CFRP NEAR SURFACE MOUNTED REINFORCEMENT (NSMR) FOR PRE-STRESSING CONCRETE BEAMS

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ABSTRACT

The increased need for rehabilitation of existing concrete structures is well known, and almost every country in the world are doing research in this field. The cause for rehabilitation varies and so does the methods to returning the structures to service. However, new technical solutions and methods that effectively can achieve more economical ways of upgrading structures in front are very welcomed. In recent years the use of CFRP plate bonding has shown to be such a method. This method implies that a thin laminate or fabric, mostly of carbon fibre reinforcement, is bonded to the surface of a concrete structure and then act compositely as an outer reinforcement layer. Even though investigations have been presented where CFRP laminates were pre-stressed before they were bonded to the surface of the structures, most of the strengthening applications world-wide have been performed without pre-stressing of the laminates or sheets. However, the risk for damage by for example vehicle impact can be disastrous for such a structure.

At Luleå University of Technology, research is taking place in the field of CFRP – plate bonding. Extensive research is focused to investigate the possibilities of using CFRP laminates as NSMR (Near Surface Mounted Reinforcement). This method may be defined as a method where laminates or rods are bonded in slots in the concrete cover. By pre-stressing the laminates a compressive force can be transfer into the concrete structure at the same time the laminates is protected in the slot.

This paper presents briefly laboratory tests and theory for rectangular concrete beams strengthen with pre-stressed near surface mounted CFRP laminates. Slots have been sawn up in the soffit of the beams and the laminates have been epoxy bonded in these slots. The laminates were pre-stressed prior to bonding. The primary results shows an increased yielding and first crack load. The failure modes were in comparison the same with or without pre-stress, failure in the laminate, but the pre-stressed beams had smaller deflections at failure.

KEYWORDS

NSMR, pre-stress, CFRP, concrete, strengthening, epoxy, carbon fibre, composite

INTRODUCTION

All over the world there are structures intended for living and transportation. The structures are of varying quality and function, but they are all ageing and deteriorating over time. Of the structures needed in 20 years from now about 85-90 % of these are already built. Some of these structures will need to be replaced since they are in such a bad condition. It is not only deterioration processes that make upgrading necessary, errors can have been made during the design or construction phase so that the structure needs to be strengthened before it can be fully used. New and increased demands from the transportation sector can furthermore be reason for strengthening. If any of these situations should arise it needs to be determined whether it is more economical to strengthen a structure or to replace it. A strengthening method that has been increasingly used the last decade is Plate Bonding with FRP materials. This technique may be defined as one in which a composite plate or sheet of relatively small thickness is bonded with an epoxy adhesive to in most cases a concrete structure to improve its structural behaviour and strength. The sheets or plates do not require much space and give a composite action between the adherents. Extensive research and laboratory testing has been carried out all over the world and at many different locations. These investigations show that the method is very effective and a considerable strengthening effect can be achieved.

It is no doubt that there is a great potential for and considerable economic advantages in FRP strengthening. However, if the technique is to be used effectively, it requires a sound understanding of both the short-term and long-term behaviour of the bonding system. It also requires reliable information concerning the adhesion to concrete and composite. The execution of the bonding work is also of great importance in order to achieve a composite action between the adherents. Of the utmost importance is the knowledge within what limits the strengthening method can be used. For example, the required concrete quality, or what thickness and/or strength are suitable for the composite plates or sheets. Strengthening for bending with unstressed laminates has been the most common way to increase the load-bearing capacity of a concrete structure with the plate bonding method while in comparison only limited research has been undertaken for beams strengthened in bending with pre-stressed laminates.

At Luleå University of Technology, Sweden, research has been carried out in the area of plate bonding. The research work started in 1988 with steel plate bonding and is still continuing, now with FRP materials. Both comprehensive experimental work and theoretical work have been carried out. The laboratory tests have included strengthening for bending as well as for shear, (Täljsten, 2001) and torsion, (Täljsten, 1998). Full-scale tests on strengthened bridges have also been performed by Täljsten (1994, 2000) and Täljsten and Carolin (1999). In the area of theory, the peeling stresses in the adhesive layer at the end of the strengthening plate have been studied in particular, but the theory of fracture mechanics introducing non-linear behaviour in the joint has also been investigated, (Täljsten, 1994, 1996, 1997).

In Sweden the FRP strengthening methods have been used in the field for almost 10 years know and both laminates and wrap systems are used. Sweden is also one of the countries around the world where a national code exists for FRP strengthening (Täljsten, 2000, 2001, 2002). However work regarding codes is ongoing all over the world, see for example Maruyama, (2001).

