LULEÅ UNIVERSITY OF TECHNOLOGY

2003:25

LICENTIATE THESIS

Fibre Reinforced Polymers in Civil Engineering

Flexural Strengthening of Concrete Structures with Prestressed Near Surface Mounted CFRP Rods

HÅKAN NORDIN

Department of Civil and Mining Engineering
Division of Structural Engineering

2003:25 • ISSN: 1402 - 1757 • ISRN: LTU - LIC - - 03/25 - - SE
ISBN: 91-89580-08-7

LULEÅ UNIVERSITY OF TECHNOLOGY

LICENTIATE THESIS 2003:25

Fibre Reinforced Polymers in Civil Engineering

Flexural Strengthening of Concrete Structures with Prestressed Near Surface Mounted CFRP Rods

Håkan Nordin

Department of Civil and Mining Engineering

Division of Structural Engineering

Luleå University of Technology S-971 87 Luleå, Sweden

PREFACE

The present thesis is based on work carried out between 2000 and 2003 at the Division of Structural Engineering, the Departement of Civil and Mining Engineering at Luleå University of Technology (LTU). The work has been carried out with the financial support of The Development Fund of Swedish Construction Industry (SBUF), the Swedish Road Administration (Vägverket) and J Gust Richert Memorial Fund.

First I would like to thank my supervisor Prof. Björn Täljsten. Your advice and ideas together with your enthusiasm is a great source of inspiration.

I would also like to thank the staff at Testlab for all their help with my laboratory work. Their help and advice have been an invaluable assistance.

All the staff at the Division of Structural Engineering should feel my appreciation for creating such a great working environment. A special thanks to the Ph.D. students for all the fun times we have had.

I finally would like to show my gratitude to my family and friends. Life is not only work, and without the support and love of family and friends in good times as well as bad, this paper would not be possible.

Luleå May 2003

Håkan Nordin

ABSTRACT

Repair and/or upgrading of concrete structures with bonded steel or FRP (Fiber Reinforced Polymers) materials or by use of external tendons have been used for some time now. In most cases the bonded FRP materials are unstressed. However if prestressing could be applied, better utilization of the strengthening material and a better strengthening result would most likely be achieved.

Increasing research is carried out in the area of repair and upgrading of concrete structures with prestressed CFRP (Carbon Fibre Reinforced Polymers) materials. Bonding prestressed FRP laminates or sheets to a concrete surface has proven to be efficient and also gives a better utilization of the strengthening material used.

External prestressed cables of CFRP materials have shown to be an alternative to steel cables in, for example, upgrading concrete structures. Good durability properties and a first-rate behaviour in creep and relaxation have given very good results so far.

One weak part for both external prestressed cables as well as bonded laminates has shown to be anchorage. For cables this is due to lower lateral properties of the cables compared to the axial properties and for laminates due to the high peeling stresses at the cut off end of the laminate. Often the anchorage device has problem to handle the high stresses that would justify the use of FRP materials in prestressing, i.e. the stress that can be achieved due to the anchorage is not high enough. However this is changing with a number of research projects around the world focusing on the anchorage issue where a number of anchorage details have been developed

The main research presented in this thesis is focused on strengthening concrete structures with prestressed CFRP rods bonded in slots in the concrete cover. The prestressing force was transferred to the concrete via adhesive bond only; no mechanical anchorage was used during the tests.

Three factors were varied during the tests; prestressing force, bond length (i.e. length of the rod) and stiffness of the rod. The results from the tests show an increased concrete cracking load as well as a increased steel yielding load.

The thesis consists of a main body and three papers. The main body covers a literature survey of some of the work done in the area. Paper A covers tests made with Glass fibre beams combined with concrete, Paper B is about strengthening with Near Surface Mounted Reinforcement with CFRP rods and Paper C covers strengthening with Near Surface Reinforcement CFRP rods, where the rods have been prestressed.

Keywords: concrete, CFRP, carbon, strengthening, NSMR, NSM, prestressing, bending, hybrid beam

TABLE OF CONTENTS

Papers included in this Thesis, presented in chronological order.

Paper A

Testing of hybrid FRP composite beams in bending
Håkan Nordin and Björn Täljsten
Submitted to Composites Part B: Engineering

Paper B

Concrete Structures Strengthened with Near Surface Mounted Reinforcement of CFRP
Björn Täljsten, Anders Carolin and Håkan Nordin
Published in Advances in Structural Engineering, International Journal

Paper C

Concrete beams strengthened with prestressed Near Surface Mounted CFRP
Håkan Nordin and Björn Täljsten
To be submitted

1 INTRODUCTION

1.1 General

It is well known that concrete is a building material with high compressive strength and poor tensile strength. A concrete 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 not unusual for the demands on the structure to change with time. The structure may have to carry larger loads at a later date, or fulfil new standards. In extreme cases a structure will have to be repaired due to an accident. A further reason can be that errors have been made during the design or construction phase resulting in need for strengthening the structure before usage. If any of these situations should arise it needs to be determined whether it is more economic to strengthen the existing structure or to replace it. In comparison to building a new structure, strengthening an existing one is often more complicated, since the conditions are already set.

1.2 Repair and upgrading systems for concrete structures

There are many different ways to repair or upgrade a concrete structure. There is often a possibility to use a cast on techniques to change the physical appearance of the structure and in that way giving it somewhat different properties in strength and stiffness. However this also means that the structure needs more space, which is not always possible.

Another way to repair or upgrade a structure is to use external prestressed tendons attached to the structure. This method is more or less the same that is used for traditional external prestressed steel tendons, both regarding strengthening and when building new structures.

In some situations a structure's statical behaviour may be changed, for example a column can be added to support a beam or a slab, which then unloads the critical section of the structure.

A sophisticated method to improve the performance of a structure is to use more advanced calculation models where considerations are taken to real dimensions, real material data, loads etc. This may also be called administrative upgrading and is often the most economical upgrading method.

In the last decades the development of strong epoxy adhesives has led to the plate bonding strengthening technique. This upgrading technique may be defined as one in which plates of relatively small thickness is bonded with an epoxy adhesive to, in most cases, a concrete structure to improve its structural behaviour and strength. One advantage with this technique is that there are no large physical changes of the structure; another is that very high strengthening effects can be achieved. If the structure is sound no damaging work on the structure, such as replacing concrete cover, will be needed. However, the surface have to be grinded or sandblasted and cleaned properly before bonding.

The introduction of Fibre Reinforced Polymer (FRP) materials to the civil engineering arena gave the engineers a material that does not corrode, that is strong, stiff and lightweight. However, these materials are still almost unknown to engineers in the civil engineering industry, although the knowledge seems to be increasing. Glass, carbon and aramid fibres are the most commonly used fibres in civil engineering were carbon is the dominating one.

As an alternative to bonding materials to a structure, external tendons of FRP can also be used. An advantage of external tendons is that they are easily replaced if needed.

For concrete it would also in many situations be beneficial if a compressive force could be applied to the structure. In new structures this is done by pre- or post-stressed steel cables, also Carbon Fibre Reinforced Polymer (CFRP) cables have been used. There are also investigations presented where CFRP laminates has been prestressed prior bonding them to the concrete surface.

If the laminates are prestressed, the bonded laminates might in most cases be used more efficient then when used without prestress. However, this method often requires a mechanical anchorage device to transfer the forces into the existing structure.

Both methods, prestressed external cables and prestressed bonded on laminates, has shown promising results as well in laboratory as in full-scale applications. However, the lack of codes and the relatively small amount of research that has been carried out in the area of strengthening with prestressed FRP so far makes it difficult to gain an acceptance for the methods both by engineers and clients.

1.3 Scope and aim of the thesis

The scope of the research presented in this thesis is to investigate a method to strengthen concrete structures with prestressed Near Surface Mounted Reinforcement (NSMR), using Carbon Fibre Reinforced Polymer quadratic rods.

The aim is to build both a theoretical as well as practical understanding of prestressing CFRP rods as NSMR. The work have been carried out in several steps starting with a pilot study where two prestressed beams were compared with a beam not strengthened and one strengthened without prestress.

Three factors are to be studied particularly to see what effect they have on the strengthening result; length of the rod, level of prestress and stiffness of the strengthening material.

The structure of the thesis is consisting of an extensive main body and three papers. The results from the research are presented in the papers and the main body contains an overview of what has been done in the area of prestressed CFRP for upgrading concrete structures and introduction to the subject. Paper A and Paper B has been done as a understanding progress leading to Paper C.

1.4 Content

Here the chapters in the main body are presented to give the reader a quick overview on what each chapter contains.

Chapter 2 give a brief introduction to the concept of prestressed concrete.

Chapter 3 covers the basis of fibre reinforced polymers. The brief content give readers with no or limited knowledge of FRP materials a background to the topic.

Chapter 4 presents literature review based on the research done in the area of external prestressed FRP rods.

Chapter 5 presents a literature review of some of the research carried out in the area of strengthening concrete structures with bonded CFRP laminates.

Chapter 6 presents a literature review from research done in the area of strengthening concrete structures with bonded prestressed CFRP laminates.

Chapter 7 presents three bridges where CFRP have been used. In the first bridge, the Stork bridge in Switzerland, two steel stay cables have been replaced with CFRP tendons. In the second bridge, the Hythe bridge in the UK, prestressed CFRP laminates have been used for strengthening and in the third bridge, the Uddevalla bridge in Sweden, NSMR rods have been used to strengthen a concrete joint in the bridge.

Chapter 8 gives a short summary of the papers outlined in this thesis.

Further, chapter 9 present a discussion regarding the use of NSMR strengthening and the results obtained from the tests presented in the papers.

Finally, chapter 10 present briefly ideas of the future needs for research in the specific area that has been presented in the thesis.

2 PRESTRESSED CONCRETE STRUCTURES

“Prestressed concrete is a type of reinforced concrete in which the steel reinforcement has been tensioned against the concrete. This tensioning operation results in a self-equilibrating system of internal stresses (tensile stress in the steel and compressive stresses in the concrete) which improves the response of the concrete to external loads.” Collins and Mitchell (1991).

The first attempts to prestress concrete structures were with normal strength steel, which were unsuccessful. The first practical use of prestressed concrete was in France 1928, when Eugene Freyssinet began to use high-strength steel wires for prestressing.

The basic idea is to create a negative moment in the construction part to enhance its capabilities. A prestressed structure can be made much thinner then a structure with normal steel reinforcement. Since the method is more costly it is mainly used on larger structures or for structures where demands on small deformations exist.

There are two different ways of prestressing, pre-tensioning and post-tensioning. And there are two ways to place the reinforcement, inside the concrete or outside as external reinforcement.

2.1 Pre-tensioning

Pre-tensioning is when the cables are stressed prior to casting of the concrete. The cables remains stressed until the concrete has cured and then it is released or cut. The cables can be bonded in two ways; to the concrete only or with a mechanical anchorage device. Pre-tensioned cables are used for structures with the reinforcement inside the structure.

As shown in Figure 2.1 the rod or strand is tensioned before the concrete is cast. After curing of the concrete the stressing force is released and the rod will introduce a compressive force to the concrete member.

