CFRP-STRENGTHENING - CONCRETE STRUCTURES STRENGTHENED WITH NEAR SURFACE MOUNTED CFRP LAMINATES

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Abstract

Rehabilitation and strengthening of existing concrete structures has come more and more in focus during the last decade. 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 bad condition. However, it is not only the 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 used. New and increased demands from the transportation sector can be another reason for strengthening. If any of these situations should arise it needs to be determined whether it is more economical to strengthen the existing structure or to replace it. There exist many different ways of strengthening an existing concrete structure, such as sprayed concrete, different types of concrete overlays, pre-tensioned cables placed on the outside of the structure, just to mention a few. A strengthen method that was used quite extensively during the mid 1970s is steel Plate Bonding, this method has gained renaissance the last decade, but now as FRP (Fibre Reinforced Polymers) Plate Bonding. 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 in order 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

At Luleå University of Technology, research is taking place in the field of CFRP-Strengthening, i.e., the process of strengthening concrete members by bonding CFRP (Fibre Reinforced Polymer) plates or sheets to their surfaces. The research work started in 1988, then with steel plates and is today continuing with FRP materials. Both comprehensive experimental and theoretical work has been undertaken. The laboratory tests include strengthening for bending as well as for shear and torsion. In addition several full-scale tests have been performed. In 1996 work with NSMR (Near Surface Mounted Reinforcement) started. Pilot tests were performed and the benefits compared to traditional Plate Bonding were found to be many.

In this paper a background and need to the use of NSMR is discussed. Also laboratory tests and theory for concrete beams strengthened with near surface mounted CFRP reinforcement are presented briefly. In addition, the use of NSMR in field applications is discussed and a field application is presented.

Strengthening concrete structures in general

As most of us know, concrete is a building material with a high compressive strength and a poor tensile strength. A beam without any form of reinforcement will crack and fail when subjected to a relatively small load. The failure occurs suddenly in most cases and in a brittle manner. The most common way to reinforce a concrete structure is to use steel reinforcing bars that are placed in the structure before the concrete is cast. Since a concrete structure usually has a very long life, it is quite common that the demands on the structure change with time. The structures may have to carry larger loads at a later date or fulfil new standards. In extreme cases, a structure may need to be repaired due to an accident. Another reason can be that errors have been made during the design or construction phase so that the structure needs to be strengthened before it can be used. If any of these situations should arise it needs to be determined whether it is more economical to strengthen the structure or to replace it. It should also be remembered that over the past decade, the issue of deteriorating infrastructure has become a topic of critical importance in Europe, and to an equal extent in the United States and Japan. The deterioration of decks, superstructure elements and columns can be traced to reasons ranging from ageing and environmentally induced degradation to poor initial construction and lack of maintenance. Added to the problems of deterioration, are the issues related to the needs for higher load ratings and the increased number of lanes to accommodate the ever-increasing traffic flow on the major arteries. As an overall result, a significant portion of our infrastructure is currently either structurally or functionally deficient. Beyond the costs and visible consequences associated with continuous retrofit and repair of such structural components, are the real consequences related to losses in production and overall economies related to time and resources caused by delays and detours. As we move into the twenty-first century, the renewal of our lifelines becomes a critical issue.

However, to keep a structure at the same performance level it needs to be maintained at predestined time intervals. If lack of maintenance has lowered the performance level of the structure, need for repair up to the original performance level can be required. In cases when higher performance levels are needed, upgrading can be necessary. Performance level means load carrying capacity, durability, function or aesthetic appearance. Upgrading refers to strengthening, increased durability, and change of function or improved aesthetic appearance. In this book, mainly strengthening is discussed.

Restoration, reparation and reinforcement of old concrete structures are becoming increasingly common. If one considers the capital that has been invested in existing infrastructures, then it is not always economically viable to replace an existing structure with a new one. The challenge must be taken to develop relatively simple measures such as rebuilding, restoration, reparation and reinforcement that can be used to prolong the life of structures. An example of reinforcement would be strengthening an existing structure to carry greater loads. This places a great demand on both consultants and contractors. There are difficulties in assessing the most suitable method for an actual subject; as for example, two identical columns within the same structure can have totally different life spans depending on their individual microclimate. It is therefore important to analyse the problem thoroughly to be able to select the correct measure. The choice of an unsuitable reparation method can even deteriorate the structure’s function. In the cases where reparation is appropriate, the intention should be to increase durability or load-bearing capacity. In comparison to building a new structure, strengthening an existing one is often more complicated since the structural conditions are already set. It can also be a problem to reach the areas that need to be strengthened. This is generally the case for traditional methods such as for example different kinds of reinforced overlays, shotcrete or post tensioned cables placed on the outside of the structure which normally need much space.

