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Anchoring Stresses between Concrete and Carbon Fibre Reinforced Laminates

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Summary

When using carbon fibre reinforced laminates for concrete strengthening, the anchoring stresses in the end zones cause special problems. A special shear test specimen is used to study the shear stress distribution and the fracture behaviour in displacement controlled tensile tests. The fracture energy and the bond strength are calculated using fracture mechanics. This paper presents the results of these experiments, and compares the bond strengths predicted by non-linear fracture mechanics and by the actually applied phenomenological design methods.

1. Carbon Fibre Reinforced Plastic (CFRP)

The evolution in the technology of new materials makes it possible to replace the classical steel plates for concrete strengthening by new high-grade materials. This has led to the idea of replacing the steel plates by fibre reinforced composite sheets made of unidirectional, continuous fibres such as glass, carbon and polymers, bonded together with a matrix such as epoxy resin [1,2]. Carbon fibre reinforced epoxy laminates are the most appropriate for strengthening concrete beams. In the early stage these laminates had to be autoclaved, which was difficult to execute in practice. Since the availability of so-called prepreg laminates, these difficulties have disappeared. Prepreg epoxy laminates are preimpregnated with an epoxy resin, which holds the fibres together. The prepreg sheets are very flexible and can be cut easily by means of scissors. At application, the prepreg sheets are impregnated again with the right mixing ratio of epoxy resin components and the chemical reaction is started. When the first layer has hardened enough, the second layer can be applied in the same manner. Several layers, up to 10, can be applied. These prepreg sheets are first developed and produced in Japan. Recently, new UD laminates, which are not preimpregnated, are available. In Belgium the first application of CFRP-laminates took place at the beginning of 1996 [3,4].

2. CFRP laminates versus steel plates

The CFRP laminates have a lot of advantages to classical steel plates. The mechanical properties are superior (table 1).

Properties	CFRP HS	CFRP HM	Steel
Characteristic tensile strength (N/mm^2)	2500	2000	360
Young's Modulus (N/mm^2)	240000	650000	210000
Fibre Cross-section (cm^2/m)	1.67	0.95	---
Fibre Areal weight (g/m^2)	300	200	---
Width of sheet (cm)	25/33	25/33	---
Length of sheet (m)	100	25	6

Table 1 Typical properties of CFRP-sheets and steel plates

The tensile strength of the prepreg sheets is 5 to 10 times higher than that of steel, whereas the modulus of elasticity is comparable to the modulus of steel. Some carbon fibre laminates reach a modulus of elasticity up to 650000 MPa. These good mechanical characteristics allow a smaller cross-section of external reinforcement. Prepreg and UD sheets are also easier to process. Since the CFRP laminates are much lighter - the density is about 3 times lower than the density of steel - the sheets can be placed with less manpower. The CFRP sheets are available on roll, which means that they are available in any length, whereas the steel plates are limited in practice to 6 metre.

Carbon fibres are very corrosion resistant. An expensive surface treatment, like for steel, is not necessary. The CFRP laminates are extremely useful in very corrosive environments, such as marine and chemical aggressive atmospheres. There are some disadvantages too. First it is a brittle material. The carbon fibre behaves linear elastic till rupture, without a plastic phase. The rupture occurs without preceding plastic deformation. The anchorage can give problems too. Due to the high stresses, the CFRP-laminates will peel off easily. The carbon fibres are all oriented longitudinally and the good mechanical properties are only valid in that direction. Without special precautions it is for example impossible to drill a hole, needed for the placement of a dowel. The fibres would be cut and would no longer be able to transfer forces.

And finally the price of CFRP-laminates is rather high. The material is much more expensive than steel but the processing cost is much lower. To calculate the total project cost using CFRP laminates all the above elements have to be taken into account.

3. Anchorage of CFRP-laminates

Because of the higher stresses in the CFRP-laminates, the stresses and stress concentrations in the anchorage zone will increase too. Without any precaution the CFRP-laminate might peel off. Extrapolation of the experimental results on the anchorage of steel plates is not allowed. Research concerning the anchoring phenomena has been started at the Reyntjens Laboratory. This investigation deals with the stress distribution and force transfer at the ends of the laminates using non-linear fracture mechanics. The aim is to obtain design rules, based on theoretical and experimental results, to make a safe and economical design possible.