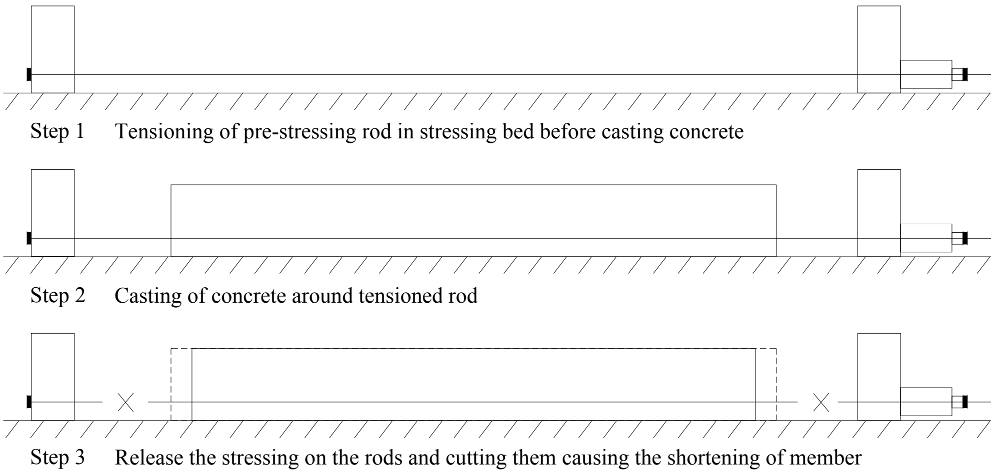


Figure 2.1 *Step-by-step for pre-tensioning, after Collins and Mitchell (1991)*

2.2 Post-tensioning

Post-tensioning is when the cables are stressed after the concrete has cured. Normally the cables are placed inside the concrete structure and in hollow tubes, e.g. ducts, that will be filled with a grout after the cables have been tensioned. Here a mechanical anchorage in the end must be used to hold the cables in place and to keep the prestress active.

An externally stressed cable is defined as post-tensioned. External tendons can be used in new structures but also on existing structures.

As shown in Figure 2.2 the concrete member is cast with a duct for the rod or strand to be placed in. After that the rod will be applied with a tension force, mostly by jacking, creating an compressive force in the member. The anchors will lock the ends of the rod that will keep the tension, e.g. the compressive force in the member, on the rod.

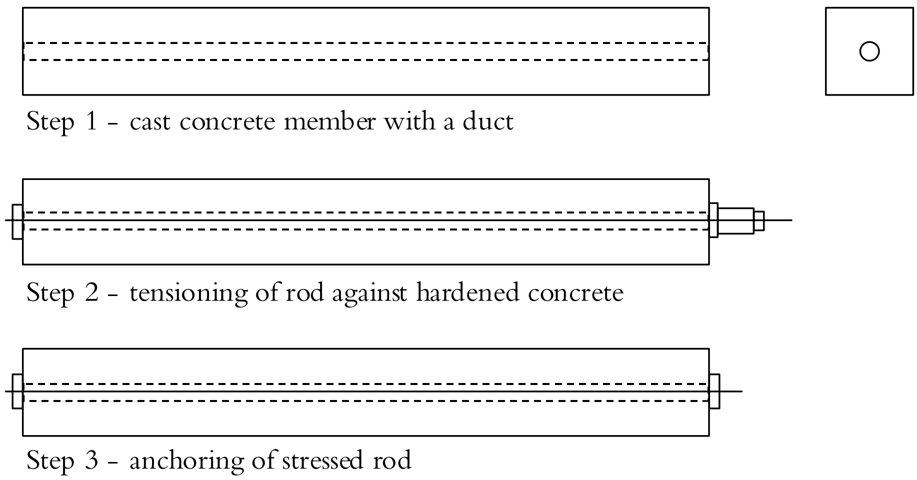


Figure 2.2 *Step-by-step for post-tensioning, after Collins and Mitchell (1991)*

2.3 FRP for prestressed concrete structures

The use of FRP as prestressed reinforcement for concrete structures has increased over the last two decades, mainly the use of CFRP. CFRP has a potential to become widely used in concrete structures with its relatively low weight, high stiffness and strength and the fact that it is non-corrosive. Therefore, no prestress loss should be experienced due to long-term corrosion in the composite. Consequently they are ideal materials with which to restore the prestress in structures whose tendons have suffered corrosion, Garden and Hollaway (1998).

However, the linear elastic behaviour of the FRP material up to failure requires special design consideration to ensure a safe construction due to possible brittle failure.

2.4 Comments

Prestressed concrete structures are a mature and well-adopted method in civil engineering. The method has been developed during most of the 20th century. Post-tensioning with steel cables have been used for upgrading of concrete structures, this technique is also possible to use with FRP cables. It is, however, important to remember the different material properties of FRP compared to steel.

3 FIBRE REINFORCED POLYMERS, FRP

3.1 Composites

The term composite often refers to a material composed of two or more distinct parts working together. Often one of the parts is harder and stronger, while the other is more of a force transferring material.

3.2 FRP

Fibre reinforced polymer, FRP, is a composite material consisting of fibres and a polymer matrix. The FRPs mostly used for civil engineering applications are CFRP (Carbon Fibre Reinforced Polymer), GFRP (Glass Fibre Reinforced Polymer) and AFRP (Aramid Fibre Reinforced Polymer). The polymer matrix used is usually Polyester, Vinyl Ester or Epoxy.

3.2.1 Fibres

In civil engineering applications the most suitable fibre has proven to be carbon fibre. Almost 95% of all applications for strengthening purposes in civil engineering are by carbon fibres. Therefore the focus in this report is placed on CFRP.

The fibres are what makes the FRP strong and there are three things that controls the mechanical properties of the FRP:

- Constituent materials
- Fibre amount
- Fibre orientation

Constituent materials
As mentioned earlier there is a wide array of different materials to use, too many to describe all in this report. What is important to remember is that the choice of fibre

material determines, together with choice of polymer, what kind of quality, properties and behaviour the FRP finally will obtain.

Fibre amount
Regarding the amount of fibre used in the FRP it is easy to say that the more fibre used the better properties will be achieved. This is somewhat true but with too high fibre content there will be a manufacturing problem. If the fibres are to tightly packed the matrix will have problems enclosing the fibres which might deteriorate the FRP. Usually a fibre amount above 70% by volume is not recommended for pultruded products such as rods and bars. In hand-lay up applications a typical amount of fibre is 35% by volume due to the handling process.

Fibre orientation
The FRP will be stiffest and strongest in the fibre direction. For example, a rod with all the fibres is very strong in its fibre direction but in perpendicular direction the FRP has not as good properties. A typical FRP product for the construction industry has therefore a anisotropic behaviour compared to steel which is isotropic. Nevertheless, the orientation of the fibres can be tailored to suit the requested properties of the FRP product asked for.

3.2.2 Matrix

The matrix, i.e. the polymer in the composite, is used to bind the fibres together, transfer the forces between the fibres and to protect the fibres from external mechanical and environmental damage.

The shear forces created between the fibres are limited to the properties of the matrix. The matrix is also the limited factor when applying forces perpendicular to the fibres.

It is important that the matrix have the capability to take a higher strains then the fibres, if not there will be cracks in the matrix before the fibres fail and the fibres will be unprotected.

3.3 Durability

Durability is one of the major issues when a new, relatively unknown, material is going to be used in structural applications. Since the use of FRP in the building industry is quite new there is no precise knowledge of the long-term behaviour. Laboratory tests have been carried out, for example Toutanji and Saafi (2001) and Hulatt et al (2002), but those are often accelerated tests to simulate a long-term influence. Before the long time effects have been seen on real structures there will always be scepticism about new materials.

3.3.1 Environmental durability

Moisture
Moisture absorption in FRP material composites depends on type of polymer matrix, laminate composition, thickness, laminate quality, curing conditions, fibre/matrix

interface and manufacturing process. In general moisture effects over short-term cause degradation in strength rather than stiffness levels. Products with an epoxy matrix are less sensitive to moisture compared to matrixes of polyester or vinyl ester.

Alkaline
The concretes alkaline environment has very little effect on CFRP, a three year exposure only reduced the ultimate capacity with 4 %, Sen et al (1998). The risk with alkaline is degradation in the matrix. Matrix damage via alkaline is generally more severe than due to moisture. In general epoxy exhibit good resistance to alkaline environment.

Aggressive chemical solutions
FRP composites are widely used in aggressive chemical applications such as oil and gas production, chemical processing and water/wastewater treatment.

High temperature
All polymeric systems degrade under high temperature, but if right type of resin is used in the matrix the resistance is increased. It is also possible to use fire protection in similar ways for steel structures; protective painting or insulation for example.

3.3.2 Creep and relaxation

Carbon fibre has an almost perfect linear behaviour to failure. For most FRP composites, creep deformation becomes a more important role at high stress levels or high temperatures or a combination of the two. Creep will not be a significant factor if the loads to the structure are kept within manufacturer recommended stress levels, Busel (2000).

The resistance to creep and relaxation is a huge advantage when using the materials in prestressed applications. If a material has problems with creep and relaxation there will be losses in the prestressing force over time. Structures can be made to make it possible to put extra stress in the material during the constructions life span, but if this can be avoided it will be beneficial.

3.3.3 Fatigue loading

FRP show significantly enhanced fatigue resistance over metallic materials, Busel (2000). Since the material is strong it is not likely to have a fatigue failure in the FRP. Although there has been limited research in larger structures it can be said that fatigue failure in the FRP is unlikely to occur except in joints, connections and for anchorage.

3.4 Comments

The material composition of FRP materials with the fibres and the matrix makes for a material with special behaviour. It is important to understand the factors affecting the behaviour of the FRP. The durability of the FRP materials is an important question since the use of FRP in the civil engineering industry is fairly new and because of the long-time behaviour for FRP in structures only have been studied in accelerated laboratory tests.

4 EXTERNAL PRESTRESSED FRP REINFORCEMENT

4.1 General

External prestressing refers to a post-tensioning method in which tendons are placed on the outside of a structural member. It is an attractive method in rehabilitation and strengthening works because

- It adds little weight to the original structure
- Its application poses little disturbance to users
- It allows monitoring, re-stressing and replacement of tendons.

The first use with external steel tendons was already back in the 1950s, but after that it lay dormant for some time. Now external prestressing techniques with steel rods have become a popular method for rehabilitation and upgrading, Collins and Mitchell (1991). However there may be a problem with corrosion in the steel that forces the use of steel protection on the external tendons, for example plastic sheeting. This problem can be resolved by the use of FRP materials. Therefore research in the area has been conducted since the early 1970's. In the beginning glass FRP was used but at the moment aramid and carbon are mainly used due to higher modulus of elasticity. It should also be mentioned that GFRP is more sensitive to stress corrosion than the CFRP.

In Japan extensive national programs have been undertaken to examine the use of FRP reinforcement in concrete structures. Several commercial tendon systems have been developed. In 1993 the Japanese were first to create a design guideline for FRP reinforcement and prestressed concrete structures for building engineering, the guidelines first came in Japanese 1995 and then in English in 1997. For civil engineering a guideline came 1996 (English version 1997).

In Canada several researchers have been investigating application of FRP prestressing tendons. At the University of Manitoba research on CFRP has been taken place, Fam et al (1997) and at the Royal Military College work on AFRP has been done, McKay and Erki (1993), just to mention some examples.

In the 70's , research started in Germany to investigate the use of prestressed GFRP tendons but it showed to be less appropriate due to its low modulus of elasticity and also problems due to stress-corrosion in the GFRP tendons. A joint venture between Strabag-Bau and chemical producer Bayer resulted, in the end of the 70's, in GFRP bars and anchorage system that has been used in Germany and Switzerland. In the Nederland's a chemical producer and a contractor, HGB, developed AFRP prestressing elements in the beginning of the 80's. At the moment the leading researcher in Europe in this field is Switzerland.

4.2 Material properties

The material properties for FRP tendons vary depending on what product and on the producer. Therefore, only a brief description of some tendons that is used will be presented in this thesis, for further information refer to the manufacturer of each system.