In recent years the development of the plate bonding repair technique has shown to be applicable to many existing strengthening problems in the building industry, not only for strengthening but also in cases of rebuilding and when mistakes have been made in the design or construction phase. This technique may be defined as one in which composite sheets or plates of relatively small thickness are 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. The adhesive that is used to bond the fabric or the laminate to the concrete surface is a hardy two-component epoxy adhesive, which together with the fibre then becomes a plastic composite on the surface of the structure. The old structure and the new bonded material create a structural relationship that has a greater strength than the original structure.

The question must be asked why advanced composites are suitable for civil engineering applications. Fibre reinforced polymer matrix composite materials have a number of advantages when compared to traditional construction materials such as steel, wood and concrete. Fibre reinforced polymers (FRPs), offer excellent corrosion resistance to environmental agents as well as the advantages of high stiffness-to-weight and strength-to-weight ratios when compared to conventional construction materials. Other advantages of FRPs include low thermal expansion, good fatigue performance and damage tolerance, non-magnetic properties, the ease of transportation and handling, low energy consumption during fabrication of raw material and structure, and the potential for real time monitoring.

Perhaps the biggest advantage of FRPs is tailorability. Reinforcement can be arranged according to the loading conditions so that a FRP structure or a component can be optimised for performance. The apparent high cost of FRPs compared to conventional materials has been a major unfavourable restraint. However, a direct comparison of the unit price basis may not be appropriate. When installation is included in the cost comparison, FRPs can be competitive with conventional materials. The lightweight of FRPs reduces transportation expenses and allows some prefabrication to take place at the factory, which reduces time at the job site. If the comparisons include life cycle costs, FRPs can have a significant advantage.

The unique properties of FRPs, like high corrosion resistance, make the life cycle cost lower than that of conventional materials. In many cases a composite structure can last much longer than conventional materials, thus ensuring a lower life-cycle cost in many cases. Also, increasing demand will drive down the cost of FRP. The introduction of fibre reinforced polymers in civil engineering structures has progressed at a very rapid rate in recent years.

The basic ideas related to the use of FRPs for structural strengthening, along with examples of application, have been presented by Triantafillou, (1998). The past and potential future use of FRP strengthening and rehabilitation have also recently been documented in many conference proceedings (Meier and Betti, 1997, Täljsten, 1997, Benmokrane and Rahman, 1998), keynote lectures (Maruyama, 1997, Neale and Labossiére, 1997) and journal articles (Thomas, 1998).

The most common way to strengthen structures has been for bending but shear strengthening is also often needed. The most common method has been to place sheets or laminates on the surface of the structure, however, further development of the plate bonding method has shown that it is favourable to place the laminates in the concrete cover of the structure. This method can be designated NSMR or Near Surface Mounted Reinforcement.

NSMR - a short Introduction

The use of Near Surface Mounted Reinforcement for concrete structures is not a new invention. A type of NSMR has been used since the 1940s, where steel reinforcement was placed in slots in the concrete cover or in additional concrete cover that was cast to the structure. A type of steel NSMR has been used since the invention of shotcrete. However, in these applications it was often difficult to get good bond to the original structures surface, and in some cases, it was not always easy to cast the concrete around the whole steel reinforcing bars. From the 1960s the development of strong adhesives, such as epoxies, for the construction industry moved the method further ahead by bonding the steel bars in sawed slots in the concrete cover. However, due to the corrosion sensitivity of steel bars an additional concrete cover was needed. For these applications epoxy coated steel bars have also been used, however, it has been shown over time that epoxy coated steel bars are not always corrosion resistant for various reasons that not will be discussed here. The use of steel NSMR has not been a great success. Nevertheless, by using CFRP NSMR some of these drawbacks presented can be overcome. First of all, CFRP NSMR does not corrode, so thick concrete covers are not needed. Secondly, the CFRP laminate can be tailor-made for near surface applications, thirdly the lightweight of the CFRP laminates makes them easy to mount. Furthermore, depending on the form of the laminate air voids behind the laminates can be avoided. Both epoxies and systems using high quality cement mortar can be used. However, before proceeding, a short description of how to undertake a strengthening work with NSMR will be given. In practical execution the following steps must in general be performed during strengthening:

- Sawing up slots in the concrete cover, depth depending on product used and depth of concrete cover.
- Careful cleaning of the slots after sawing, high-pressurised water, approximately 100 - 150 bars, is recommended. No saw mud allowed in the slot
- If an epoxy system is used, the slot must be dry before bonding. If a cement system is used it is mostly recommended that the existing surfaces are wet at the time of concrete mortar casting.
- Adhesive is applied in the slot or with a cement system; cement mortar is applied in the slot.

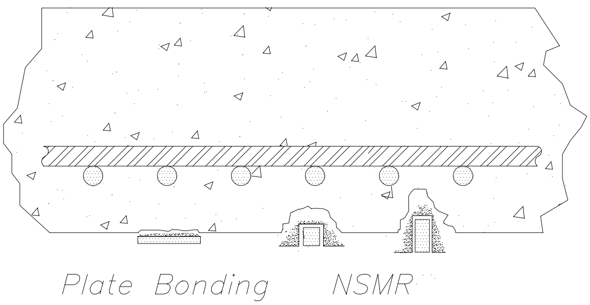


Figure 1. Comparison between laminate Plate Bonding and NSMR

The NSMR laminates are mounted in the slot and the excess adhesive or cement mortar is removed with a spatula or similar. It is interesting to compare traditional laminate and sheet Plate Bonding with NSMR, and this is done in figure 1 and table 1. In figure 1, the difference between laminates and NSMR can be seen. The fracture energy to remove NSMR is in many cases much larger than for bonded laminates.

Furthermore, NSMR resists end peeling much better than bonded laminates and they are considerably more protected against fire, vandalism and impact from e.g. vehicles. However, in some applications it demands a greater effort to carry out the work on site. An overview of the main characteristics and some typical aspects of these three types of strengthening methods with FRP are given in table 1, see FIB Bulletin 14, 2001, Täljsten 2002.

Table 1. Characteristics and aspects of externally bonded FRP reinforcement

	Laminates	**Sheets**	**NSMR**
Shape	Rectangular strips	Thin unidirectional or bi-directional fabrics	Rectangular strips or laminates
Dimension: thickness width	 Ca: 1.0 - 2.0 mm Ca: 50 - 150 mm	 Ca: 0.1 - 0.5 mm Ca: 200 - 600 mm	 Ca: 1.0 - 10.0 mm Ca: 10 - 30 mm
Use	Simple bonding of factory-made profiles with adhesives	Bonding and impregnation of the dry fibre with resin and curing at site	Simple bonding of factory made profiles with adhesive or cement mortar in pre-sawed slots in the concrete cover
Application aspects	For flat surfaces Thixotopic adhesive for bonding Not more than one layer recommended Stiffness of laminate and use of thixotropic adhesive allow for certain surface unevenness Simple in use Quality guaranteed from factory Suitable for strengthening in bending Needs to be protected against fire	Easy to apply on curved surfaces Low viscosity resin form bonding and impregnation Multiple layers can be used, more than 10 possible. Unevenness needs to be levelled out Need well documented quality systems Can easily be combined with finishing systems, such as plaster and paint Suitable for shear strengthening Needs to be protected against fire	For flat surfaces Depends on the distance to steel reinforcement A slot needs to be sawn up in the concrete cover The slot needs careful cleaning before bonding Bonded with a thixotropic adhesive Possible to use cement mortar for bonding Protected against impact and vandalism Suitable for strengthening in bending Minor protection against fire

Theory

The theory derived for the ultimate bending capacity can be found in Täljsten, 2000, 2001, 2002, Nordin et al., 2001. The model is based on the Bernoulli´s hypothesis. The model considers the anisotropy of the composite material when used for bending. This model is also accepted by the Swedish Road Administration to be used for FRP strengthening.

