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Adhesive bonding of textile-reinforced concrete parts

Markus Feldmann[(1)], **Daniel Pak**[(1)], **Achim Geßler**[(1)], **Uwe Reisgen**[(2)] and **Jens Schoene**[(2)]

[(1)]RWTH Aachen University, Lehrstuhl für Stahlbau und Leichtmetallbau, Mies-van-der-Rohe-Straße 1, D-52064 Aachen, GERMANY, e-mail: ag@stb.rwth-aachen.de
[(2)]RWTH Aachen University, Welding and Joining Institute, Pontstraße 49, D-52062 Aachen, GERMANY

SUMMARY

The aim of this work is the development of bonding technologies for plane, textile-reinforced concrete elements. Comprehensive tests on single yarns, as well on structural members, have been performed so that the load-carrying behaviour of eligible connections be characterized. Employing such connections with subsequent grouting, the load-carrying capacity of the undisturbed specimen can be achieved. Still, a further insight into the optimization of the bonding process itself is needed. The process should aim for a simplified production, as well as for an improved reproducibility, which is a precondition for perspective numerical modelling approaches.

Key words: *textile-reinforced concrete, joining technology, bonding technology, epoxy resin.*

1. INTRODUCTION

Within the scope of the DFG-supported Collaborative Research Centre SFB 532 at RWTH Aachen University, fundamental concepts for the new high-strength composite material "textile reinforced concrete" have been developed, allowing innovative applications which have been impossible to implement so far using conventionally reinforced concrete materials, particularly with regard to durability [1].

The application of corrosion-resistant high-performance filament yarns for reinforcement allows a significant reduction of minimum concrete cover thickness [2], which results in a thin-walled composite material with comparably high load bearing capacity, allowing a novel architectural appearance beyond the production of thin concrete prefabricated members [3]. Therefore, the textile-reinforced concrete is particularly suitable for planar components such as façades [4], single or double curved free-form surfaces [5], and sandwich structure applications [6] (Figure 1).

Fig. 1 TRC lattice structure and student café with TRC sandwich elements (source: BAUKO2, RWTH Aachen University)

From a perspective of serial production, joining concepts taking into account the specific properties of textile-reinforced elements are required. The fundamental aim of developing efficient joining techniques is to avoid the loss of load carrying capacity, i.e. the strength of a joint should at least comply with the strength of an undisturbed base material. The examinations carried out within the scope of the SFB 532 at RWTH Aachen University have established that it is basically possible to fulfil these expectations: this applies to punctiform joints [7] as well as to bonded plane joints. The results from the tests on the latter are referred to in detail in the following sections.

The bond behaviour of textile-reinforced concrete differs fundamentally from those of steel concrete. This is due to the fact that the rovings consisting of multiple filaments do not represent a homogeneous material. Since only the ultrafine constituents of the matrix, which is usually the cement paste, are capable to pass the outer boundary of the yarn and wet the filaments to a certain depth, a non-uniform stress distribution in the yarn cross-section develops where the bond stresses are mainly carried by the outer filaments [8]. Successive failure of the filaments occurs since that the yarns do not achieve the high material strength of the fibres.

A highly effective method for the improvement of the load-carrying behaviour and, consequently, the bond behaviour of a textile reinforcement is coating. Within the scope of the SFB 532, epoxy resins, unsaturated polyester resins, vinyl ester urethane hybrid resins and dispersions on acrylate basis have been applied. The polymer impregnation leads to a substantially improved load transmission between the individual filaments and, consequently, the homogenization of the yarn cross-section. It has been demonstrated that impregnated yarns, also due to the mechanical interlocking within the concrete matrix, are capable to carry higher forces in the pull-out test than unimpregnated yarns.

2. EXPERIMENTS

2.1. General information

The examined bonding geometries are shown in Figure 2. For the purpose of the development of filigree and visual appeal of structures, thickness increase in the region of the joints should be avoided by designing coextensive joints. Since both, the doweled connection and the textile key connection (Figure 2 (a) and (b)) have demonstrated, in the tests carried out by Piegeler et al. [9, 10], to be unsuitable for bonding textile-reinforced concrete components regarding the load transmission, subsequently, only the test results gained from the key and slot joint specimens with concrete inlay and subsequent grouting (Figure 2 (c) and (d)) are presented. For a characterization of the load-carrying behaviour of the bonded joint, the concrete elements are subjected to tensile tests and also to bending tests. The properties of the bondline itself are to be determined before by bonded yarn pull-out tests.

