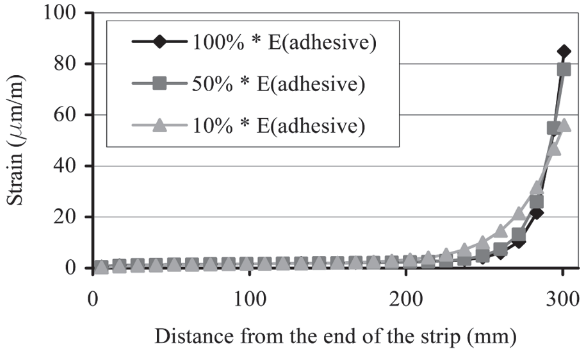

Figure 20 — Average strain in the CFRP for the three point bending test (1 kN bending load).

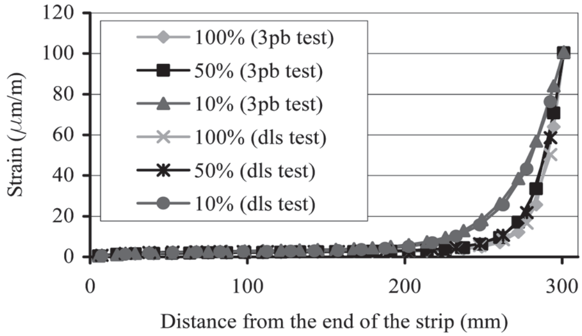

Figure 21 — Strain development along the laminate at $\sigma_f = 16.7$ MPa.

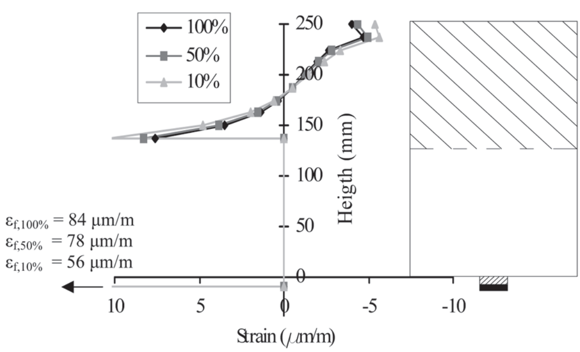

Figure 22 — Strain in the cross section at midspan.