One of the largest advantages of FRP tendons is its low weight to high strength ratio. Compared to steel tendons FRP tendons can be made with down to one tenth of the weight. However it is important to remember that FRP and steel has different material properties and different behaviour when loaded. In Table 4.1 a short comparison is made between steel, GFRP, AFRP and CFRP. Note that this is the characteristics of FRP tendons from specific manufacturers and might not be valid to other tendons even though the same fibres are used. One manufacturer of each material has been chosen, the aim of the table is to give the reader quick information of the difference between the materials. As can be seen in the table it is important to know the materials so that the best suited material is used for a project.

Table 4.1 *Characteristics of steel and FRP tendons, Pisani (1997)*

Typical proporties	Steel (ASTM Grade 270, Euronorm Fe7S1860)	GFRP Glassline®	AFRP Arapree®	CFRP Leadline®
Fibre volume fraction (%)	---	65	50	65
Density (g/cm^3)	7.85	2.15	1.25	1.6
Tensile strength, 20ºC (MPa)	1860	1500	1490	1840
Tensile modulus, 20ºC (GPa)	195	50	62	147
Ultimate elongation (%)	> 3.5	3.0	2.4	1.3
Thermal expansion coefficient, axial direction (10^{-6}/ºC)	12	5.2	-1.8	0.68
Thermal expansion coefficient, radial direction (10^{-6}/ºC)	12	~35	~35	~20
Strength decrease after a 100 year loading (%)	~0	30	35	~0
Relaxation, 20ºC (%)	3	4	>30	3

Experimental tests have shown that the load-displacement relationship of concrete beams reinforced with FRP has almost the same behaviour as beam reinforced with steel, Mutsuyoshi et al (1991).

FRP tendons lack the ductility under extreme loading exhibited by steel, which means that a CFRP prestressed beam may simultaneously provide greater ultimate load capacity and lower energy absorption than a similar steel prestressed beam, Stoll et al

(2000). Research has shown that a prestress loss within 5 – 7 percent can be expected, Grace and Abdel-Sayed (1998).

4.3 Prestressing systems

Although FRP materials have many good qualities for prestressing purposes there is still research needed in the area. One problem with external FRP tendons is the anchorage. Due to its anisotropy as a material, perpendicular forces might crush the FRP tendon, which has been a fact for some wedge systems. However, newer systems seem to overcome this problem.

EMPA Switzerland has developed a system where they use a conical anchorage system. In general, the anchor casing is made of steel, but it can also be made of a fibre composite, Meier (1998), see also section 4.3.2.

4.3.1 Tendons

FRP tendons are available in the form of rod or cable, rectangular strip, braided rod and multi-wire strand. Here is a short presentation of four different commercially available rods, Arapree, Technora, Leadline and CFCC, Benmokrane et al (2000).

Arapree (ARAamid PREsressing Element) is made of Twaron HM aramid fibres impregnated with epoxy resin using a pultrusion process with 45% fibre and 55% matrix by volume. The tendons are available as strips or as circular rods, the rods are sand coated on the surface for better bond.

Technora is a pultruded product made of Technora aramid fibres impregnated with vinyl ester resin, with a content of 65% fibre and 35% matrix by volume. There are plain rods and rods with externally spiral winding available.

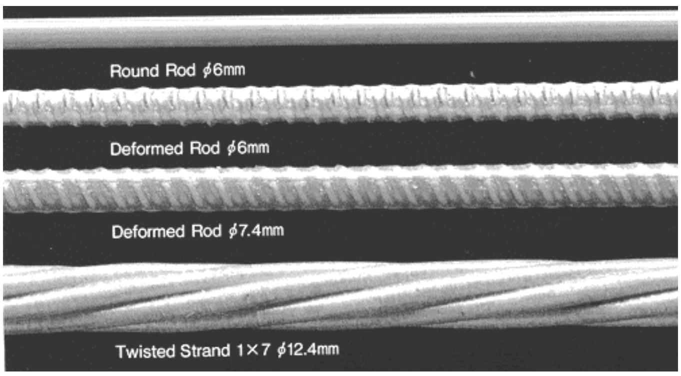


Figure 4.1 *Example of Technora rods and strands, Karbhari (1998)*

Leadline is composed of pitch-based carbon fibre and a epoxy resin in a pultrusion process. The rods are made with 65% fibre and 35% matrix by volume and are available as round, indented and rib shapes rods.

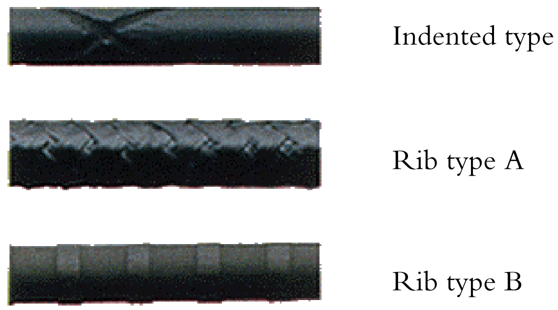


Figure 4.2 *Example of Leadline rods and strands, Karbhari (1998)*

CFCC (Carbon Fibre Composite Cable) is composed of PAN type carbon fibre impregnated with epoxy resin. The cable is formed by twisting a number of small diameter rods, similar to a conventional strand, with 65 % fibre and 36% matrix by volume.

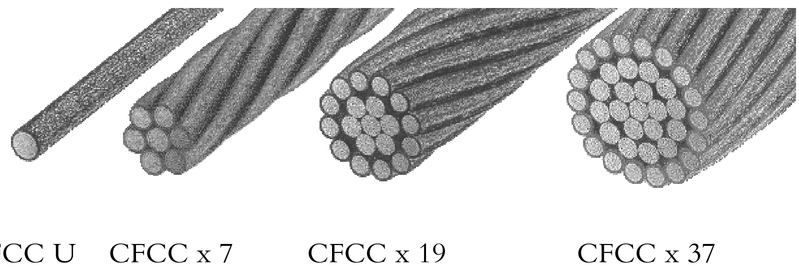


Figure 4.3 *Example of CFCC strands, Karbhari (1998)*

Table 4.2 *Manufacturers data for FRP rods, Benmokrane et al (2000)*

Tendon	Nominal diameter [mm]	Cross-section [mm^2]	Mean tensile strength [MPa]	Elastic modulus [GPa]	Ultimate strain [%]	Density [g/cm^3]	Poisson's ratio
Arapree-8	7.5	44.2	1506	62.5	2.40	1.25	0.38
Technora	8	50.2	2140	54	3.70	1.30	0.35
Leadline	7.9	46.1	2550	150	1.30	1.67	n.a.
CFCC	7.5	30.4	2120	137.3	1.57	2.10	n.a.

4.3.2 Anchorage

A key design issue for composite cables is how to harness all of the available tensile strength. Conventional anchoring systems for steel cables cannot be used with large composite cables because of the material's relatively low lateral properties, including shear strength. Cable manufacturers have developed new anchorage systems, enabling composite cables to achieve upwards of 90 percent of the total ultimate strength of the individual strands before failure in the anchorage.

There are mainly two types of anchors used, wedge anchor and grout potted anchor.

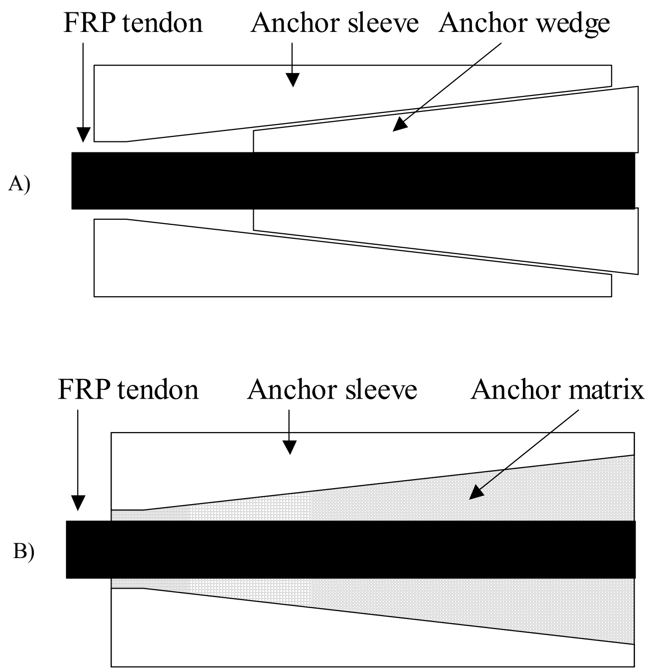


Figure 4.2 *Sketch of A) a wedge anchor and B) a grout potted anchor*

The wedge anchor system is about the same type as those used in steel systems. One of the problems with this type of anchors is the local damage to the tendon that can occur, however tests have shown that tendons still are efficient after such a local damage, Nanni et al (1996). It has been proposed that the wedge surface is gritted to ensure proper gripping, see for example Nanni et al (1996). Al-Mayah et al (2001) has tested a stainless steel wedge anchor with positive results.

A grout-potted anchor is when the tendons are placed in a cone that is filled with resin or grout. One problem with this type is failure due to pull-out from the cone. What is also interesting is the stress distribution inside the cone, as shown in Figure 4.3 mixed elastic modulus can be efficient for decreasing end stresses.

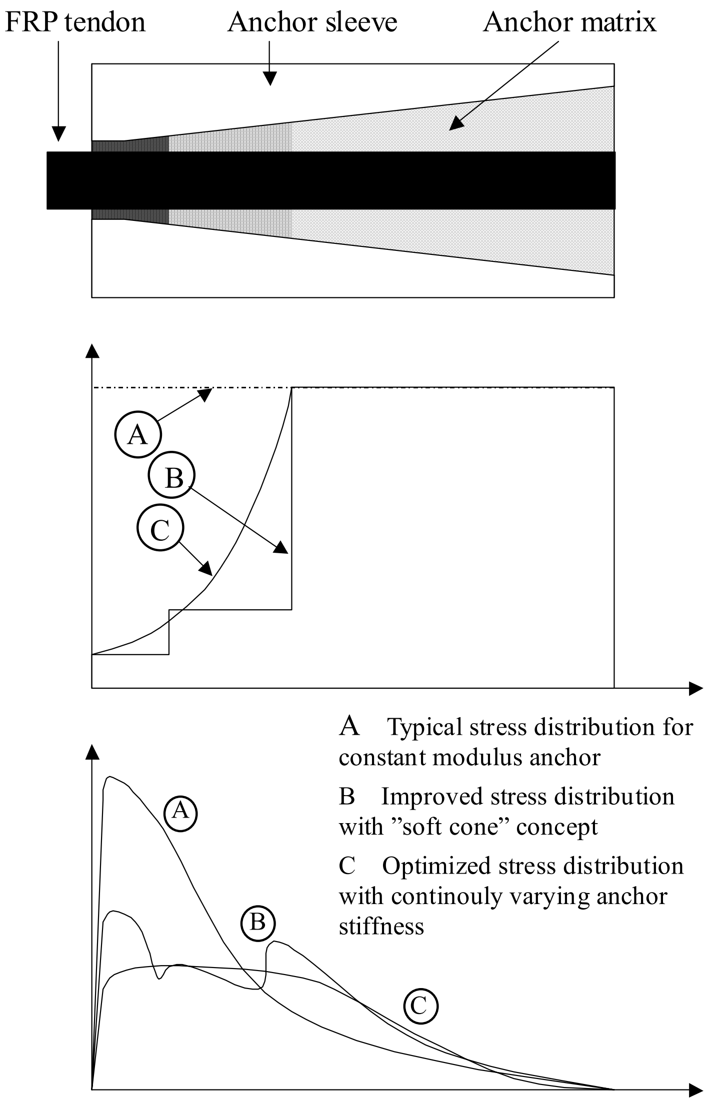


Figure 4.3 *Stress distributions in a cone with the stress on the vertical axis, from Erki and Rizkalla (1993)*

In Figure 4.3 a cone is filled with three different grouts with increasing stiffness. At the end of the anchor the modulus of elasticity of the grout is lower, the result is a better stress distribution with lower stress peaks. In the diagrams first the modulus of elasticity is shown with A constant modulus, i.e. same material through the cone, B three different modulus and C a continuously changing modulus. At the lower part the result as stress distribution from the different approaches are presented.