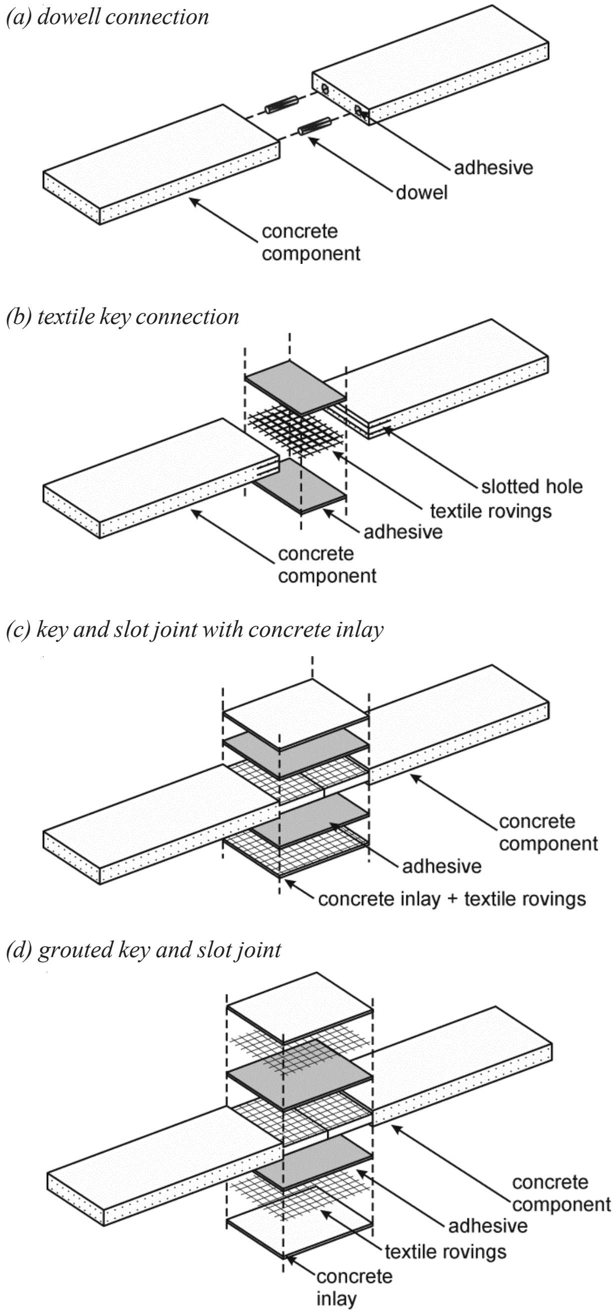

Fig. 2 Tested bonding technologies and geometries [11]

2.2. Materials – fine concrete

For the manufacturing of the tested specimens, the standard concrete mixture used in the SFB 532 with the nomenclature "PZ-0899-01" has been applied. The penetration of close-meshed textiles has been ensured by a small maximum grain diameter of *0.6 mm* and a high flowability. By adding coal fly ash and silica fume in particular, the calcium hydroxide content and the alkali ion concentration of the pore solution have been reduced. For the composition and the mechanical properties of the fine concrete mixture refer to Refs. [10] and/or [12].

2.3. Materials – adhesive

2.3.1. General information

For the manufacturing of the specimens, particular requirements resulting from various interactions are set to two adhesive systems. According to Ref. [8], high-modulus adhesive systems have demonstrated to be particularly advantageous for the impregnation of AR glass textiles, since those system types cause a mainly homogeneous stress distribution in the rovings.

Adhesive bonding of impregnated textiles is, in principle, comparable to the bonding of plastics. Due to the similarity in material between the polymer used for impregnation and the "bonding adhesive", both materials show comparable surface energy values. The wetting characteristic of an impregnated textile surface is, therefore, a major criterion for the selection of the "bonding adhesive" and it may be necessary to optimize the adhesion using suitable measures, e.g. primer coating or other surface pre-treatments. In order to transmit high loads within the reinforcement via the shortest possible joint lengths, both adhesive systems must possess a high strength. The contact with the concrete matrix necessitates further requirements which must be met by adhesives. Adhesives must feature sufficient chemical resistance to the alkaline environment of the concrete and must be insusceptible to the influence of moisture. These requirements are generally met by duromer (thermoset materials) and, in particular, by epoxy resin adhesives. An additional property which is crucial for practicability is the temperature resistance of the adhesives.

2.3.2. Adhesive for the impregnation of the textile reinforcement "EP-I"

For the impregnation of textile fabrics, a two-component adhesive system based on bisphenol-A epichlorohydrin resins has been used in combination with a curing agent which consists of multifunctional amines, hereafter called "EP-I". The stiff, laminating epoxy resin is developed especially for the production of glass-, coal- and aramide-fibre reinforced moulded (shaped) parts and it does not contain solvents or fillers. The specific viscosity of the system guarantees, on the one hand, the good wetting of fibres and it prevents, on the other hand, the leaking of the resin from the surfaces of textile fabrics oriented vertically during the curing process. The adhesive has been characterized in detail in Ref. [8] (nomenclature "EP STF STD"). The impregnated textiles have been cured at room temperature without pressure application for at least five days after which the concreting of the test specimens has been carried out.

2.3.3. Adhesive for the joining of polymer impregnated textiles "EP-F"

For the adhesive bonding of the polymer-impregnated rovings and thus for the actual joining of the concrete parts, a two-component structural adhesive, hereafter called "EP-F", has been used. It is a viscoplastic system on epoxy resin basis (bisphenol-A epichlorohydrin resin) developed for adhesive bonding of metals (e.g. aluminium, steel and brass), plastics and fibre-reinforced materials. The curing agent component consists of modified polyamines. The curing of the adhesive has been carried out at room temperature. Curing may also be accelerated by additional tempering. However, in order that a negative influence of the hydration process on the concrete, and, in particular, the shrinkage processes, be avoided, the specimens have not been subjected to heat treatment.

Table 1 shows a list of some important characteristics of the adhesive bonding systems "EP-I" and "EP-F".

2.4. Materials – textiles

AR glass textiles, produced by the Institut für Textiltechnik at the RWTH Aachen University (ITA) and impregnated using a cold curing adhesive system on epoxy resin basis ("EP-I") have been used for all specimens as reinforcement material. The glass textile has a biaxial structure where, in *0*°-direction, two rovings each are combined (2 x VET-RO-ARG-2400-01-05). These "double rovings" have been arranged in a distance of *12.5 mm* each, the individual rovings have a fineness of *2400* tex. AR glass rovings with a titre of *1200* tex (1 x VET-RO-ARG-1200-01-05) have been used as wefts which have been arranged in a distance of *8.4 mm*. This type of weave is called an open tricot weave with a mesh length of *4.20 mm* (Figure 3).