STRENGTHENING WITH PRE-STRESSED FRP

There are several reasons why a pre-stressing force shall be applied to a concrete structure. One reason to pre-stress is that the applied axial load induces a bending moment that opposes the self-weight of a concrete structure, (Garden and Hollaway, 1998). Another reason is that the first crack load is considerably increased compared to non pre-stressed strengthened beams and beams without strengthening, this can increase the durability of the concrete structure. However, the ultimate load is approximately the same as non pre-stressed strengthened concrete structures, (Wight et al., 1995). When pre-stressing for strengthening purposes there is also a reduction of cracks and crack widths. Research in the area of strengthening with pre-stressed FRP has mainly been done with FRP plates, such as failure modes (Garden and Hollaway, 1998), short-time behaviour of pre-stressed FRP (Triantafillou and Deskovic, 1991; Triantafillou et al., 1992), flexural rehabilitation (Quantrill and Hollaway (1998), etc. El-Hacha et al. (2001) have carried out tests on concrete beams pre-stressed with CFRP sheets at room and low temperatures. EMPA in Switzerland has also done research in the area of pre-stressed strips, (Meier, 2001). The results from these tests show a significant increase in flexural stiffness and ultimate capacity compared to unstrengthened control beams. However, the same tests also show problems with pre-stress losses. They also point out that the flexural behaviour of the strengthened beams is not adversely affected by reduced temperature (-28 ºC), and pre-stressed CFRP sheets could be used to increase and restore the original strength of damaged concrete beams under extreme environmental conditions. Tests reported by Wight and Erki, (2001a) on severely damaged CFRP strengthened concrete slabs shows that both higher load capacities and reduced deflections could be achieved with pre-stressed CFRP sheets in comparison with non pre-stressed sheets. A pre-stressed CFRP plate or sheet has a compressive effect on the base of the beam, which tends to confine the concrete, resulting in a reduction in the amount of shear cracking which could initiate failure in the shear spans. As a result, the failure surface is shifted downwards, appearing to occur most readily at the adhesive/CFRP interface or within the bottom layers of the concrete (Garden and Hollaway, 1998). One of the most important advantages when strengthening a structure with pre-stressing members is the reduction of stress in existing tensile steel reinforcement. This should indicate an increase of the fatigue behaviour of the members in the structure, (Garden and Hollaway, 1998 and Wight and Erki, 2001b).

PRE-STRESSING WITH NSMR

The CFRP Plate Bonding method does have some drawbacks. For example a strengthened bridge can be sensitive to impact forces and protection of the laminates is needed. It is also complicated to pre-stress the CFRP laminate plates and large peeling stresses can be introduced at the cut off end of the plate. Often it can be complicated to anchor the plates to the structure. Here NSMR (Near Surface Mounted Reinforcement) pre-stressed laminates can be an alternative. With NSMR the added CFRP reinforcement is placed into sawed slots. Tests with circular FRP rods have earlier been performed by De Lorenzis et al., (2000) and with rectangular rods by Täljsten, (1999), Täljsten and Carolin, (2001), Carolin et al., (2001) and Nordin et al. (2001).

As opposed to external strengthening techniques the use of NSMR will, in a better way, protect the strengthening material from external damage such as vehicle impact. It may also be easier to work with in some cases compared to the use of traditional CFRP laminates. Another advantage is that the concrete surface will not be completely covered as in some cases with CFRP wraps, thus preventing the formation of built-in moisture in the structure and possible freeze-thaw problems. However, it has to be remembered that this technique can only be used on structures with sufficient concrete cover since the rods are mounted in this cover. In figure 1 the principles for NSMR are shown. It can be seen from figure 1 that it is possible to achieve increased bond surface with NSMR compared to traditional laminate Plate Bonding. Instead of a normal concrete surface failure as with laminate Plate Bonding a larger volume of the concrete will fracture at failure, or more energy is needed to fracture a NSMR strengthened concrete structure than a laminate strengthened structure.