Tests with varied anchorage bond lengths have been conducted, Benmokrane et al (2000), which shows that the shape of the load-slip curve pull-out tests of grouted anchors is similar to both the pull-out capacity and initial stiffness increased with the increase in bonded length. Although the pull-out capacity increases with longer bond lengths, the maximum bond stress decreases. This indicates that the bond stress distribution along the bonded length of the rods is not uniformed.

4.4 Comments

The uses of external tendons of FRP materials have been developed since the 1970s. The biggest problems have been the anchorage systems; wedge anchors have crushed the rods creating durability problems. Today anchorage systems, both with wedge anchors and grout-potted anchors, have been developed that function properly. The many different kinds of cables give the engineers the possibility to choose a cable that suits the needs for the project.

5 STRENGTHENING WITH CFRP

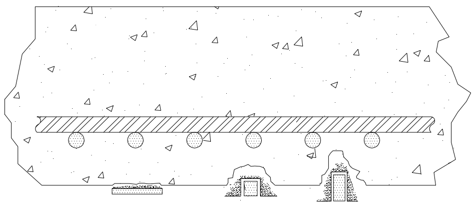
5.1 General

There are many different methods to strengthening a concrete structure such as; changing the cross-section, external prestressing, changing the static system or using the plate bonding technique.

In this chapter only strengthening for bending will be addressed. There are many other areas of use for strengthening with CFRP, such as steel columns, shear strengthening of concrete structures etc, Carolin (2003).

In recent years the development of the plate bonding repair technique has been shown to be applicable to many existing strengthening problems in the building industry. 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 adhesives most used to bond the fabric or the laminate to the concrete surface are two-component epoxy adhesives. The old structure and the new bonded-on material create a new structural element that has a higher strength and stiffness than the original one.

In Figure 5.1 are two CFRP strengthening methods shown, strengthening with laminates and strengthening with NSMR rods.



Laminate and NSMR

Figure 5.1 *Sketch of the difference between plate bonding and near surface mounted reinforcement*

5.2 Sheets and laminates

The method of plate bonding started by the use of steel plates in the mid sixties and was quite extensively used during the 70ties. However, one problem with using steel plates is the risk of corrosion another problem is that steel plates are quite heavy to lift and laborious to mount. In addition the steel plates needs to be joined by overlap plates due to limitations in transportation lengths and weight. Consequently if the plate bonding methods was going to be used more widespread, a invention was needed. The invention was to use a material that does not corrode, is strong and stiff and yet lightweight. Carbon fibre laminates fulfilled theses demands. In the late eighties the Swiss Federal Laboratories for Material Testing and Research (EMPA) started to us CFRP for strengthening and 1991 the first bridge in Switzerland was strengthened, Meier et al (1992).

One of the advantages with plate bonding is its possibility to be used for many geometrical shapes. Another advantage of plate bonding is that the method can be applied with dynamic loads on the structure during the work, Täljsten and Carolin (1999). Furthermore, the method doesn't need large material transportation or special expensive equipment. In addition the strengthening method does not change the physical dimensions of the structure

Today strengthening concrete structures in bending with CFRP laminates and fabrics is a widely accepted repair and strengthening method. Many researchers have performed tests and derived theories in this field. A large number of structures all over the world have been strengthening with this technique. National codes have been compiledand several are in the process of being written.In Sweden, for example, a guideline exist for CFRP strengthening of concrete brdges accepted by the Road Administration since 1999, Täljsten (2003).

Figure 5.2 *Heavily degraded beam with concrete removed before strengthening*

Next, a brief description of how to undertake a strengthening work with laminates and fabrics will be given. In practical execution the following steps must in general be performed during strengthening:

- Pre-treatment of the surface with grinding or sandblasting. The aggregates shall be uncovered, this to increase the bond for the adhesive to the concrete. In some situations, with extensive corrosion, the concrete behind the steel bars need to be removed, the steel bar protected against future corrosion and the surface levelled out before CFRP strengthening can be used, see for example Figure 5.2.

- Careful cleaning of the surface is important. Dust, grease and other contaminates may lower the quality of the bond. Larger holes and irregularities on the surface shall be filled with putty.

- A primer for the system chosen is applied and allowed to harden. Some laminate systems do not use a primer.

- The application of the adhesive depends often on the strengthening system used. For fabrics the adhesive is placed on the concrete surface and the fabric on the adhesive, a new layer of adhesive is den rolled on on the fabric. The procedure is the repeated until enough layers have been mounted. For laminates, the adhesive is mostly applied on the laminate and the laminate and the adhesive is the mounted to the concrete surface.

- Adhesive is applied on the surface. Then the laminate or the fabric area placed on the surface. If fabric is used adhesive is applied on the fabrics after bonding and additional layers of fabrics can be used. At the end adhesive is placed on the fabrics, this is not needed with laminates.

In Figure 5.3 a column strengthening with fabrics is shown. Protective clothing shall always be wear to minimise the contact with epoxy.

Figure 5.3 *Strengthening of a column using CFRP fabrics*

5.3 NSMR

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 is placed in slots in the concrete cover or in additional concrete cover that is cast onto the structure (Asplund, 1949). Here steel bars are placed in slots in the concrete structure and then the slots are grouted. It has also been quite common to use steel bars, fastened to the outside of the structure, covered with shotcrete. However, in these applications it is often difficult to get a good bond to the original structure, and in some cases, it is 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 is still needed. For these applications, epoxy coated steel bars have also been used. However, it has been shown that over time, epoxy coated steel bars are not always corrosion resistant for various reasons that will not be discussed here. The use of steel NSMR cannot be said to have shown great success. Nevertheless, by using CFRP NSMR some of these drawbacks that steel NSMR possess can be overcome.

Firstly, CFRP NSMR does not corrode; so thick concrete covers are not needed. Secondly, the CFRP laminate can be tailor-made for near surface applications and moreover, the lightweight of the CFRP laminates makes them easy to mount. Finally, depending on the form of the NSMR rod air voids behind the laminates can be avoided. Both epoxies and systems using high quality cement mortar can be used. Next 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 slots in the concrete cover, with the depth depending on the product used and the depth of concrete cover.
- Careful cleaning of the slots after sawing using high-pressurised water. No saw mud is allowed to remain in the slot.
- If an epoxy system is used, the slot must be dry before bonding. If a cement system is used it is generally 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.

The NSMR laminates are mounted in the slot and the excess adhesive or cement mortar is removed with a spatula or similar.

There are mainly three types of laminates that have been used in NSMR applications;, circular rods De Lorenzis et al (2000), De Lorenzis and La Tegola (2002) and De Lorenzis (2002), rectangular laminates Täljsten and Carolin (2001) and quadratic rods Carolin et al (2001).

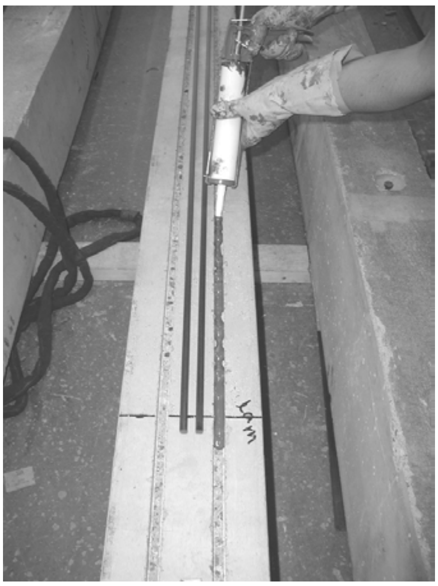


Figure 5.4 *Slots being filled with epoxy adhesive, laboratory tests in Luleå 2001*

5.4 Comparison between Laminates, sheets and NSMR

The CFRP strengthening systems described in Table 5.1 may be used for different applications. For example CFRP fabrics are often used for curved surfaces whereas CFRP laminates for flat surfaces. A NSMR rod may be used for both flat and curved surfaces as long as the radius are not too small.

Before a project is planned it needs to be considered what system suits the strengthening object best. All systems have their strengths and weaknesses that have to be understood if a optimised strengthening will be achieved.

In Table 5.1 some characteristics and aspects of externally bonded FRP reinforcement are listed.

Table 5.1 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 and bending 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

5.5 Comments

The use of CFRP materials for strengthening concrete structures is now a widely used method for repair and upgrading. Laminates and sheets are the most used methods, but lately the use of Near Surface Mounted Reinforcement (NSMR) with CFRP rods have increased.

6 STRENGTHENING WITH PRESTRESSED CFRP

6.1 Why strengthening with prestressed FRP

There are four main reasons why it can be an advantage to prestress the strengthening material.

- Better utilisation of the strengthening material
- Unloading of the steel reinforcement
- Decreased crack size and mean crack distance
- Higher steel yielding loads

The largest advantage with prestressing the strengthening material is the increased steel-yielding load. Studies has shown almost 50% increase in steel yielding compared to unstrengthen structures and up to 25% compared to not prestressed strengthened structures, see for example Wight et al (1995a) and Nordin et al (2001).

Figure 6.1 shows the typical behaviour of beams loaded with four-point bending. The values are from Nordin et al (2001) but other studies show the same behaviour, El-Hacha et al (2001b) and Wight et al (1995). The plot in Figure 6.1 shows three important stages, concrete cracking, steel yielding and ultimate load. A non prestressed strengthened beam has about the same cracking load as a non-strengthened beam, where the beam with prestressed strengthened FRP has about twice the load. For steel yielding the strengthening effect is almost double for prestressed strengthening compared to non prestress, Wight et al (1995a).

In Figure 6.1 a load versus midpoint deflection plot is drawn. Two dotted ellipses encircle A) the concrete cracking load and B) the steel yield load.

When strengthening with un-stressed FRP it is often the strain in the steel reinforcements that is the limiting factor. Even if the strengthening material carries larger parts of the load, the steel reinforcement has yielded. This also imply a low utilisation of the FRP laminate, NSMR or sheet used. A low utilisation lead to higher costs for the client. This means in many situations that it would be beneficial if the structure could be unloaded before strengthening. However, this is not always possible.