Table 1 Characteristics of epoxy resin system „EP-I" and „EP-F" (manufacturer information) (- not specified)*

Characteristics	Unit	EP-I	EP-F
Pot life	[min]	? 15	8 to 10
Temperature range	[°C]	–60 to +50	-55 to +80
Optimal processing temperature	[°C]	20 to 35	20 to 25
Hardening (room temp., no annealing)	[4]	2 to 4	7
Mixture ratio (resin – curing agent)	[-]	100 : 35	100 : 50
Shear modulus	[N/mm²]	*	679.8
Young's Modulus of elasticity	[N/mm²]	3866 ± 232	*

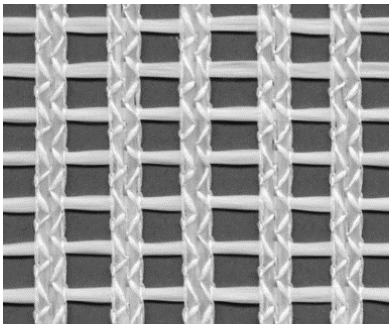

Fig. 3 Layout of textile rovings (source: Institut für Textiltechnik (ITA), RWTH Aachen University)

2.5. Tensile tests on impregnated single rovings

2.5.1. Tensile tests on undisturbed yarn

For the characterisation of the load-carrying behaviour of the polymer-impregnated textile, in a first step, yarn pull-out tests have been carried out on undisturbed rovings (*0°*-direction). With average stress at failure of *1375 N/mm²*, the impregnated rovings show average failure strain of *23.4 ‰*; Figure 4 shows exemplarily the stress-strain-curves of an unimpreganted roving and of an impregnated roving.

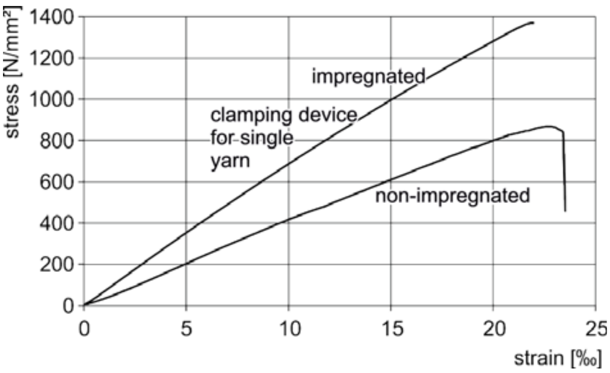

Fig. 4 Pull-out-tests: impregnated and unimpregnated rovings (2 x VET-RO-ARG-2400-01-05)

The Figure 4 illustrates that the impregnated roving, due to the optimised internal bond between the individual fibres, has a considerably higher strength and stiffness than the unimpregnated roving. If the initial unimpregnated fibre has a strength of *1750 N/mm²*, the strength loss of the unimpregnated yarns is, on average, approximately *50%*. The strength loss of the impregnated yarn, compared with the initial fibre strength, is only approximately *20%* [9].

2.5.2. Characterisation of the bondline characteristics in the yarn pull-out test

For a reference characterisation of the load-carrying behaviour of the yarn, tensile tests on single-strap joints have been carried out. Adhesively bonded yarn specimens have been tested with joint lengths between *20* and *50 mm*. Due to the structure of the textile, there is, on the one hand, a flat ”roving underside“ and, on the other hand, an almost oval “roving top side”. Preliminary tests have demonstrated that the adhesive bonding of the “roving undersides“ is advantageous, thus all further specimens have been prepared accordingly.

In order that an optimal surface pre-treatment may be determined, yarn pull-out tests have been additionally carried out. For the treatment of the impregnated roving surfaces (degreasing, brushing and second degreasing), the degreasant has been varied: acetone, ethanol or isopropyl alcohol. Due to the highest average failure loads, isopropyl alcohol has been chosen for the treatment of all further specimens [9].

Depending on the joint length, the adhesively bonded yarns have shown three different types of failure:

* Adhesive failure between “joining adhesive” and impregnated yarn surface;
* Break-off of the polymer coating;
* Failure in the net section.

The influences of the joint length on the adhesive strength and the failure load of the bonding are depicted in Figure 5.

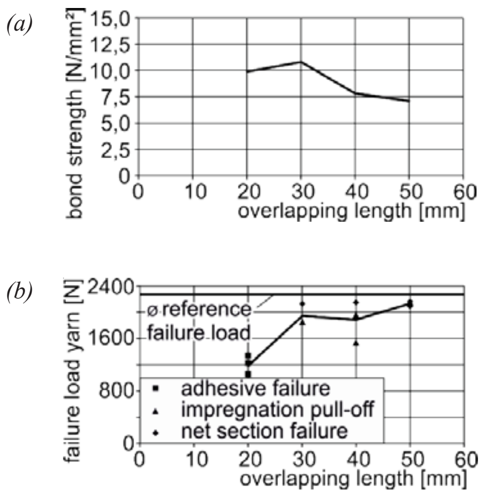

Fig. 5 Interdependence of bond strength (a) and failure load (b) with joint length (the bonded yarn tensile test)

For the determination of the adhesive strength a simplified assumption of a constant stress distribution in the bondline has been made. Figure 5(b) shows the medium failure loads of the respective test series as well as the results of the individual test specimens with the allocation of the cause of failure.