Preliminary shear experiments have been done at the Reyntjens Laboratory [5]. Two concrete

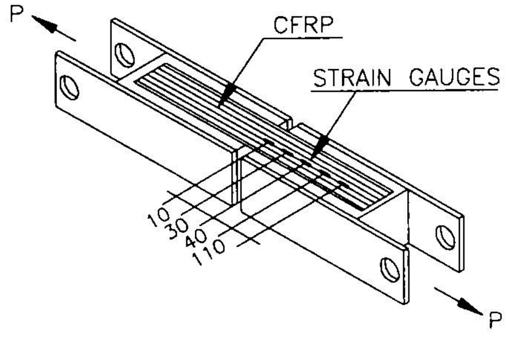


Fig. 1 Test specimen

prisms (150 mm x 150 mm x 300 mm) are connected by gluing 3 layers of CFRP laminates at two opposite sides (figure 1). On the other sides steel plates are glued to apply the tensile force. The test specimen is loaded in a displacement controlled tension machine. Two cardan transmissions assure that the tensile forces act centrically.

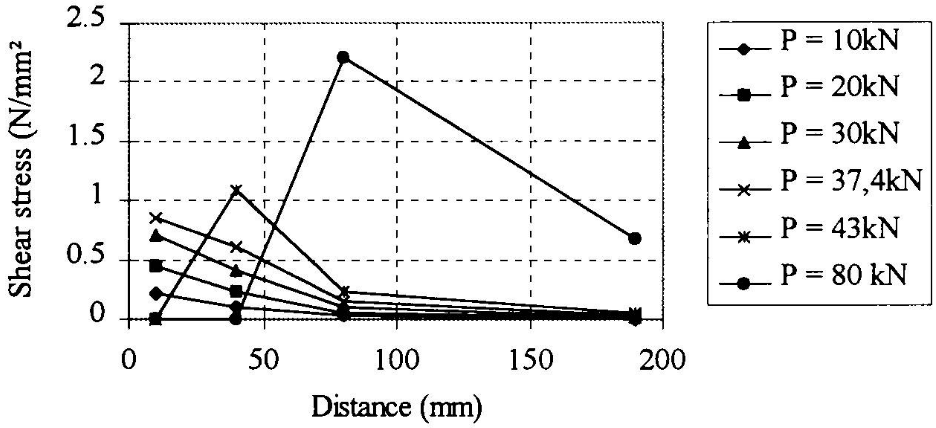


Fig. 2 Shear stresses of specimen A6 (100mm x 200mm)

The load, the deformation of the gap between the two prisms and the strains of the CFRP laminates are recorded during testing. The deformations of the gap are registered with two LVDT-transducers placed at two opposite edges. The strains are measured with strain gauges glued on the CFRP-sheets.

Two series of test specimens, A and B, were manufactured. The compressive strength were respectively 47.9 N/mm^2 and 46.0 N/mm^2.

The results show that at the end of the CFRP-sheet a shear stress peak occurs at low forces. When a maximum shear stress is reached the concrete starts to crack. At increasing load, the shear stress peak occur further away from the end zone and the maximum shear stress attains higher values (figure 2). This behaviour seems to be the same as for externally bonded steel plates. The fracture load was compared with the fracture load calculated with the method of Van Gemert [6,7], and with the theory proposed by Täljsten [8] (table 2).

Test Specimen	Bond Length	Measured fracture load	Theoretical fracture load		Difference	
			Täljsten	Van Gemert	Täljsten	Van Gemert
	(mm)	P(kN)	P (kN)	P (kN)	(%)	(%)
A1	175	38.7	37.7	18.9	2.6	51.2
A2	150	36.2	31.3	16.2	13.5	55.2
A3	225	41.2	36.2	24.3	12.1	41.0
A4	200	32.1	30.9	21.3	3.7	33.6
A5	200	48.5	43.9	27.0	9.5	44.3
B1	200	55.1	44.1	30.0	20.0	45.6
B2	250	50.8	43.7	37.5	14.0	26.2
B3	250	46.1	35.6	30.0	22.8	34.9
B4	250	34.0	27.6	28.3	18.8	16.8
B5	200	42.4	39.0	24.0	8.0	43.4

Table 2 Test results

The theory used by Täljsten is based on a non-linear fracture energy concept. Steel plates to concrete connections were tested in pure shear, i.e. mode II failure. Both symmetrical and non-symmetrical overlap-joints were considered. When a brittle adhesive (G> 1.0 Gpa), such as most epoxy adhesives, is used, the NLFM theory leads to the following expression:

$$P_{\max} = b\sqrt{\frac{2E_{CFRP}\,t_{CFRP}\,G_f}{1+\alpha}}$$

$$\alpha = \frac{E_{CFRP}\,t_{CFRP}}{E_{concrete}\,t_{concrete}}$$

with	E	modulus of elasticity (N/mm^2)
	t	thickness (mm)
	G_f	fracture energy (Nmm/mm^2)
	b	width of CFRP laminate (mm)

The difficulties of this method are the exact definition of "the fracture energy" and how to calculate this fracture energy from the measured values of the load, deformation and shear stresses. This method can not be used as a design rule. For that purpose a relation between the concrete properties, which can be easily determined, and the fracture energy is needed. Research should be done in that area, especially concerning the fracture energy in glued connections between concrete and other materials, like steel or CFRP-sheets.