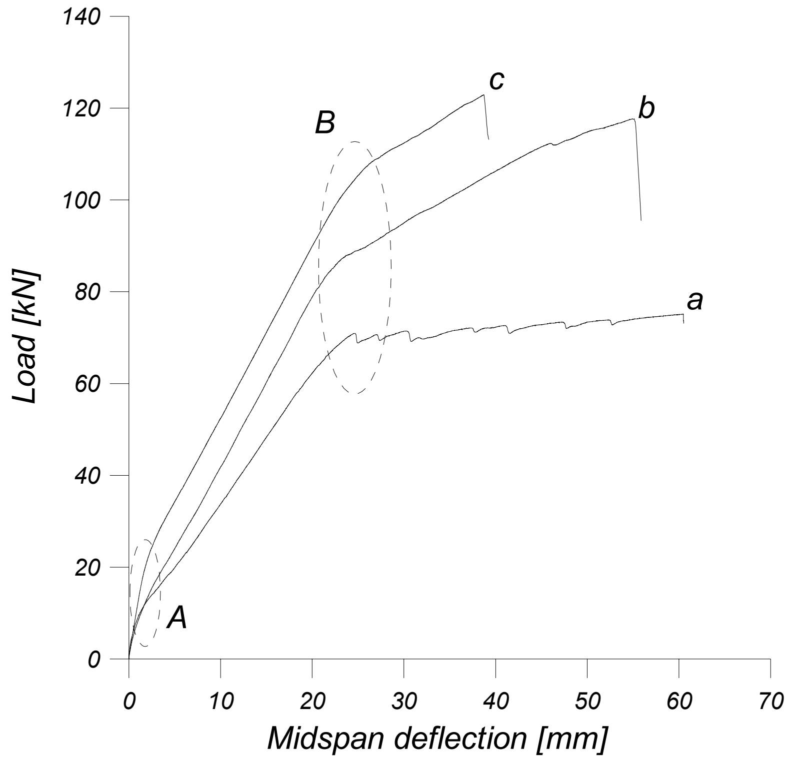


Figure 6.1 *Beams strengthened with CFRP, (a) unstrengthened, (b) strengthened without prestress and (c) strengthened with prestress*

Nevertheless, if the FRP material can be prestressed the stress on the steel will be decreased and with the FRP stressed there will be higher utilisations of the FRP material and in addition lower deflections may be obtained. Now the strengthening material and the steel reinforcement will work together directly from loading leading to higher concrete cracking load, (A), and in addition the steel yielding will occur at a higher loads as well, (B).

In Figure 6.2 a theoretical stress and strain distribution is shown for a concrete beam without external loads. In b) the strain distributions of a strengthened beam without prestressed FRP (continuous line) and with prestressed FRP (dotted line) are shown. In c) the stress distribution for a beam strengthened without prestress is shown and in d) the stress distribution of a rectangular beam with prestressed FRP can be seen.

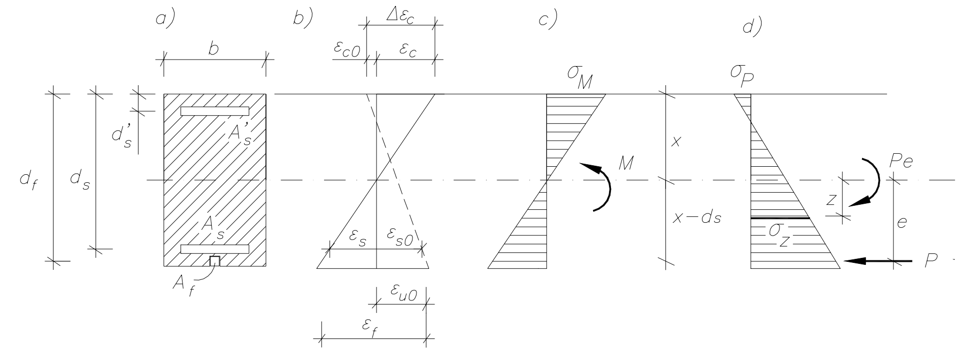


Figure 6.2 *The theoretical stress distribution, c) is without prestress and d) is with prestress, Nordin et al (2001)*

By prestressing the FRP the crack load is increased and the steel-yielding load is increased. As for pre- or post-stressed steel structures the ultimate load is not increased since the same amount of strengthening material is added, Wight et al (1995a), El-Hacha et al (2001a) and Nordin et al (2001).

6.2 Sheets and laminates

Sheets and laminates is the strengthening technique with prestressed CFRP that have been investigated most. Although there have been problems with end peeling the results have been interesting when using mechanical anchorage, Wight et al (1995a) and El-Hacha et al (2003).

It has been found that the pultruded composite plates, similar to those used in practice, fail progressively when plate fracture occur, and considerable further load may be carried after the first fracture. Such a failure in practice would provide a visual warning of imminent structural collapse, Garden and Hollaway (1998).

Applying a prestress to the plate prior to bonding also affect the mode of failure. The plate 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). Prestressing produced significant increases in the load which causes yield of the internal steel over a non-prestressed specimen Quantrill and Hollaway (1998).

If there are imperfections on the tension face the FRP sheet might separate itself from the beam surface, Wight et al (1995a). This indicates that the pre-treatment of the surface is more important when prestressing the laminates, mainly due to the higher shear stresses. The shear stress dramatically increases near the end of the sheets Wight et al (1995a). This makes an anchorage system useful for prestressing applications.

In Figure 6.3 a sketch shows an example on how to strengthen with prestressed FRP. An adhesive is applied to the FRP material, and then the FRP is placed on the surface of the structure. When the FRP is placed a force is applied to the FRP, a force that has to be applied during the curing of the adhesive. When sufficient curing of the adhesive has been achieved the applied force is released and the FRP is cut.

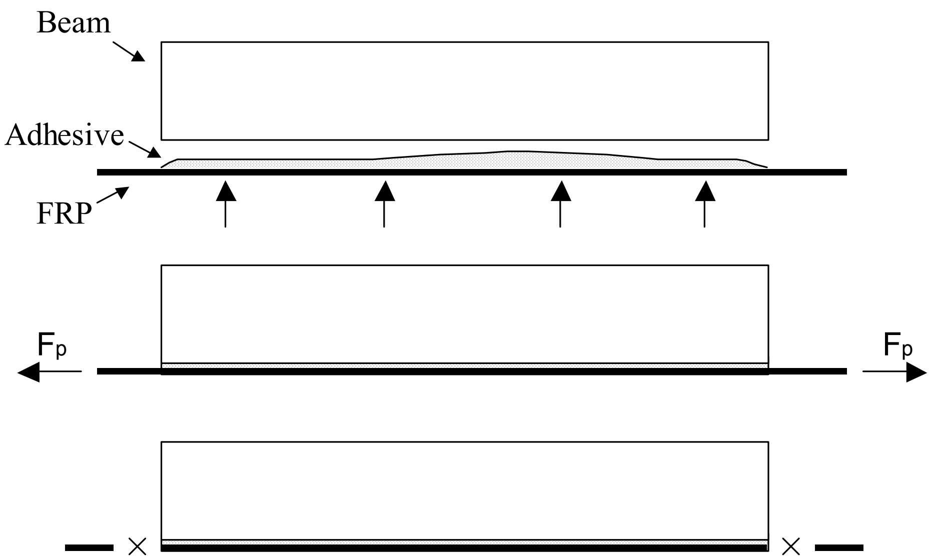


Figure 6.3 *Post-Reinforcing with pre-tensioned FRP Sheets, from Triantafillou and Deskovic. (1991). The FRP is applied to the surface and a prestressing force, F_p, is applied. After curing the prestressing force is released and the FRP are cut*

6.2.1 Prestressing systems

Mainly three systems have been investigated for prestressing FRP plates and laminates for strengthening of structures.

- "Unloading" the beam by, for example, hydraulic jacks and then strengthen, this will give a kind of prestress when the load is released.
- Prestressing the FRP against external independent structures
- Prestressing the FRP against the strengthened beam itself.

One of the biggest issues with strengthening with prestressed FRP has been how to do it in the field. Often the physical appearance of the construction makes the methods used in the laboratory more or less useless in the field. A complete system has to have both a prestressing technique and an anchorage system.

A system to prestress plates and strips has been developed in Switzerland where a hydraulic cylinder miniature press is used Andrä and Maier (1999), see Figure 6.4.

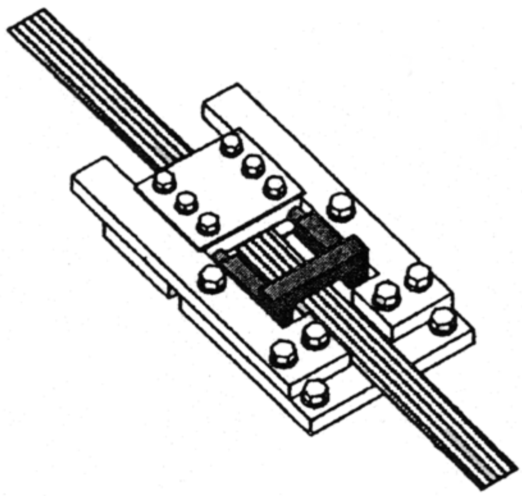


Figure 6.4 *Sketch of the prestressing system developed at EMPA Switzerland, Andrä and Maier (1999)*

El-Hacha et al (2003) describes a method that has larger parts but has shown promising results, see Figure 6.5. On the left side an anchor plate that has been glued on to the FRP is bolted to an angle iron that is bolted to the beam. On the right side bars has been welded on the anchor plate, the bars goes trough the angle iron and is then attached to a hydraulic cylinder that applies the prestressing force.

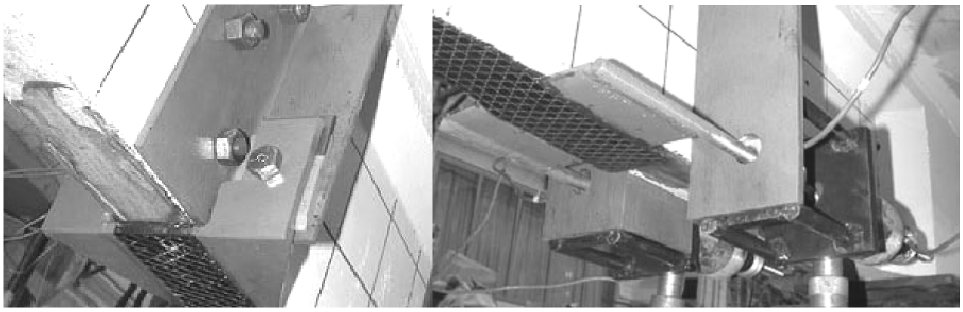


Figure 6.5 *Anchorage system for the prestressing El-Hacha et al (2003)*

This can also be made in a smaller scale, Garden and Hollaway (1998). Here a block is bonded to the laminate and bolted in to the concrete creating a fixed anchor system, see Figure 6.6.

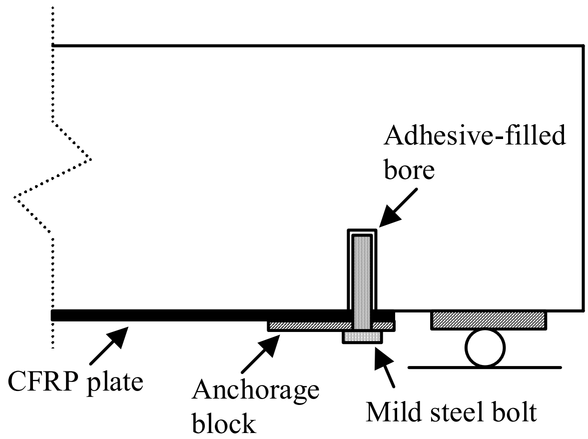


Figure 6.6 *Example anchorage for strips, after Garden and Hollaway (1998)*

6.2.2 Quality

Before a strengthening is performed, it is important that the original structures condition is examined to verify if the strengthening technique will be applicable, Täljsten (2002). If the existing concrete is in too poor condition strengthening with prestressed laminates might not be possible.

The quality of the system is highly dependent on the surface that the FRP will be bonded to. The surface will be sandblasted or grinded and cleaned with pressurised air or a vacuum cleaner before bonding to achieve the best bond between the materials. Not lose particles, grease or other contaminations are allowed on the surface at time for bonding. During the strengthening the climate demands stated by the manufacturer of the products must be achieved. Also it is important that the products included are used in the correct manner. After the strengthening is completed the FRP composite can be tapped on using, for example, a hammer to find any possible voids, Täljsten (2002).