As far as the adhesive strength is concerned, the stress distribution within adhesive joints of short overlap lengths (*20, 30 mm*) is homogeneous within the range of scattering, Figure 5(a). The expansion of the joint length causes a decrease of the adhesive strength, corresponding with less increase of the failure load. Consequently, the increase of the adherend deformation respectively results in the development of stress peaks at the overlap ends. The failure load of the reference yarns has not been quite achieved, not even in the case of the largest examined joint, with a length of *50 mm*, although the achieved failure load has been close to the referent failure load.

2.6. Textile reinforced concrete specimens

2.6.1. Reference specimens

All test specimens have had a cross-section of *25 x 150 mm*^{2} and a length of *1 m*. At a distance of *5.0 mm* from the upper and the lower surface, one layer of polymer-impregnated textile (2D-04-06) has been positioned for reinforcement purposes. In order to produce reference specimens and also concrete elements of the joined test bodies with a formwork, casting has been carried out horizontally, accepting different surface structures of the produced specimens. For the installation in the test setup, the tensile test specimens have had to be shortened by *5.0 cm* each.

2.6.2. Key and slot joint with concrete inlay

The joint geometry of the key and slot joint specimen with concrete inlay is depicted in Figure 6.

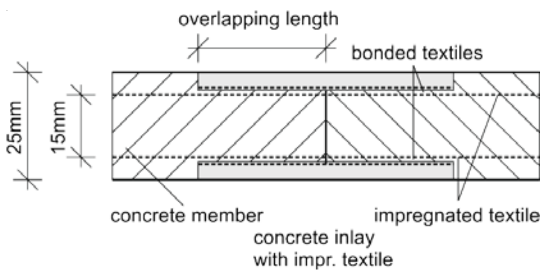

Fig. 6 Geometry of the key and slot joint with a concrete inlay

The joining of the textiles has been carried out by using single-overlap joints on both top and bottom of the concrete specimens. Bonding of the reinforcement has been carried out at the "roving undersides" of the body sides pointing outwards. The "textile strap" is in an exposed position at the surface of the concrete inlay which is produced at the same time as the concrete specimen using exactly the same concrete mixture. For both the main concrete specimens as well as the concrete inlays, during the production, the joining area is not covered by concrete – the oozing out of the concrete between the meshes of the textile have had to be avoided by all means.

2.6.3. Key and slot joint with subsequent grouting

Despite the greatest care the development of joints with concrete inlays has shown to be problematic. The single rovings in concrete parts and inlays often show minor and differently pronounced ripples vertically to the adhesive joint. As a consequence of not being able to avoid the flatness imperfections completely, not even by a careful orientation of textiles immediately after polymer impregnation, irregular and/or insufficient adhesive bonding of the yarns and locally differing bondline thickness has taken place. The results of the tensile tests (explained in detail in Section 2.7) show correspondingly high scattering of the determined failure loads. In order to optimise the characteristics of the key and slot joint specimen, a method which allows the joining of the elements and the production of a coextensive structure in separate working steps has been chosen. For this purpose, in a first step, the textile straps have been joined with the exposed textile of the key and slot joints.

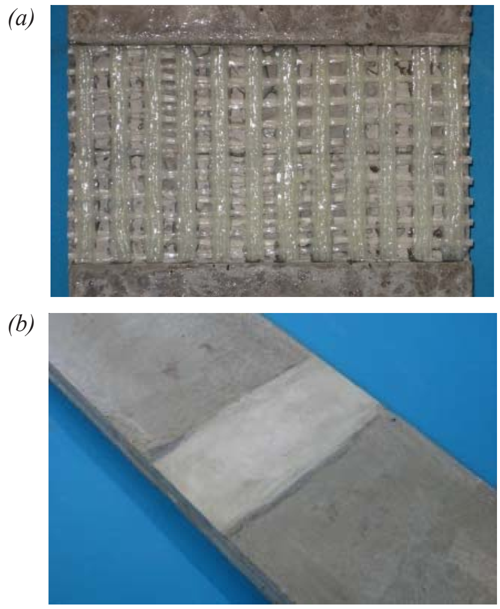

Fig. 7 Bonded textile straps (a); and the final key and slot concrete member with subsequent grouting (b)

The flexibility of the impregnated textiles, which is available to a limited extent, allows the compensation of the irregularities of the yarns in the joining point of the concrete part as well as a precise orientation of longitudinal rovings and transverse rovings of the textiles, Figure 7. The grouting of the joining points with the fine concrete mixture has been carried out after the curing process of the adhesive has been completed.

2.7. Tensile tests on textile concrete parts

2.7.1. Experimental set-up: tensile tests

The changes in length of the test specimen have been measured via three inductive displacement transducers (Figure 8). Two displacement transducers have been attached on one side of the specimen in the edge area.

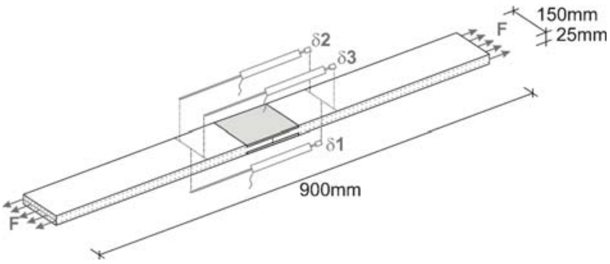

Fig. 8 Geometry of specimens for the tensile tests, configuration of measuring devices [11]

An additional displacement transducer has been positioned centrally on the opposite side (Figure 9(a)). In this manner, it is possible to detect irregular deformations and/or inclination of the body. Particular attention has been given to the clamping of the test bodies for load application in the test rig so that a premature failure of the test bodies at the clamping device may be prevented. The tests have been carried out with displacement control and at a test speed of *1 mm/min*.