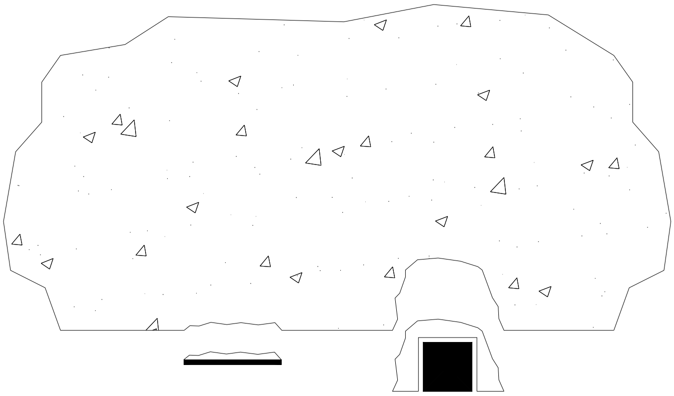

Figure 1. Schematic sketch of NSMR

THEORY

Here very simple equations to express the influence of pre-stress and bond are given. However, these equations are not used in the evaluation but are rather to give an understanding of the problem studied. The stress and strain distribution of a rectangular pre-stressed beam with NSMR is shown in figure 2. Here figure 2b) shows the strain distribution where it has been assumed that plain sections remain plain during loading. In figure 2c) and 2d) the stress distribution due to the bending moment and the pre-stressing force is shown.

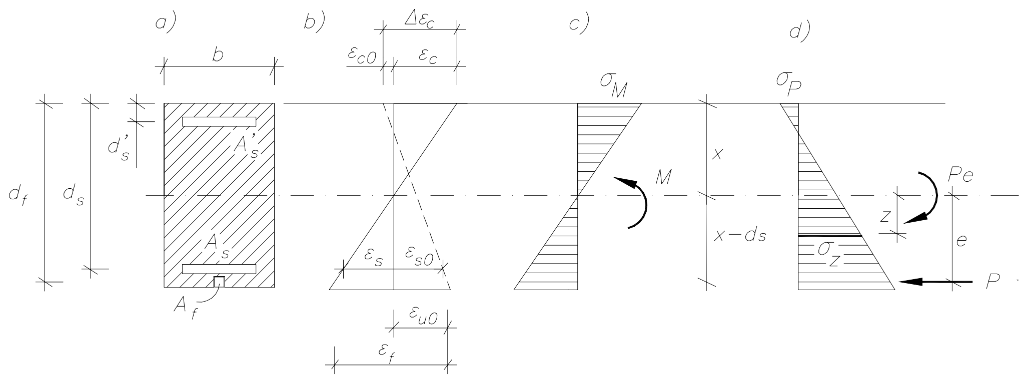

Figure 2. Stresses and strains acting on a pre-stressed rectangular cross-section

From figure 2 is it possible to derive the following equation:

$$\left(\sigma_P + \sigma_M\right)_z = \frac{M}{I} z + \left(-\frac{P}{A} - \frac{P \cdot e}{I} z\right) \quad (1)$$

where the bending moment, M, acts on a cross section together with a pre-stress force P. Here, e is the level arm from the centre of gravity to the pre-stress force, z is the distance from the centre of gravity to studied lamella. A and I are the cross sectional area and moment of inertia for an uncracked section respectively. Furthermore to calculate the shear stress in the bond zone a simplified differential equation can be derived, see also figure 3:

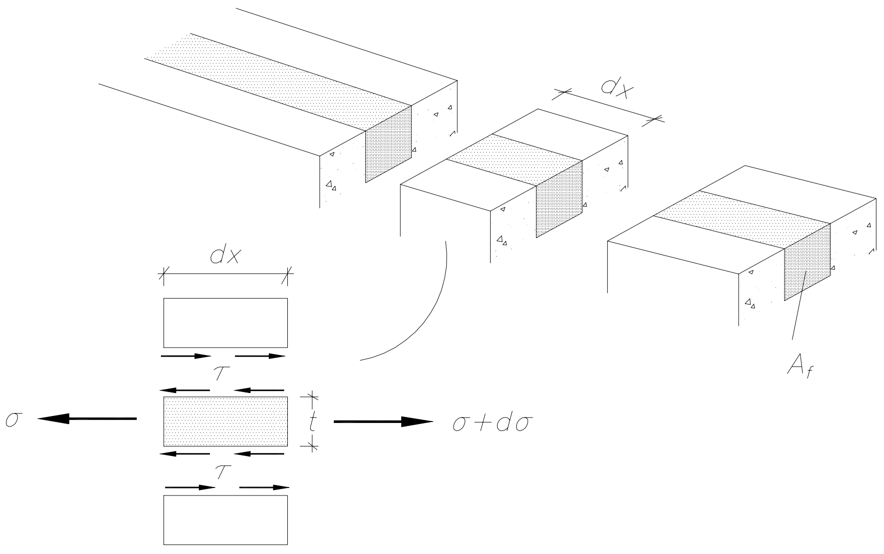

Figure 3. Shear stresses acting on a small element dx of NSMR rod

The cross sectional area is given by:

$$A_f = t^2 \tag{2}$$

The stress in the rod can be expressed as:

$$\sigma = \frac{F}{A_f} = \frac{F}{t^2} \tag{3}$$

and a force equilibrium from figure 3 gives:

$$\int_{A_f} (\sigma + d\sigma - \sigma) dA_f - \int_{A_\tau} \tau(x) dA_\tau = 0 \tag{4}$$

$$d\sigma \cdot t^2 = \int_0^t \int_0^{dx} \tau(x) dx dy \tag{5}$$

$$d(E \cdot \varepsilon) \cdot t^2 = t \cdot \tau(x) dx \tag{6}$$

$$\tau(x) = E \cdot t \cdot \frac{d\varepsilon}{dx} \tag{7}$$

Equation (7) applies to one side of the rod, therefore the expression must be divided with 3 to take in consideration the three surfaces of the rod which give:

$$\tau(x) = E \cdot \frac{t}{3} \cdot \frac{d\varepsilon}{dx} \tag{8}$$

LABORATORY TESTS

The laboratory test presented in this paper shall be considered as a pilot test. The tests were made to gain understanding of the possibility to pre-stress NSMR carbon fibre rods and to understand the behaviour at failure. For this reason the measurements were limited and so were the number of beams tested.

The beams were subjected to a four-point bending as shown in figure 4 with a free span of 3600 mm, the beams tested were 4 meters long with a cross section of 200 x 300 mm. Four beams were tested, one reference beam [Ref], one beam strengthened without pre-stress [NP] and two strengthened with pre-stress [P1,P2]. The beams that were strengthened had a slot, underneath the beam, that been sawed with a cross section 15 x 15 mm. The beams were reinforced for shear with ϕ10 steel stirrups at 75 mm spacing and with 30 mm concrete cover. The longitudinal steel reinforcement was ϕ16, two at the top and two at the bottom, placed directly inside the stirrups.

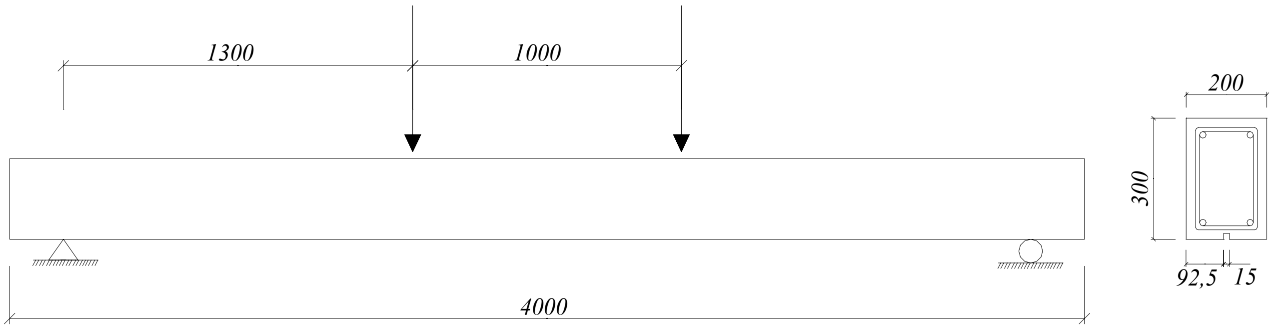

Figure 4. Beam test setup

The material data of the concrete and CFRP rods are recorded in table 2. The NSMR rods were delivered by BPE® Systems AB in Sweden. For the steel reinforcement the characteristic value of the steel has been used, i.e. f_{yd} = 500 MPa and E_s = 205 GPa. The adhesive used was BPE Lim 465, with the following material properties; Young´s modulus, E_a = 7.0 GPa, compressive strength, f_{ca} = 103 MPa and tensile strength, f_{ct} = 31 MPa with a viscosity of 28 Pas.

Table 1. Data of the materials used in test

	f_{cc} [MPa]	f_{ct} [MPa]	E_f [GPa]	ε_{fu} [‰]	f_f [MPa]
Ref	61	3.5	---	---	---
NP	64	3.6	160	17.5	2 800
P1	68	3.8	160	17.5	2 800
P1	68	3.8	160	17.5	2 800

The rods were subjected to a pre-stressing force until the strain of approximately 2000 micro strain was achieved, this corresponds approximately to a stress of 320 MPa. No mechanical anchorages were used in the test, the shear force was transferred by bond only.