6.3 Near surface mounted reinforcement

The idea of Near Surface Mounted Reinforcement is to insert the added reinforcement into sawed grooves in the concrete cover. Some researchers have tested NSMR with circular rods, De Lorenzis (2002) and Hassan and Rizkalla (2001). A pilot study with rectangular rods has earlier been undertaken at Luleå University of Technology, Täljsten and Carolin (2001). The sawing of grooves is only possible on structures with enough "depth " to the steel reinforcement. One should remember that the thickness of the concrete cover is depending of the workmanship when the structure was built rather then the code that design was based upon. Anyhow, it is easy to believe that the method is more suitable for outdoor structures such as bridges then indoor structures with normally less concrete cover.

6.3.1 Pre-treatment

Full-scale tests have shown that the pre-treatment when using plate bonding may be work intense and therefore expensive. In traditional plate bonding the concrete laitance layer must be removed and the aggregates must be exposed to ensure good anchorage before the composite can be applied. This can in the most cases be done by sandblasting and is then neither complicated nor expensive. However, if the surface has irregularities, from formwork for instance, or if the sand blasting doesn't has any effect then the surface needs grinding or a more powerful treatment to uncover the aggregate. Whichever method chosen, the work will be time consuming and costly.

For NSMR, a groove has to be sawn, this may be difficult to do by hand only, since the equipment is heavy. But if a stiff "rail" is used as support for the saw the work will become much easier and then the grooves will become straight and are possible to make also on rough surfaces. After the grooves have been sawn the concrete has to be chiselled out and the grooves cleaned from contamination. If the right equipment is used this might be less work intense then the pre-treatment for plate bonding

6.3.2 Force transfer

The insertion of the reinforcement should vouch for a better force transfer between the concrete and the composite compared to plate bonding. The bonded area will change and be dependent of the geometry of the inserted reinforcement. If the rods are placed too close to each other, a possible failure may occur from interaction between the two rods.

If the strengthening work has been performed correctly there should not be problems with the FRP bond to the adhesive, this goes for both plate bonding and NSMR. Then the energy needed to get a failure in the concrete to adhesive bond is larger then the plate bonding technique.

6.3.3 Different bonding agents

Another issue is the use of thermosetting polymers such as epoxy. Epoxy can be, if it is handled in a wrong way, allergenic and harmful. Therefore, the possibility to replace epoxy by cement grout would be preferable. The use of polymer cement as bonging agent when strengthening with NSMR has proven to work well with unstressed CFRP, Carolin et al (2001). The downside is that the cement has much longer curing time then epoxy, which may create problems if used with prestressed CFRP.

Another way to do the bonding is to use injection or infusion. Different application techniques can be found in Täljsten and Elfgren (2000). This can be made with , for example, vacuum injection as in Figure 6.7. The first advantage is that with this method it is possible to avoid hand contact with the epoxy adhesive and wastage at the work site can be kept to a minimum. Furthermore, the quality of the composite can be improved. However, this method requires a large investment and there can be some difficulties in achieving a high degree of vacuum with surfaces of rough texture or in complicated geometries and locations. This implies higher prices for the strengthening work. For this application, a low viscosity cold-cured epoxy adhesive is used.

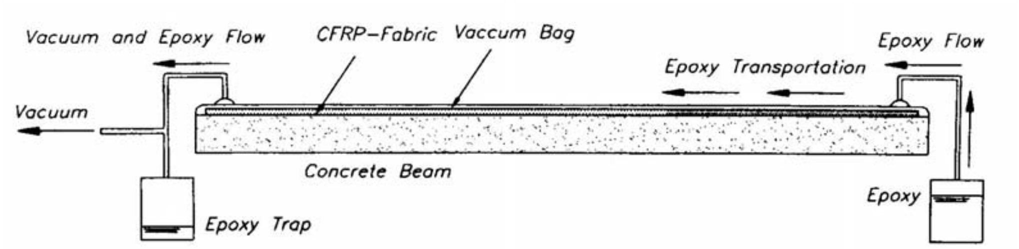


Figure 6.7 *Vacuum injection system with a CFRP-fabric for strengthening purposes, Täljsten and Elfgren (2000)*

6.3.4 Prestressing system

Due to that limited research has been published regarding the use of prestressed Near Surface Mounted CFRP rods there is no practically useful method developed at the moment. The use of unstressed Near Surface Mounted CFRP rods in concrete structures have applied in real structures, but no recorded use of prestressed NMSR have been found.

Prestressing
Prestressing NSMR has so far only been done in laboratory environments. The prestressing operations done have used external supports to prestress against, see Figure 6.8. This is in most cases not possible to do on a real structure; therefore a prestressing system has to be developed.

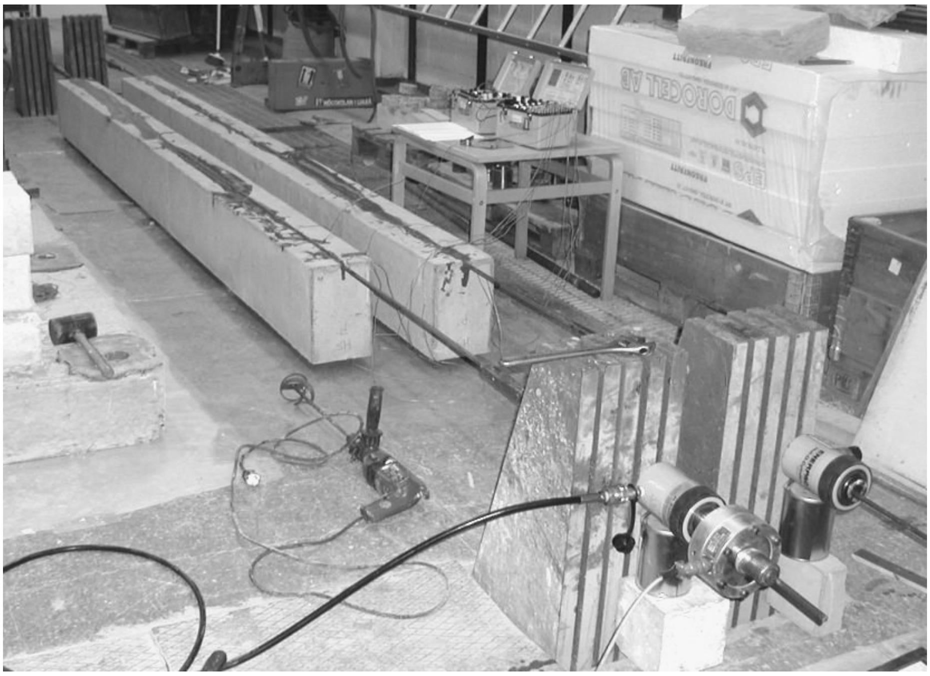


Figure 6.8 *Prestressing in laboratory, Luleå University of Technology 2002*

Since there has not been any reports found containing prestressed NSMR with a anchorage system the technique described here is without anchorage. When prestressing NSMR the rod is placed in the adhesive filled groove and then the prestressing force is applied, similar to Figure 6.3. When the adhesive has cured the prestressing force is released and the force is transferred via the adhesive to the concrete. Because there is no anchorage there will be loss of the strain in the rod at the end. The strain loss is large at the ends and then decreased over 200 mm, after that there is only a small loss of prestressing strain in the rod.

Mechanical anchorage

Although it is possible to avoid failure at the end without mechanical anchorage it would be beneficial to use such devices. A mechanical anchorage would help decreasing the loss of strain at the ends when releasing the prestressing force. It might also be able to help keeping the prestress in the rod over a long-time perspective, without mechanical anchorage it is likely that there will be problems with creep.

One other important aspect for a anchor system is for the prestressing operation. Without a anchor to apply the prestressing force to it is difficult to get higher prestressing levels.

A mechanical anchorage system has to contain a device placed in the groove or a expanded section of the groove. The device has to be bonded to the CFRP rod, either by a wedge anchor or with adhesive. Then there is mainly two alternatives, the devise will be locked to the soffit only or it will be bonded deper in the structure. If the anchor is to be bonded to the soffit, for example with a V-shape, it is important that the concrete can take the stresses that will occur, otherwise the concrete might be crushed at the ends. The alternative of bonding the anchor deeper in the concrete can be maid by bolts drilled in to the concrete, similar to the method used for plates shown in Figure 6.6.

No matter what method that will be used for anchoring the ends it is still an important area that needs research. Not before a sufficient anchor system is developed will the method of prestressed NSMR be possible to use outside the laboratory.

6.3.5 Quality

Traffic running underneath a bridge with low clearance results, sooner or later, in damages on the bridge from vehicle impact. For a concrete bridge this is not critical but can cause severe damages to an unprotected and badly designed reinforcement. Plate bonding as well as external post tensioning can be sensitive for vehicle impact if that has not been considered in the design. Damages caused by under passing trucks can be seen in Figure 6.9.

Figure 6.9 *Damages of strengthening system caused by vehicle impact, Carolin et al (2001)*

Fire, vandalism and environmental loads can also harm the composite. A damage of the reinforcement can give severe problems and eventually failure of the structure. With NSMR the fragile composite will be better protected from outer damage than traditional plate bonding and external post tensioning.

6.4 Comments

Strengthening concrete structures with prestressed CFRP have proven to be an effective alternative to unstressed CFRP. Both concrete cracking load and steel yielding load is increased compared to structures strengthened with unstressed CFRP. The main problem with strengthening with prestressed plates has been the end zones. Without mechanical anchorage there have been peeling failures at the ends.

The use of prestressed NSMR rods has shown to in a better way be able to transfer the stresses from the rod to the concrete. Although there are losses in the strain at the ends when releasing the prestressing force there have been no peeling failure during bending.

7 FULL SCALE APPLICATIONS

Here three bridges are briefly presented. Carbon fibre systems have in different ways been used for the bridges. In the first bridge, the Stork bridge in Switzerland, two of the steel stays cables have been replaced with CFRP tendons. In the second bridge, the Hythe bridge in the UK, prestressed CFRP laminates have been used for strengthening and in the last bridge, the Uddevalla bridge in Sweden, NSMR rods to strengthening a concrete joint have been used.

7.1 Stork Bridge

EMPAs' design of the anchor system has been used at one of the first cable-stay bridge applications for composite cables. Located in Winterthur, Switzerland, the Storchenbrucke ("Stork Bridge") carries vehicles over railroad tracks. The bridge is a single A-frame pylon cable-stayed bridge with 12 pairs of cable stays. The bridge has a total length of 124 m and the pylon is 38 m in height. Two steel cables (one pair) were replaced with CFRP cables. The installation took place in April 1996.

The composite strands are fabricated from 24K tow, with 17 tows comprising each strand. Fibre volume is 65 - 70 percent in these strands. Anchors for the two stays are high-strength alloy steel with a seven-step gradient of load transfer medium. A polyethylene duct, identical to those used on the steel cable, sheaths the cables, and polyethylene foam keeps the cable from rattling inside the sheath during high winds.

Table 7.1 *Material properties, Meier (1995)*

	Tensile modulus [GPa]	Tensile strength [MPa]	Ultimate strain [%]
CFRP rods	165	3300	2
Carbon fibre	228	4800	2.1

Bundles of 19 CFRP rods were tested at EMPA in static and fatigue loading. The static load-carrying capacity reached 92 percent of the sum of the single-wire capacity. Fatigue tests showed the superior performance of CFRP under cyclic loading. A 1,200-ton stay cable and anchorage of a 241-rod cable were tested at EMPA to over 8 million cycles at 3.2 times the service load stress levels, without any signs of damage.

Because the composite cables are working together with steel cables, EMPA designers performed a thoroughly static evaluation to ensure that the difference in thermal expansion and stiffness would not compromise the bridge's suspension. The composite cables will experience 10 percent greater load than the steel cables during the summer due to steel's higher thermal expansion rate.