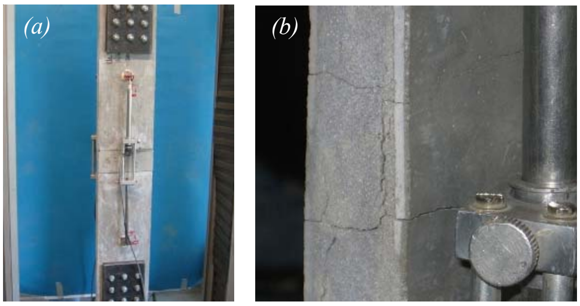

Fig. 9 Test set-up for the tensile tests (a); and concrete splitting under pure tension along reinforcement (b) [9]

2.7.2. Tensile tests on undisturbed reference specimens

The development of joint geometries that achieve the strength of the undisturbed joining members under various types of load demands, as a first step requires the characterisation of the load carrying behaviour of the undisturbed reference specimens.

In order that the influence of the roving orientation may be identified, the orientation of the roving surfaces has been varied. As far as failure load, failure strain and stiffness are concerned, a significant influence of the textile orientation has not been observed. The crack formation in the specimens where the textile surfaces are oriented outwards has been completed slightly earlier than expected. The first-crack loads of all reference specimens are within the range of *10* to *12 kN* at an average strain in the tensile region of *0.10* to *0.20 ‰*.

All the reference specimens show longitudinal cracks at the reinforcement (splitting along reinforcement), which, under high loads, lead to the spalling of the concrete cover (Figure 9(b)). Splitting along the reinforcement is particularly pronounced on those specimens with the textile surfaces oriented outwards, so starting from loads of approximately *25* to *30 kN* already first longitudinal cracks occur. In contrast to this, longitudinal crack formations generally occur in the specimens with the textile surfaces oriented to the interior just immediately before the failure load is achieved. All the reference specimens have failed abruptly through the breaking of the reinforcement, showing large-area spalling of the concrete cover (Figure 9(b), centre).

The factors listed here have, in accordance with Piegeler [9], been identified as the causes of the longitudinal crack formation, especially in case of the outward-oriented top sides of the textiles:

* Orientation of the textile surfaces;
* “Flatness imperfection/ripples” of the textile;
* Splitting tensile load caused by transverse rovings;
* Separation effect of the textile area opposite to the concrete cover;
* Concentration of the splitting tensile strength at the “double rovings”;
* Concentration of the splitting tensile strength vertically to the textile area.

The average stiffness of the undisturbed reference specimens corresponds approximately to the stiffness of the single rovings in the yarn pull-out tests. The results of the tensile tests are listed in Table 2.

In comparison with the yarn reference, the strength loss of the reference specimens is approximately *37%*.

Table 2 Tensile tests: undisturbed reference [9]

Specimen no.	$\sigma_{fracture}$ [N/mm²]	$\varepsilon_{fracture}$ [‰]	F_{Tex} [kN]	Orientation Textile
16_1	1042.06	12.89	44.79	top side outside
16_2	1163.87	17.24	50.03	top side outside
16_3	1053.16	13.75	45.27	top side inside
16_4	1052.47	15.51	45.24	top side inside
16_5	1168.43	15.18	50.22	top side inside
Mean value	1096.00	14.92	47.11	

2.7.3. Tensile tests on key and slot specimens with concrete inlay

The failure of key and slot specimens with a concrete inlay is in general characterised by the separation of impregnation polymer from the textile surface in the joint area. Adhesive failure between the surfaces have occurred mainly in the specimens with a very short joint length of *10 mm*. Fracture of the undisturbed cross-section have not occured. At loads between *16* and *24 kN* longitudinal crack formation in the reinforcement for all specimens has occurred. The splitting tensile crack formation has always started in the edge at the transition between the joining point and the undisturbed part. Fracture of the specimens has occurred abruptly and is generally initiated by the failure of the bondline in the side regions.

Figure 10 shows a selection of stress-strain curves of a reference specimen and of the joined specimens. A minimum of three specimens has been used for testing each joint length. Figure 10 shows that the mean stiffness of the joined specimens does not achieve the stiffness of the references.

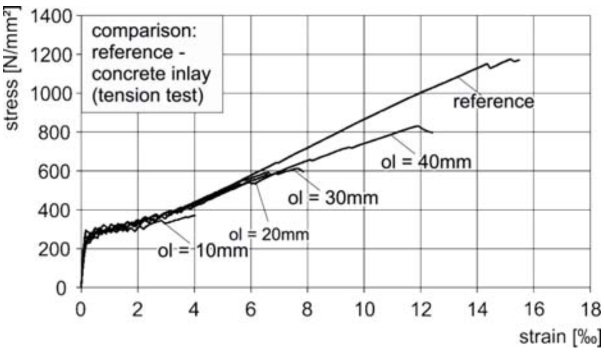

Fig. 10 Stress-strain behaviour of the selected key and slot specimens with a concrete inlay

The development of the adhesive strength and of the failure load of the textile depending on the joint length is depicted in Figure 11: With longer joint length the adhesive strength decreases – also the longest, examined joint length of *40 mm* does not clearly achieve the failure load of the reference specimens.