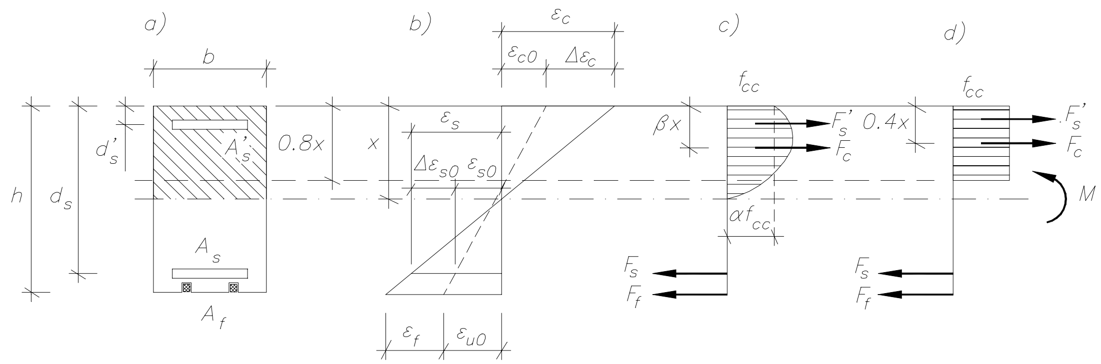


Figure 2. Principles for strengthening in bending

It is important to notice that if there exists a strain field on the structure due to for example the dead load this must be considered in design for strengthening. In Figure 2b) this is shown schematically, where ε_{u0} is the initial strain in the bottom face of the cross section. The influence of the creep in the concrete is taken care of with a reduced modulus of elasticity as in normal concrete design. A calculation is then made to control whether the concrete is uncracked or not. The studied section can be considered uncracked if the tensile capacity of the concrete is not exceeded. However, if the type of failure that can occur is assumed to be failure in the composite material without yielding in the compressive reinforcement, the bending capacity can then be expressed as, (see also Täljsten, 2000):

$$M = \frac{x-d_s'}{h-x}\left(\varepsilon_{fu}+\varepsilon_{uo}\right)A_s'E_s\left(0.4x-d_s'\right)+A_sf_s\left(d_s-0.4x\right)+\mu\varepsilon_{fu}E_fA_f\left(h-0.4x\right) \qquad [1]$$

a horizontal equilibrium equation for the section in Figure 2d) gives:

$$0.8f_{cc}bx+\frac{x-d_s'}{h-x}\left(\varepsilon_{fu}+\varepsilon_{u0}\right)A_s'E_s = A_sf_s+\mu\varepsilon_{fu}E_fA_f \qquad [2]$$

where x can be solved with an equation of the second degree:

$$C_1x^2+C_2x+C_3=0 \qquad [3]$$

where

$$\left.\begin{aligned} C_1 &= 0.8 f_{cc} b \\ C_2 &= -0.8 f_{cc} bh - \left(\varepsilon_{fu} + \varepsilon_{u0}\right) A_s' E_s - A_s f_s - \mu \varepsilon_{fu} E_f A_f \\ C_3 &= \left(\varepsilon_{fu} + \varepsilon_{u0}\right) A_s' E_s d_s' + \left(A_s f_s + \mu \varepsilon_{fu} E_f A_f\right) h \end{aligned}\right\} \quad [4]$$

If a pre-stressing force can be applied to the structure, the dead load can be removed or at least decreased. This is shown in figure 3. Here the strain field over the cross section has been changed so that we even have a small tensile force on the top of the beam.