7.2 Hythe Bridge, Oxford

Hythe Bridge, constructed in 1874, consist of inverted Tee section cast iron beams. The bridge was to have its capacity raised from 7.5 tonnes to 40 tonne assessment load.

From December 1998 to April 1999 the Hythe Bridge in Oxford was strengthened with prestressed CFRP strips. Prior to the strengthening Mouchel Consulting undertook a feasibility study into methods of strengthening the bridge, with objective to raise its capacity. Three methods were studied; steel plates, unstressed composite plates and stressed composite plates. It was concluded that the stressed composite solution offered the most satisfactory solution, providing that a system could be developed and demonstrated to be effective.

In may 1998 three iron cast beams, with a length of 4.7 m and flange width at 305 mm, with prestressed CFRP plates were tested. The results were a complete success resulting in the use of the technique on the Hythe Bridge. Material properties for the CFRP laminates are presented in Table 7.2.

Figure 7.2 *Photograph of the Hythe Bridge, Darby et al (1999)*

The degree of prestress was designed to remove all tensile stresses from the cast iron beams under the full 40 tonnes loading. Four CFRP laminates per beam were stressed to a total of 18 tonnes. Prestress effectively counteracts the dead load effects, releasing additional capacity for the live load, Darby et al (1999).

Table 7.2 *Material properties*

	Tensile modulus [GPa]	Tensile strength [MPa]	Ultimate strain [%]
CFRP laminates	160	2800	1.75

The Hythe Bridge demonstrated that stressing of CFRP could be successfully undertaken under extreme site conditions. As a conclusion from the strengthening work it was drawn that prestressing composite materials offers a means of strengthening structures that can be more economic than unstressed composite materials or steel plate bonding.

7.3 Uddevalla Bridge

The Uddevalla Bridge is able stay bridge with a length of 1712 m and with a span of 414 m. The pylons are 149 m. The bridge was constructed between 1996 and 2000.

During the construction process it was noticed that it was not enough steel reinforcement in the joint between the pre-cast bridge decks and the on-site cast land ramp. Due to a tight time schedule concrete had to be cast over the area. To solve the problem it was decided to strengthen the joint using CFRP materials. Because it would be a road structure (asphalt etc.) on top of the concrete it was not possible to use surface bonded CFRP laminates. The decision was made to strengthen the joint using NSMR rectangular laminates. The NSMR technique would, in this case, in a better way protect the CFRP from abrasion and other types of damage that could be caused to the CFRP if it was bonded to the surface. Slots were sawed in the concrete and CFRP laminates were placed in the adhesive filled slots. The cross section and the material data of the CFRP laminates used for the Uddevalla bridge is shown in Table 7.3

Table 7.3 *Material data of CFRP laminates*

	Tensile modulus [GPa]	Tensile strength [MPa]	Ultimate strain [%]
CFRP rods	145	2700	1.8

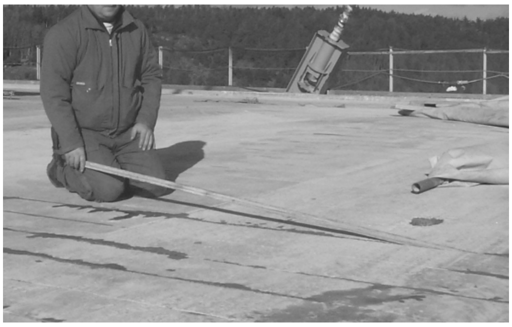


Figure 7.2 *Placement of CFRP strips*

The strengthening was carried out during the autumn 1999. It took two men four days to finish the strengthening work and a total of 160 m CFRP laminates were used.

7.4 Reflections from full-scale applications

The methods used in the above applications have all worked well for its purpose. CFRP cables, prestressing surface bonded laminates and using NSMR laminates bonded in the concrete cover.

For the CFRP cables the use of the developed anchorage system was of great interest. The importance of a functional anchor is also great for steel cables, but with the anisotropy of the CFRP cables makes it even more important. With the Stork Bridge EMPA has shown that it is possible to replace steel cables with CFRP cables.

The strengthening of the Hythe Bridge with prestressed CFRP showed that the method is both possible and efficient. It was done under extreme site conditions and still the results were a success, the prestress counteracted the dead load effects that released additional capacity for the live load.

For the Uddevalla Bridge the strengthening was needed due to not enough steel reinforcement. The use of NSMR was chosen and proved to work well. The strengthening work could be carried out in only a few days with minimum number of workers.

8 SUMMARY OF PAPERS

The thesis consists of a main body and three papers. While the main body give a more general view on strengthening with prestressed CFRP the three papers have each a specified focus. Paper A is about FRP together with concrete in a hybrid beam, paper B describes strengthening of concrete structures with quadratic NSMR rods and paper C focuses on prestressed strengthening of concrete structures with quadratic NSMR rods. Although paper A is different then paper B and C it has functioned as a good introduction in the area of Fibre Reinforced Polymer materials and their properties and behaviour.

8.1 Paper A

This paper presents tests where hybrid composite beams have been investigated. The hybrid beam consists of a glass fibre I-beam with carbon fibre strengthened bottom flange and a rectangular concrete block in the compressive zone. The interaction between the concrete and composite beam were obtained in two ways; casting in steel dubs and bonding a hardened concrete block by an epoxy adhesive. As a reference, a beam without concrete in the compressive zone was also tested. The idea of combining carbon, glass and concrete was to utilize the stiffness contribution from the carbon and the compressive strength from the concrete. The glass fibre I-beam would then take up the main part of the shear force. The results from the test showed that a good composite action could be achieved between carbon, glass and concrete. However, it could also be noticed, as expected, that an I-beam is not the ultimate form for a composite load-carrying structural member due to stability problems. In the tests, problems arose due to lateral instability, but this was solved by placing stiffeners manufactured from wood between the flanges of the FRP beam over the supports. With a few modifications of the hybrid beam it is believed, that it would be possible to create both a technical and economical hybrid profile that benefits from carbon, glass and concrete.

The tests presented in this paper show, in a short-time perspective, that a hybrid FRP-girder could be a promising load-carrying structural element. The low weight combined with high strength is an excellent alternative to traditional steel and concrete beams. It is, however, important to understand the materials and their strengths and weaknesses, for example the stability issue is of tremendous importance. The tests presented in this study, show that it is possible to manufacture a beam combining GFRP, CFRP and concrete for use in structures, i.e. hybrid beams.

The results from the tests show that it is possible to manufacture a FRP hybrid beam with concrete that can have excellent stiffness and be able to bear heavy loads. However, concrete is needed in the compressive zone to achieve sufficient stiffness and to take up the compressive forces.

If FRP I-beams are to be used efficiently, stiffeners have to be used. However, unlike steel it is not possible to weld these to the FRP, but epoxy bonding gives a good force transfer. A better alternative though would be to manufacture more optimal cross-sections, for example beams with double webs.

The steel dubs used worked well as a mechanical connection between the concrete and FRP. In production, traditional production techniques will therefore be possible. An advantage compared to steel and concrete beams would not only be better durability but also less weight, which will make the working procedure simpler and faster. The epoxy-bonded concrete connection worked somewhat better then the steel dubs in the laboratory. However, this technique would be more complicated since it would require extensive lifting of the pre-cast concrete on site. Here, using a FRP deck might be a solution to replacing the concrete.

The analytical theory used in the paper, based on linear behaviour, has proven to work well with the laboratory tests. The structural behaviour of the hybrid beam should therefore be fairly simple to calculate. It is however, important to take in consideration the anisotropy of the FRP beam.

Since there are many possibilities to manufacture different shapes for FRP beams it would be better to manufacture beams more adapted to the material properties of the FRP, and not be bound to the traditional shapes used for steel structures. By doing that it should be possible to avoid such weak spots as the flange-web intersection as occurred with the beams presented in this paper. With today's pultrusion technology, there are many possibilities for manufacturing tailor-made hybrid composite beams.

8.2 Paper B

The need of maintenance, repair and upgrading of concrete structures has increased considerably over the last decade and will most likely continue to do so. There can be several reasons for this, but it can often be attributed to normal change of use, increased demands on the structure, errors in the design and/or construction phase or in the worst case, accidents. Different methods have been developed over the years for solving different rehabilitation problems. Recently, advanced composites used for external bonding in the form of fabrics or laminates have become an accepted method. Several thousands of objects around the world have been upgraded with advanced composites bonded to its surface. In most cases, this method is very competitive regarding both structural behaviour and economy, but there are also some drawbacks. The surface bonded composite material is relatively sensitive to fire, accidents or vandalism. In addition, the pre-treatment is relatively intensive and time consuming. However, if the composite material is placed in slots in the concrete cover some of these drawbacks can be overcome. This paper presents work carried out on near surface mounted reinforcement (NSMR) at Luleå University of Technology in Sweden.

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 is placed in slots in the concrete cover or in additional concrete cover that is cast onto the structure (Asplund, 1949). Here steel bars are placed in slots in the concrete structure and then the slots are grouted. It has also been quite common to use steel bars, fastened to the outside of the structure, covered with shotcrete. However, in these applications it is often difficult to get a good bond to the original structure, and in some cases, it is 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 is still needed. For these applications, epoxy coated steel bars have also been used. However, it has been shown that over time, epoxy coated steel bars are not always corrosion resistant for various reasons that will not be discussed here. The use of steel NSMR cannot be said to have shown great success. Nevertheless, by using CFRP NSMR some of these drawbacks that steel NSMR possess can be overcome.

There is no doubt that strengthening concrete structures with NSMR is an effective method. The tests presented in this paper show promising strengthening results and a considerable strengthening effect could be noticed. Prestressing increased the steel yielding load and delayed concrete cracking. The 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.

8.3 Paper C

Strengthening concrete structures with fibre reinforced polymer materials have grown to be a widely used method over most parts of the world today. As a way of higher utilization of the FRP (Fibre Reinforced Polymers) prestressing of the FRP is an interesting patch to move forward. Most of the research done with prestressing Carbon Fibre Reinforced Polymers (CFRP) for strengthening has been with surface bonded laminates. However, in this paper prestressed CFRP quadratic rods are placed in the concrete cover in sawed grooves. This have proven to be an efficient way of bonding CFRP to the concrete, and will also transfer the shear forces between the CFRP and the concrete in a better way compared to surface bonded laminates. In this study concrete beams have been strengthened with prestressed CFRP rods. In the study no mechanical device has been used to keep the prestress, which then means that the adhesive has to transfer all shear stresses to the concrete. Tests show that the prestressed beams exhibit a higher first crack-load as well as a higher steel-yielding load compared to non-prestressed strengthened beams. The ultimate load at failure is also higher, compared to non-prestressed beams, but in relation not as large as for the cracking and yielding. All strengthened beams failed with fibre rupture.

In this study a total of 15 full-size concrete beams have been tested. The beams tested were four meters long and with a cross-section of 200x300 mm. The longitude reinforcement was 2 Ø16 Ks 500 at the upper and lower part of the beam and stirrups at a spacing of 75 mm Ø10. A 15x15 mm groove was sawn in the bottom of the beams see Figure 4. One beam was a reference that was not strengthened, four beams were strengthened without prestressing and the remaining 10 were strengthened with prestressed CFRP rods. During the tests three variables were changed for the NSMR rods; bond length, modulus of elasticity and the prestressing force.

The results from the tests show that strengthening technique using CFRP bonded in the concrete cover is a excellent way to transfer the stresses between CFRP and concrete, both for non-prestressed and prestressed CFRP. The problems with end peeling of the strengthening material that have been a major problem when prestressing surface bonded CFRP laminates have not existed with NSMR rods.