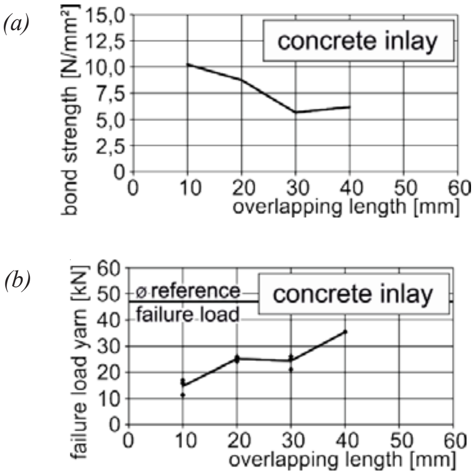

Fig. 11 Interdependence of bond strength (a); and failure load (b) and joint length (tests on the key and slot specimens with a concrete inlay) [9]

2.7.4. Tensile tests on key and slot specimens with subsequent grouting

The key and slot specimen with subsequent grouting have shown that it is possible to increase the failure loads of the specimens by up to *64 %* [9]. Failure occurs in general under separation of the impregnation polymer from the yarn surface (splitting along reinforcement, Figure 12).

Fig. 12 Splitting cracks in the joint area of a key and slot specimen with a concrete inlay (a); subsequently grouted joint (b) [9]

The failure of the adhesive bonding between impregnation polymer and joining adhesive has been observed in individual cases only. Starting at overlap lengths of *40 mm* the failure of several specimens in the undisturbed cross-section has been observed.

The stress-strain curves from exemplary tests depicted in Figure 13 show that, compared with the undisturbed reference specimens, no loss of stiffness of the joined specimens has been observed.

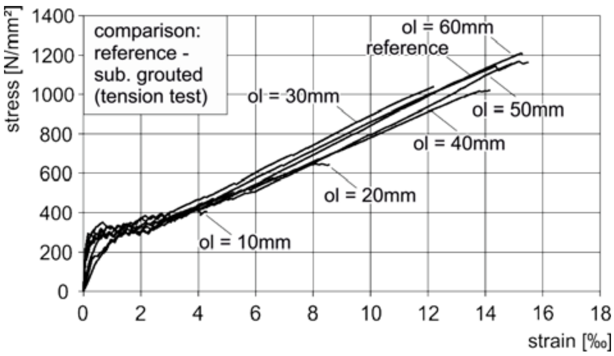

Fig. 13 Stress-strain behaviour of the selected key and slot specimens with a subsequently grouted joint

Figure 14 shows the development of the adhesive strength and the failure load relative to the joint length in key and slot specimens with a subsequently grouted joint. The decrease of the adhesive strength and/or the failure load curve show that with an increasing joint length, and/or increasing failure force, an inhomogeneous stress distribution exists. Starting from a joint length of *30 mm*, a clear decrease of the adhesive strength occurs which has already been observed during the yarn pull-out tests (Figure 5) and in the tests on the key and slot specimens with concrete inlay (Figure 11). The decrease is, however, less than the one for the key and slot specimens with concrete inlay, therefore, clearly, a higher adhesive strength is maintained.

(a)

(b)

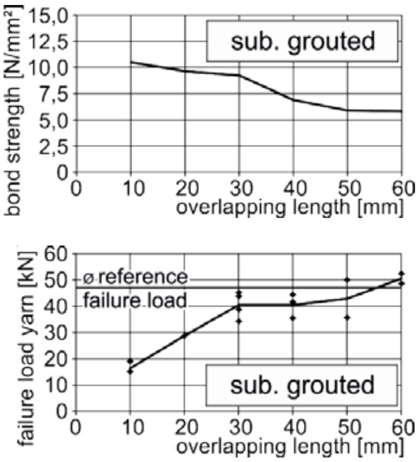

Fig. 14 Interdependence of bond strength (a) and failure load (b) with joint length (tests on the key and slot specimens with a subsequently grouted joint) [9]

Hence, the higher stiffness of the specimens is mainly to be attributed to a more regular and more homogeneous adhesive bonding of the individual rovings. Furthermore, this results in the fact that starting from a joint length of *60 mm*, the medium failure load of the undisturbed references is achieved. It has to be noted that the results of the tensile tests on the test specimens with a joint length of *50 mm* have shown, in this case too, a manufacture-induced scattering.

2.8. Bending tests on textile concrete parts

2.8.1. Experimental set-up: bending tests

The width between supports in the four-point bending test has been *0.9 m*, and the loads have been applied at the third points (Figure 15).

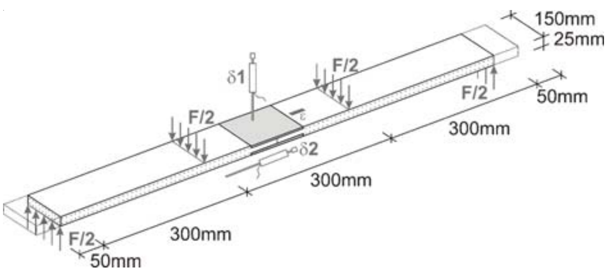

Fig. 15 Geometry of the specimens for the bending tests, configuration of the measuring devices [11]

The deflection at midspan, as well as, the deformation at the specimen underside, have been measured via inductive displacement transducers (Figure 16(a)). For the determination of the concrete upsetting in the compression area of the specimen, a strain gauge (DMS) is placed onto the concrete surface. The tests have been carried out with displacement control at a deformation speed of *1 mm/min*.

2.8.2. Bending tests on undisturbed reference specimens

In the bending test, the undisturbed reference specimens have shown a high ductility with deflections of up to *101 mm*. The load carrying behaviour is mainly characterised by splitting tensile crack formation and the break-off/spalling of the concrete cover (Figure 16(b)). The splitting tensile cracks mainly stem from bending cracks in the regions of load application with cylinder forces of approximately *1.0* up to *1.4 kN*. With increasing load, the longitudinal crack formation also increases and results, when the support is reached, in the complete loss of the bond with subsequent failure of the specimen. This failure behaviour has been observed particularly in the specimens in which the textile topside points to the outside. Fracture of the reinforcement has not occurred when the textile topside points to the outside. If the textile surface points to the inside, however, a decreased longitudinal crack formation occurs at a slightly increased load level (approx *1.2* to *1.4 kN*). If the textile surface is on the inside, a failure of the textile reinforcement is observed in the majority of cases.