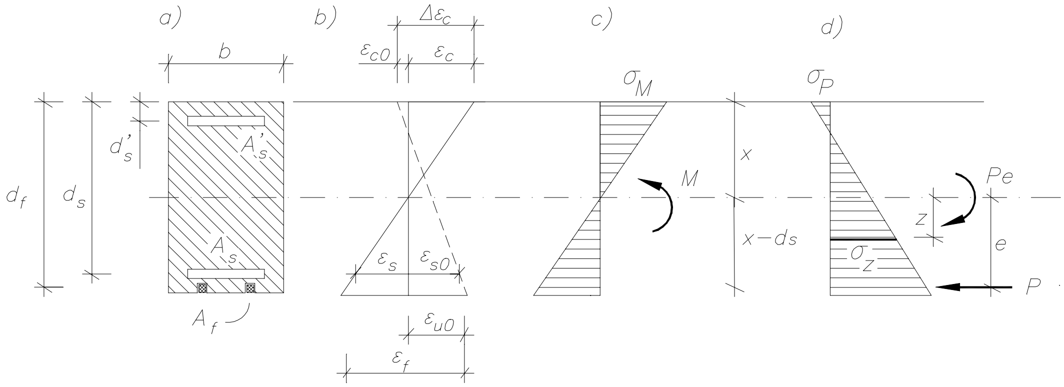


Figure 3. An applied pre-stressed force by using NSMR

Anchorage is not covered here. However, the anchorage should be better for inserted reinforcement compared to surface bonded reinforcement, but will most likely be dependent on the geometry of the rod, see also figure 3. Extensive research and testing is currently being carried out at Luleå University of Technology. Some of this research is reported in Nordin et al., 2001, 2002.

Laboratory tests

Since 1996 several laboratory tests with NSMR have been carried out at Luleå University of Technology, Division of Structural Engineering. Here a pilot test will briefly be discussed. A more thoroughly presentation of the tests can be found in Täljsten and Carolin, 2001, and Carolin et al. 2001.

Four rectangular concrete beams were manufactured, three were strengthened and one served as a reference beam. The geometry and loading conditions is shown in figure 4. In this figure the placement and size of the slots can also be seen. All of the beams were loaded in deformation-controlled mode with a head displacement of 0.6 mm/min. Measurements were taken of the load, mid-deflection, settlement at the support and strains in the laminates. Crack distribution and widths were recorded at every 10 kN. The NSMR laminates were manufactured by vacuum infusion at SICOMP AB and measurement after test has shown a fibre content of 50 % in the laminates. For the laminates vinylester 411 C50 was used for the matrix and to bond the laminate to the concrete beam the epoxy adhesive BPE 417 manufactured by BPE® Systems AB was used. The cement grout used for bonding Beam C3 was BEMIX High Tech 310. However, before these rods were bonded into the slots the surface was pre-treated by bonding quartz sand to the NSMR rods. The material data for the steel reinforcement, concrete and carbon fibre used can be found in table 2.

Table 2. Material data

	f_{cc} [MPa]	f_{ct} [MPa]	f_{st} [MPa]	E_s [GPa]	f_{cu} [MPa]	E_f [GPa]	ε_{fu} [%]
Concrete	60.7	3.6					
Steel			490	200			
Carbon Fibre					4140	230	1.8