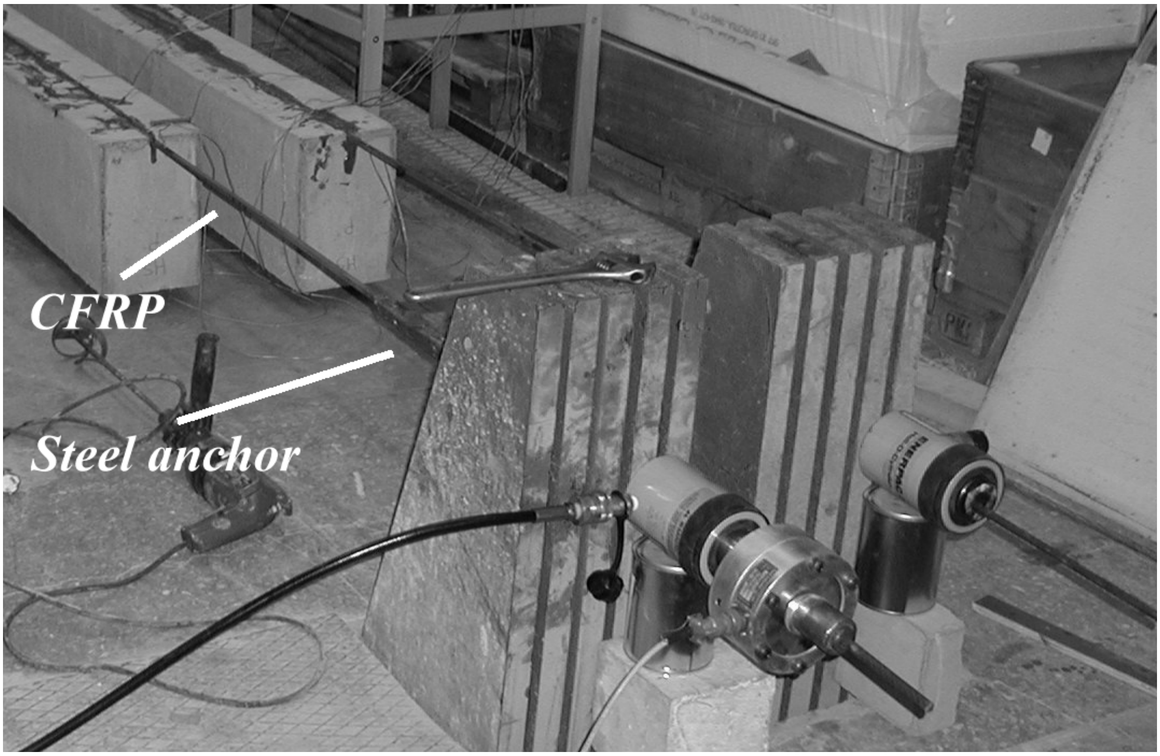

Figure 5. Pre-stressing setup

RESULTS

The results from the tests are presented here as load-deflection curves for the four beams, and shown in Figure 4. All strengthened beams had fibre fracture as failure mode. The strengthened beams give an increase of ultimate load by almost 70 % compared with the reference beam. Beams P1 and P2 had a 37 % increase in load before the steel yielded compared with the unstressed beam NP and an increase in the cracking load of about 100 % compared with the reference beam but the same ultimate load as NP.