(a)

(b)

Fig. 16 Concrete cracking (a) and concrete spalling (b) during the bending test [9]

The failure load cylinder force for the concrete specimens with textile surface on the inside, averages *2.99 kN*. The load-carrying capacity is lower by *10%* if the textile surface is oriented to the inside. This may be explained by different failure mechanisms, depending on the textile orientation. The crack distances are approximately *1.0* to *2.5 cm* at the undisturbed reference specimens. The textile failure stress is averagely at *1088 N/mm²*. The corresponding textile strain is, averaged, *18.16‰*.

2.8.3. Bending tests on key and slot specimens with concrete inlay

In all bending tests on the key and slot specimens with a concrete inlay the failure of the adhesive bond has been decisive, breaking in the undisturbed cross-section has not been observed. Starting from joint lengths of *10 mm*, mainly adhesive failure between impregnated yarn surface and joint adhesive has occured. Furthermore, with an increasing joint length, the break-off of the impregnation polymer of the yarn surface has occurred. The failure of the adhesive bond is due to insufficient bonding and/or due to the fact that the yarn surfaces did not come close enough to one another.

The failure load cylinder forces and the corresponding deformations of the joined concrete parts with different joint lengths are shown, in comparison with the reference tests, in Figure 17. The joined concrete parts also have a high ductility. Specimen stiffness is increasing – analogous to the yarn pull-out tests – with increasing joint length. The first-crack loads (bending cracks) appear at cylinder forces from approximately *0.3* to *0.5 kN* and thus do not achieve the load level of the undisturbed reference specimens. The cracks develop in the region of the cross-section weakening at the joint. It applies to all specimens, that the average crack distance is approximately *2.0* to *3.5 cm*. As in the case of the undisturbed reference specimens, distinctive splitting tensile cracks in the region of the lower reinforcement layer have been observed on the joined pieces. These longitudinal cracks have developed on all of the specimens initially at the joint at cylinder forces of approx. *0.7* to *0.9 kN*. A further load increase has resulted in the expansion of splitting tensile cracks, which, however, have not initiated the failure in any of the tests.

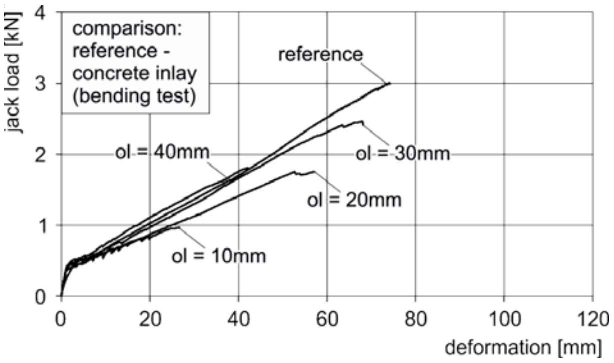

Fig. 17 Jack force – a displacement diagram of the selected key and slot specimens with a concrete inlay

The dependence of the adhesive strength and the failure load on the joint length is depicted in Figure 18. The failure loads of the reinforcement are determined by iteration of the textile strain. It becomes clear that, again, the adhesive strength decreases with a longer joint length, (Figure 18(a)). The decreasing failure load at the joint length of *40 mm*, compared with that of *30 mm*, is to be attributed to manufacturing errors with the result of an inhomogeneous stress distribution in the bondline. The medium textile failure load has achieved its maximum – with a joint length of *30 mm* – *85%* of the reference level.

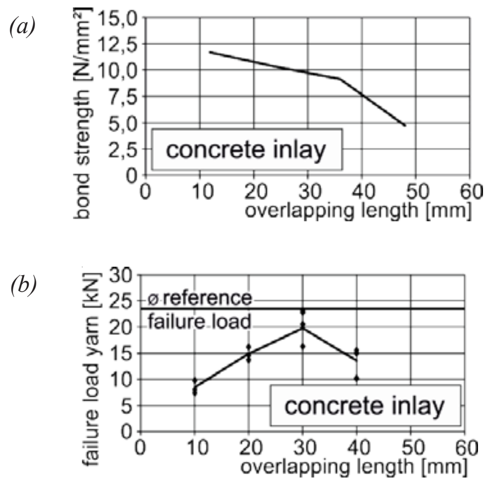

Fig. 18 Interdependence of bond strength (a) and failure load (b) with joint length (the tests on the key and slot specimens with a subsequently-grouted joint) [9]

2.8.4. Bending tests on key and slot specimens with subsequent grouting

For the subsequently-grouted key and slot specimens (Figure 7) only a set of bending tests have been performed with a reduced selection of joint lengths. While with the smaller joint length the failure observed was a failure of the adhesive bond by break-off of the impregnation polymer of the yarn surface, the longer joint length actually led to breaking in the undisturbed cross-section.

The failure load cylinder forces and the corresponding deformations of the joined concrete parts with different joint lengths are shown in a comparison with the reference tests in Figure 19.