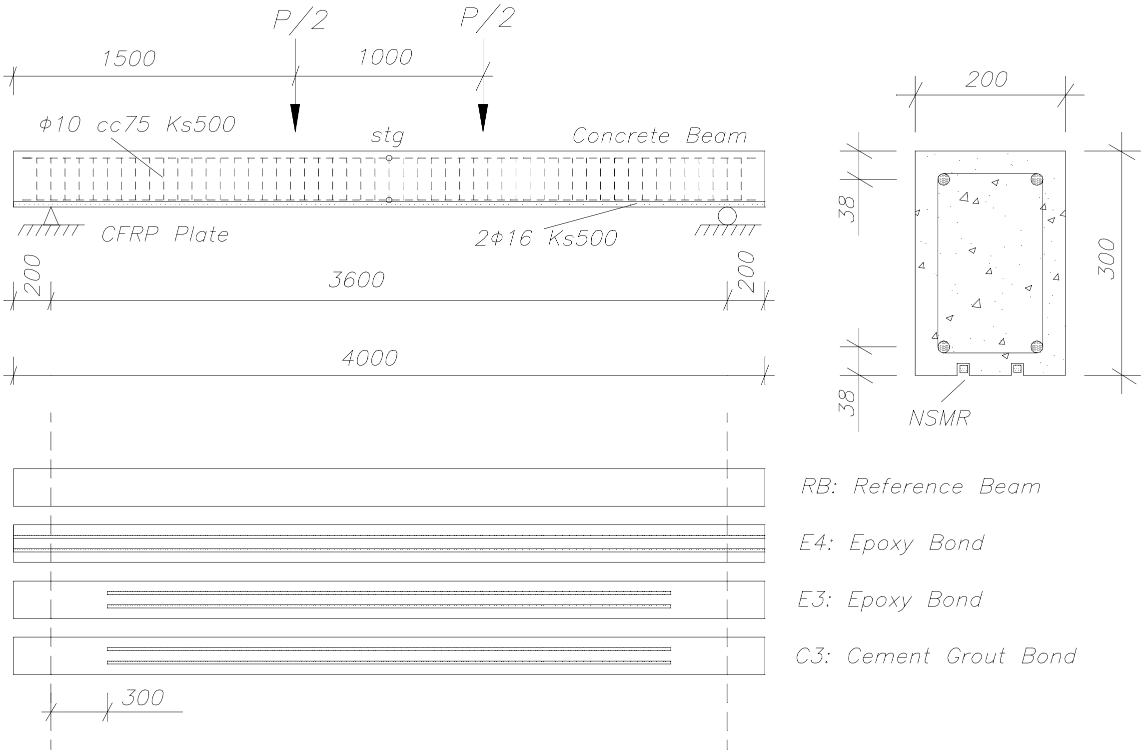
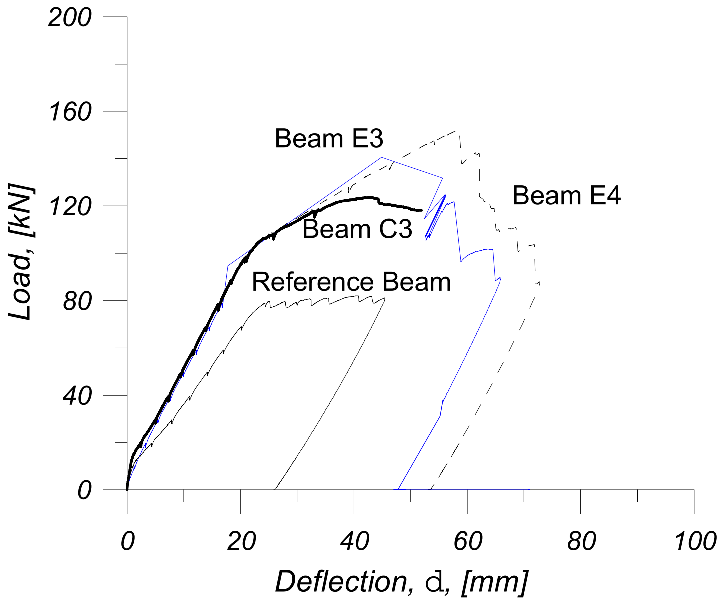
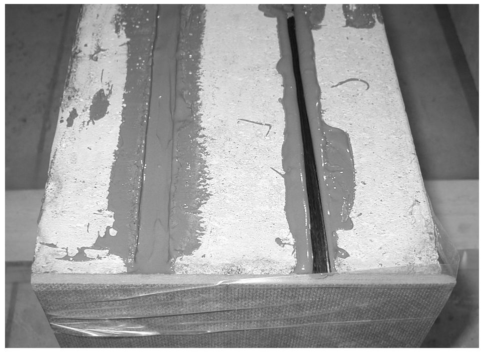


Figure 4. Test set up and dimensions of the test beams.

The Load deflection curves from the tests are presented in figure 5 and in table 3. In figure 5 a photo of Beam E3 during preparation is also shown. It can clearly be noticed in figure 5 that Beam B4, as expected, has the best failure envelope. The failure for Beam E4 was failure in the rod. Beam E3 and Beam C3 follow each other up to the level where an anchorage failure arises in the cement grout for Beam C3. For beam E3 and C3 anchor failure arose. For Beam C3 cracks parallel to the laminates appeared and while the load increased the mortar started to fall down from the beam. Beam E3 showed a more ductile behaviour. In table 3 the ultimate load, strains in centre of the CFRP rods and deflections are given.