The method of Van Gemert is a design rule. The only parameter needed is the tensile strength at the concrete surface, which can easily be measured by means of the pull-off test.
The fracture load found in this way gives the load at cracking of the concrete in the initial force

transfer zone. It does not take into account the reserve available after first cracking. This explains the differences with the experiments. A triangular shear stress distribution is assumed on the basis of a large number of experiments (figure 3). With this assumption an anchorage length is calculated. A large safety factor is used to apply this method for design cases.

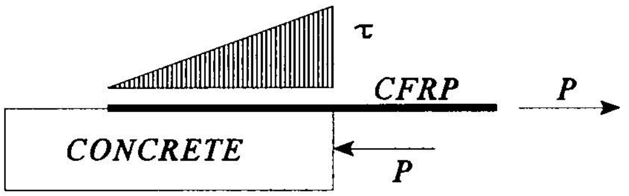


Fig. 3 Shear stress distribution (Van Gemert)

$$P_{max} = \frac{b\, l f_{ctk,s}}{2}$$

with	b	width (N/mm^2)
	l	bonding length (mm)
	$f_{ctk,s}$	pull-off strength of concrete surface (N/mm^2)

The bonded length of the CFRP-sheets on the test prisms were varied too. The fracture load increases when the bonded length increases (figure 4).

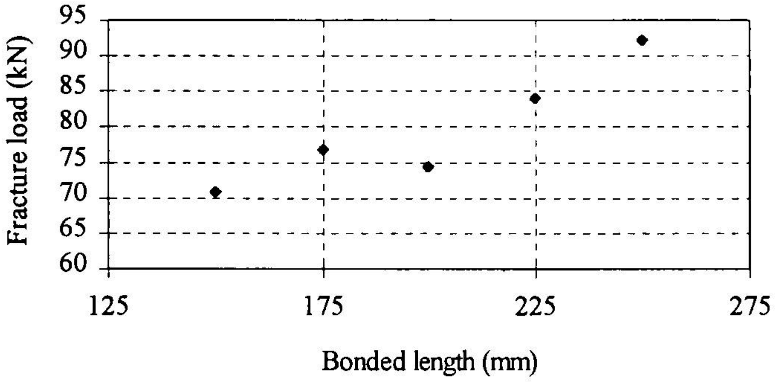
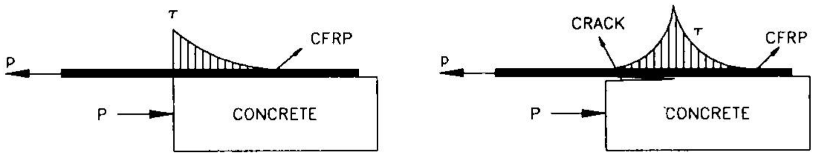


Fig. 4 Influence of bonded length to fracture load (width 80 mm)

However the influence of the bonded length will decrease at larger lengths. Before cracking, the shear stresses reach a maximum value at the end of the CFRP-sheet (figure 5). When the shear stress exceeds the pull-off strength of the concrete surface, the concrete starts to crack [6].
At higher loads, the maximum shear stress shifts to the right (figure 5) and attains higher values. When the direct tensile strength, which is larger than the pull-off strength, is reached, the crack will extend and the sheet will peel off in a brittle way.



Before cracking **After cracking**

Fig. 5 Shear stress distribution before and after cracking

Once the tensile force from the CFRP-sheet is transfered into the concrete, there are nearly no shear stresses between the remaining sheet and the concrete. This means that when the bonded length exceeds a critical length, the fracture load remains constant. The determination of this critical length can be done experimentally.
In figure 4, the fracture load has not yet attained a constant value, which means that the critical bonded length is at least larger than 275 mm.

4. Conclusions

The use of carbon fibre reinforced materials offers great opportunities in concrete strengthening. A lot of research has to be done to really understand the behaviour in the concrete-CFRP connection. The end zones are the most critical points. Because of the higher stresses in the CFRP laminates, the risk of peeling off increases. Experiments show that the behaviour of externally bonded CFRP-laminates is similar to externally bonded steel plates. A non linear fracture mechanics based design is possible, if the fracture energy G_f of the bonded connection is known. Actually G_f must be determined experimentally, but further research should allow to calculate G_f from the characteristics of the connection and its constituents.

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