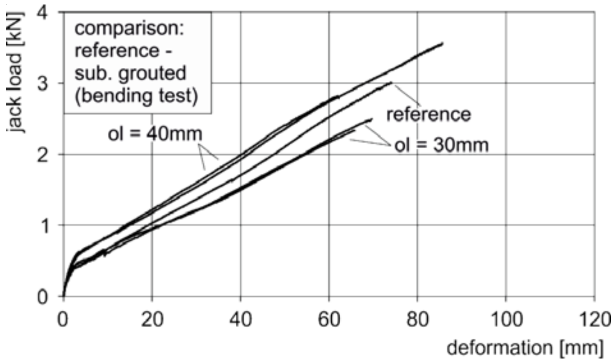

Fig. 19 Jack force – a displacement diagram of the selected subsequently-grouted key and slot specimens

Ductility and stiffness are similar to the reference test, however, with the increase of joint length, the stiffness slightly increases again, as observed for the yarn pull-out tests. The first-crack loads (bending cracks) appear at cylinder forces from approximately *0.7* to *0.9 kN* and thus, are higher than for the specimens with inlays but do not quite achieve the load level of the undisturbed reference specimens. The cracks develop in the region of the cross-section weakening at the joint, but also close to the load introducing supports. This applies to all of the specimens with an average crack distance of approximately *1.0* to *2.5 cm*. As in the case of the undisturbed reference specimens, the distinctive splitting tensile cracks have been observed too, in the region of the lower reinforcement layer of the joined pieces. A further load increase has resulted in the expansion of splitting tensile cracks which, in the case of the longer joint length, have initiated the failure.

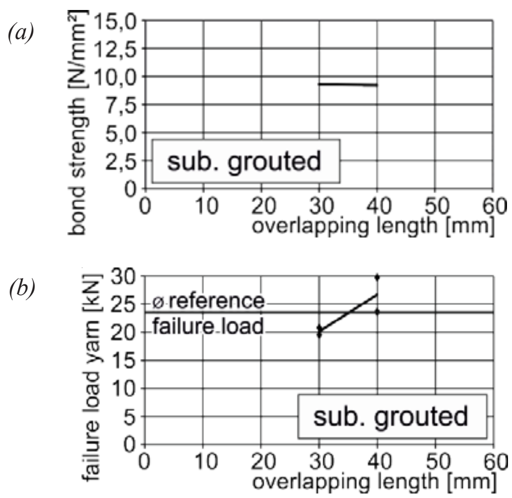

Fig. 20 Interdependence of bond strength (a) and failure load (b) with joint length (tests on the key and slot specimens with a subsequently-grouted joint) [9]

The dependence of the adhesive strength and the failure load on the joint length is depicted in Figure 20. The failure loads of the reinforcement are determined by iteration of the textile strain. With only two joint lengths being tested no certain conclusion may be drawn, however the increasing failure load up to the level of the undisturbed specimens signals that, in comparison with the other test specimens, it has been possible to maintain the adhesive strength on a relatively high level.

3. PROSPECTS

The reference load of the undisturbed part, in the case of the key and slot specimens with grouted joint and a joint length of *60 mm*, has been achieved in the tensile test. To all the specimens applies the bond line showing inelastic properties. Joint length and failure load have not developed in proportion to one another. A significantly inhomogeneous stress distribution has been noticed to exist in the adhesive layer starting at a joint length of *20* and *30 mm*.

Future tests should always be carried out on yarn and also on component basis. As for the inhomogeneous stress in the bond line, the optimisation of the bond line thickness should be pursued in order for the increase of transmissible loads via the respective joint length to be achieved. Since the bond between joining adhesive and impregnated yarn surface fails by separation of the polymer coating, it is to be investigated to what extent a direct fusion between textiles is suitable for the increase of transmissible forces. Based on what has been said, the adhesive efficiency of the impregnation polymer should be re-evaluated, too. For a further research on the load carrying behaviour of the components, tests under combined tensile and bending load should be carried out.

While the techniques introduced within this research are all limited to join textile reinforced components with a maximum of two textile layers, a new system for multiple textile layers has been under development and will be tested in the future. While the textile layers are exposed and overlapped, the whole connection is grouted using an epoxy resin or a similar grouting component (e.g. an elastomer system [13, 14], Figure 21).

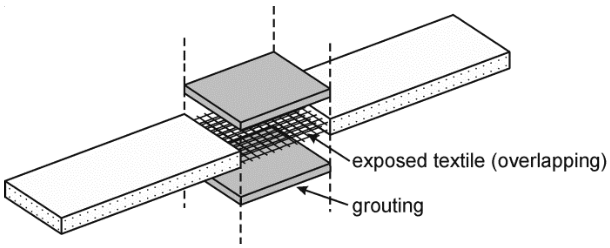

Fig. 21 Multiple layers of exposed, overlapping textile with subsequent grouting

4. ACKNOWLEDGMENTS

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SPAJANJE LIJEPLJENJEM BETONSKIH DIJELOVA OJAČANIH TEKSTILOM

SAŽETAK

Cilj ovoga rada je razvoj tehnologije lijepljenja materijala u slučaju običnih, betonskih elemenata ojačanih tekstilom. Kako bi se opisao mehanizam ponašanja nosivosti lijepljenih spojeva, provedena su opsežna ispitivanja kako na pojedinim vrstama tekstila tako i na elementima konstrukcije. Korištenjem takvih spojeva u kombinaciji s naknadnim injektiranjem može se postići nosivost neporemećenog uzorka. Ipak, daljni uvid u optimizaciju procesa lijepljenja je nužan. Proces lijepljenja materijala trebao bi težiti pojednostavljenoj proizvodnji, ali i boljim uvjetima reproduciranja koji su preduvjet za provođenje numeričkog modeliranja.

Ključne riječi: *beton ojačan tekstilom, tehnologija spajanja materijala, tehnologija lijepljenja materijala, epoksidna smola.*