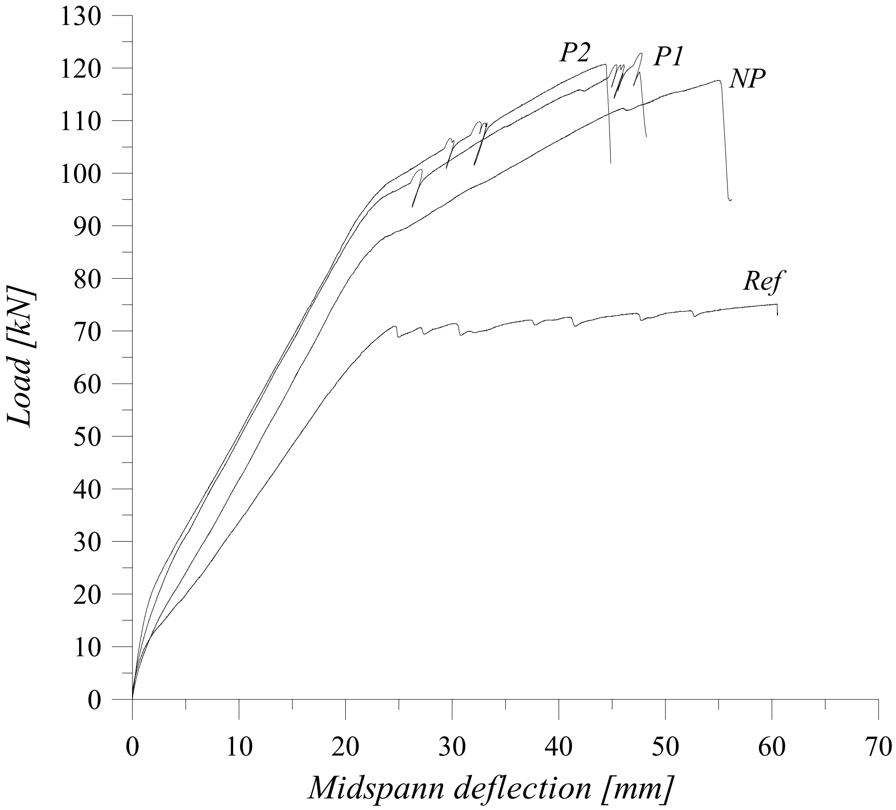

Figure 6. Results from tests

If figure 5 is studied it can be noticed the stiffness of the beam was about the same for non pre-stressed and pre-stressed beams but the pre-stress force has helped in delaying concrete cracking and yielding of the steel reinforcement. It can also be noticed that the non pre-stressed beam NP had a larger deflection than the pre-stressed beams P1 and P2. In table 3 the first crack, steel yielding and ultimate load together with maximum deflection are shown. All strengthened beams failed by fibre failure in the NSMR rod.

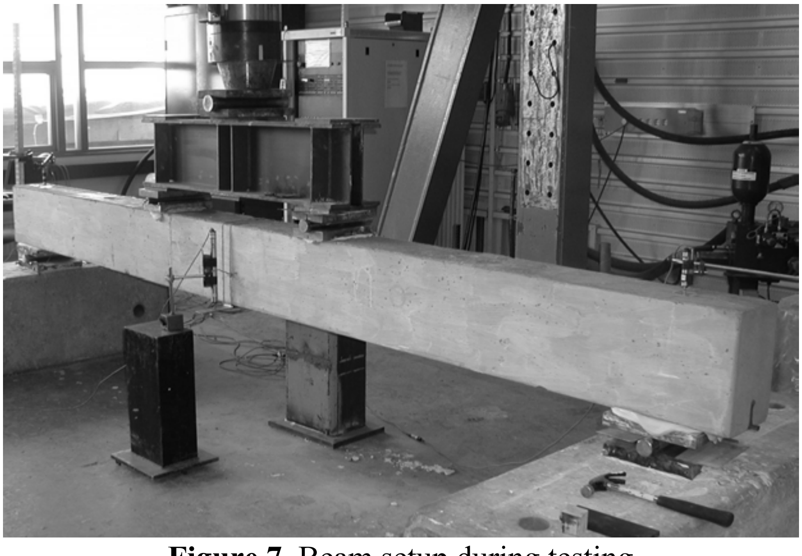

Figure 7. Beam setup during testing

Table 2. Loads and deflections from tests

Beam	First crack [kN]	Steel yielding [kN]	Ultimate load [kN]	Ultimate deflection [mm]
Ref	10	71	75	60
NP	13	84	118	55
P1	19	96	121	46
P2	21	99	121	44

CONCLUSIONS

The tests show a large increase in crack and steel yielding loads. The increase in load for steel yielding can be very important for a constructions life, the fatigue behaviour will improve and as a consequence the crack widths will be smaller which can result in increased durability.

It must be remembered that the study is limited and too definite conclusions shall not be drawn from the results. However, the performed tests show promising results worthwhile to continue work with in the future. It is also worthwhile to mention that in these tests no mechanical anchorages were used, only bond transferred the shear stresses between the CFRP rod and the beam.

FUTURE WORK

In the spring of 2002 an extensive testing program will be undertaken. Here not only different pre-stressing forces and CFRP materials will be investigated but also the distance to the support and mechanical anchor devices. During these tests extensive measurements will be taken and a great focus will be placed on the theory for force transfer between the CFRP rods and the concrete beams.

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