Rectangular rods, 10 x 10 mm bonded in slots in the concrete cover

Figure 5. Load- deflection curves for the tested beams and beam E4 during preparation

Table 3. Results from tests

Beam	P_{test}, [kN]	d_{test}, [mm]	ε_{fc}, [%]
C3	123.5	43.0	0.74
E3	140.0	51.5	1.12
E4	152.0	58.5	1.15
Reference	79.0	24.0	---

Theoretical calculations of the load capacity for the tests were also performed, the results from these calculations are shown in table 4. In table 4 the measured strains at failure for the laminates have been used for calculating the theoretical failure loads.

Table 4. Theoretical calculations compared with load at failure

Beam	P_{test}, [kN]	P_{theory}, [mm]	P_{test}/P_{theory}
C3	123.5	149.3	0.83
E3	140.0	167.7	0.83
E4	152.0	196.3	0.77
Reference	79.0	---	---

It can be noticed in table 4 that the theory described earlier in this paper overestimates the failure load. The reasons for this can be numerous. For Beams C3 and E4 where we had anchorage failure, the theory described in this paper will not cover this. However, for beam E4, higher failure load was expected, but it is possible that the strain in the utmost fibres was unevenly distributed, exceeding the ultimate strain capacity and that a propagating failure arose for the tests beam not covered in the measurements. Tests with NSMR and cyclic load during strengthening has also been undertaken, these tests are reported in Carolin et al, 2002 and in Hejll and Norling, 2001.

Field applications

The field-application presented here was carried out during the fall of 1999. The reason for strengthening was a mistake at the construction site. The amount of steel reinforcement needed in a joint between a pre-cast concrete element and on site cast concrete was not sufficient and strengthening was demanded. The reason for choosing NSMR for this application was the CFRP laminates resistance to corrosion and stiffness and strength comparable to steel. The cross section of the laminates used was 5 x 35 mm, with a Young´s modulus of 160 GPa and an ultimate strain at failure corresponding to 1.6 %. Nevertheless, the main factor to the NSMR advantage was that the laminate could be placed in the concrete cover and that no great work effort was needed. However, laminate Plate Bonding was also discussed, but since the bridge has a long life and the sealing on the bridge deck is replaced every 20 years the risk of ripping the laminate off the surface was estimated to be very likely. Another reason was the wearing surface in form of warm asphalt that was going to be applied.

First the slots (40 x 8 mm) were sawn up in the concrete cover. The slots were cleaned carefully and allowed to dry before the adhesive was applied. The strengthening system chosen was BPE® NSMR. In figure 6a, the laminates and the slots in the concrete cover can be seen prior to bonding. In figure 6b the laminates are bonded in the slot and in figure 6c the result after strengthening but before the surface is asphalted is shown.

6a) Slots in front of the worker holding a NSMR laminate

6b) Bonding the NSMR laminates in the cleaned and dry slots

6c) Results after bonding but before sealant and asphalt

Figure 6. Strengthening of a concrete joint with NSMR.

The client, The Swedish Road Authority, considered the strengthening work successful and it is today an accepted method of strengthening concrete bridges.

Future work

Several research programs are ongoing at Luleå University of Technology, Division of Structural Engineering. A project that is almost finished is “Behavior of Plate Bonded Concrete Beams in Cold Climate”. Here CFRP strengthened concrete beams, both laminates and NSMR, have been tested at - 30 °C and compared with beams tested in room temperature. The primary results from these tests are that no decrease in load could be noticed for beams tested in cold climate. Results from these tests will be reported. During spring 2002, focus will be placed on NSMR applications. Firstly, anchorage will be studied, secondly the possibility to use pre-stressed NSMR will be investigated further and thirdly a full-scale application to strengthen a road bridge for the Swedish Road Authorities will be carried out. In addition ongoing research regarding shear and torsion strengthening will be continued.

Conclusions

There is no doubt that strengthening concrete structures with NSMR is an effective method. Compared to laminate plate bonding several benefits can be noticed, not only higher fracture energy at failure but also better protection against fire, vandalism and impact.

The pilot tests presented in this paper show promising strengthening results and a considerable strengthening effect could be noticed. Theory presented covers traditional design for bending, however, more work is needed to also cover anchorage and other types of strengthening applications.

The field application presented shows that it is easy to strengthen structures and the method is not only time saving but also beneficial from a financial point of view.

Acknowledgement

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