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. Together with higher crack loads the cracks also go smaller, this should indicate a better behaviour for the serviceability limit.

With fairly simple equations it is possible to get an estimated value of stresses and strain in the midpoint beam that is, compared with tests, in good agreement. It is also possible to calculate the end stresses during bending, it is just important to remember the non-linear behaviour of the beams and the linear behaviour in the theory.

It is the authors' belief that it will be possible, and in some cases beneficial, to strengthen concrete structures with prestressed NSMR rods. The force transfer between CFRP and concrete works very well, even without mechanical anchorage devices. With a anchorage devoice the results should be even better when it come to end strain and stress in the rod.

9 DISCUSSION

The discussions will be focused on the research presented in the papers in this thesis.

9.1 FRP beams

Beams made of FRP materials can be an effective alternative to the traditional materials used in the construction industry. The manufacturing of the beams makes for a variety of different shapes that can be custom made for each project.

The type of beams used in Paper A was not an optimum solution for FRP beams. The beams were manufactured to be as traditional steel beams with the aim to see how it would be possible to use the traditional shapes from steel structures. The problem with the FRP I-beams was mainly that the connection between flange and web was to weak.

If FRP materials are to be used in new structures as, for example, beams it is important to understand the weaker points of the materials so that the beam will be manufactured to suit its purpose.

Due to that it is to costly to build FRP beams in CFRP materials most beams made and tested have been GFRP beams, and in some cases combined with concrete. The combination with a stiffer material is most likely needed to ensure a structure that the users, for example pedestrians on a bridge, do not feel insecure using it.

9.2 Strengthening with NSMR

The tests performed with beams strengthened with Near Surface Mounted Reinforcement of CFRP rods have shown that the strengthening method is effective with impressive results. The method the CFRP will have a better force transfer and at the same time be somewhat protected against external damaging such as vehicle impact.

Using quadratic rods have shown to be a great way of bonding the rods in the slots. The adhesive thickness can be controlled to be the same for all three sides of the rod, optimising the shear stress at all sides.

The use of polymer cement as bonding agent instead of epoxy adhesive proved to be competitive method. The load for that beam at failure was comparable to the ones strengthening with epoxy bond. However, there is a time aspect that might limit the use of cement as a bonding agent. The curing time before the cement is able to transfer forces to the concrete is much longer then the time that the epoxy adhesive needs. This means that if a bridge is to be strengthened it has to be closed for a long time if cement is used. Here there must be a discussion with the owner of the structure to choose the suitable method.

The tests with prestressed CFRP bonded in the slots gave higher concrete cracking load and higher steel yielding load. The tests were a pilot study and the results from those tests show promising results for future research.

9.3 Strengthening with prestressed NSMR

Strengthening concrete structures with prestressed near surface mounted rods have shown to be an effective method. The force transfer between the CFRP and the concrete seems to work better then surface bonded laminates. The problems with end peeling of the laminate that prestressed surface bonded laminates may have, has not occurred when using NSMR.

The tests have been carried out without mechanical anchorage but there is still a need for an anchorage system. With an anchorage system the strengthening effect may be improved if the end strain losses at the end of the rods could be minimized. An anchorage system is also needed to be able to prestress the rods in a field application, in the tests the prestress have been done against external supports which often is not possible outside the laboratory.

In the tests uncracked beams have been tested and the concrete cracking load has been increased with the prestressing. On a real structure one other factor comes in, reducing existing cracks. With the prestressing force cracks could be reduced, or even removed, at the same time as the load needed for new cracks to occur is increased. The durability for the structure should also be improved since the serviceability limit has been increased.

The method of using prestressed NSMR is fairly new and not much research have been done. There are still many factors that have to be studied, but with the result from the tests presented in the paper as a base future research in this field will be very interesting. It is very important that the method and the effects from it are fully understood so that a sound and safe strengthening can be achieved.

10 FUTURE WORK AND RESEARCH

As the results from the tests presented in Paper B and Paper C has shown that the prestressing NSMR technique can be an efficient strengthening method, however it is still some issues that have to be investigated before in field tests can be done. Here a few thoughts are presented.

The composite
In the tests the modulus of elasticity has been tested at two levels, different prestressing forces have been investigated and two bond lengths of the rods. But only one size of the rod, cross-section, have been tested. Testing of different cross-section might show what the most optimised size of the cross-section is.

Acnhorage and prestressing system
The most important part is to develop an anchorage system that can be used for prestressing the rods in the field. It is not likely to use the same prestressing technique in the field as have been used in the laboratory. The other reason for having an mechanical anchorage device is to try to reduce, or even remove the loss of strain that occur at the end of the rods when releasing the prestressing force.

Fibre optics
An interesting aspect would be to be able to have fibre optics embedded in the FRP. In that way it would be possible to monitor the behaviour of the FRP in field, possibly over a long time.

Durability
The long-time behaviour of the prestressed strengthened CFRP has to investigate. What happens to the prestress over a long time? If there is a significant loss of strain that has to be taken in consideration when designing the strengthening. There is no doubt that without a mechanical anchorage system this will be a problem, but with a correctly developed anchor it should be possible to get good long-time behaviour.

Theory
The theory has to be further developed. A more thoroughly understanding of the failure modes must be reached. In addition the long-term effects of prestressed NSMR rods should be investigated. It is important to try to obtain a complete theoretical investigation as possible for understanding the process of strengthening with prestressed NSMR CFRP. But it is also important to develop calculation methods that can be used by designers.

In particular shall the anchorage issue be studied more in detail, here fracture mechanics may be a part of the solution.

Field applications
With a developed anchorage system, the next step will then be to use the method on a real structure in field. Here it will be of great importance to have the possibility to continuously monitor the structure, both before and especially after strengthening.

11 REFERENCES

Andrä H-P. and Maier M., (1999), "Post strengthening of reinforced concrete structures by prestressed externally bonded carbon fibre reinforced polymer (CFRP) strips" Conf. Proceedings: Structural Faults and Repair, 1999

Al-Mayah A., Soudki K.A. and Plumtree A. (2001), "Experimental and Analytical Investigation of a Stainless Steel Anchorage for CFRP Prestressing Tendons", PCI Journal, March-April 2001, Vol 46 no 2, pp 88-100

Asplund, S.O. (1949), "Strengthening Bridge Slabs with Grouted Reinforcement", Journal of the American Concrete Institute, Vol. 20, No. 6, January, pp. 397-406

Benmokrane B., Zhang B. and Chennouf A. (2000), "Tensile proporties and pullout behavior of AFRP and CFRP rods grouted anchor applications" Construction and Building Materials 14, Elsevier Science Ltd. 2000, pp 157-170

Busel J.P. (editor) (2000) "Product Selection Guide: FRP Composite Products for Bridge Applications" MDA, The Market Development Alliance of the Composites Industry, First Edition, 2000, pp 264

Carolin A., Nordin H. and Täljsten B., (2001), "Concrete beams strengthened with prestressed near surface mounted reinforcement (NSMR)" International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 1059-1066

Carolin A (2003) "Carbon Fibre Reinforced Polymers for strengthening of structural elements" Doctoral Thesis 2003:182, Div. of Structural Engineering, Luleå University of Technology, Sweden, ISBN 91-89580-04-4

Collins M.P. and Mitchell D., (1991), "Prestressed concrete structures" Prentice Hall, Englewood Cliffs, New Jersey 07632

Darby J., Skwarski A., Brown P. and Haynes M., (1999), "Prestressed advanced composite plates for the repair and strengthening of structure" Conf. Proceedings: Structural Faults and Repair, 1999

De Lorenzis L., Nanni A. and La Tegola, A., (2000), "Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods" Advanced Composite Materials in Bridges and Structures, Proc. of 3rd Int. Conf., Ed. Humar, J.L. and Razaqpur, A.G. Ottowa, ISBN: 0-7709-0447-5, pp. 521-528.

De Lorenzis L., and La Tegola A. (2002) "Analytical modeling of bond of near-surface mounted reinforcement in concrete" Bond in concrete – from research to standards Proceedings of the 3rd International Symposium, ISBN 963 420 714 6, pp 724 – 734

De Lorenzis L. (2002), "Strengthening of RC structures with near-surface mounted FRP rods" Doctoral Thesis, University of Lecce, Italy

El-Hacha R., Gren M. And Wight G. (2001a), "Conrete beams post-strengthened with prestressed carbon fibre reinforced polymer sheets" Conf. Proceedings: Structural Faults & Repair, London June 2001

El-Hacha R., Gren M. And Wight G. (2001b), "Prestressing system for FRP sheets: Long-term and low temperature effects" Conf. Proceedings: Structural Faults & Repair, London June 2001

El-Hacha R., Gren M. And Wight G. (2003), "Innovative System for Prestressing Fiber-Reinforced Polymer Sheets" ACI Structural Journal, May-June 2003, pp 305 - 313

Erki M.A. and Rizkalla S.H. (1993) "Anchorage for FRP reinforcement" Concrete international 1993

Fam A.Z., Rizkalla S. and Tadros G. (1997) "Behaviour of CFRP for Prestressing and Shear Reinforcements of Concrete Highway Bridges" ACI Structural Journal, Vol 94, No. 1, Jan-Feb, pp 77-86

Garden H.N., Hollaway L.C. (1998), "An experimental study of the failure modes of reinforced concrete beams strengthened with prestressed carbon composite plates" Composites Part B 1998, pp 411-424

Grace N.F. and Abdel-Sayed G., (1998), "Behavior of Externally Draped CFRP Tendons in Prestressed Concrete Bridges", PCI Journal, September 1998 vol 43 no 5, pp 88-101

Grace N.F. and Abdel-Sayed G., (1999) "Use of CFRP/CFCC strands in prestressed concrete bridges" Conf. Proceedings: Structural Faults and Repair, 1999

Grace N.F., Tang B.M. and Abdel-Sayed G., (2001), "New approach to multi-span CFRP continuous prestressed bridges" International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 11177-1184

Harada T, Matsuda H., Khin M., Tokumitsu S., Enomoto T. and Idemitsu, (1995), "Developement of non-metallic anchoring devices for FRP tendons", Non-metallic (FRP) Reinforcement for Concrete Structures, 1995

Harajli M., Khairallah N. and Nassif H. (1999), Externally prestressed members: Evaluation of second-order effects" Journal of Structural Engineering, Vol. 125 No. 10, October 1999

Hassan T. and Rizkalla S. (2001), "Strengtheing of bridgslabs with FRP systems" Conf. Proceedings: Structural Faults & Repair, London June 2001

Hulatt J., Hollaway L. and Thorne A. (2002), "Preliminary investigations on the environmental effects on new heavyweight fabrics for use in civil Engineering" Composites: Part B 33, 2002, pp 407 - 414

Karbhari V.M. (1998) "Use of Composite Materials in Civil Infrastructure in Japan" From < http://beijing.itri.loyola.edu/compce/toc.htm> May 2002

Maruyama K., (2001), "Strengthening of concrete structures using continuous fibre reinforcing materials" Conf. Proceedings: Concrete Under Severe Conditions – Environment and Loading, University of British Columbia, Vancouver June 18-20, 2001, Edt. Banthia N., Sakai K. and Gjörv O.E., ISBN 0-88865-782-X, pp 1817 – 1826.

McKay K.S. and Erki M.A. (1993) "Flexural behaviour of Concrete Beams Pretensioned with Aramid Fibre Reinforced Plastic Tendons", Canadian Journal of Civil Engineering vol 20

Meier U (1998), US-Patent 5,713,169, Feb 3, 1998

Meier U (1995). "Extending the Life of Cables by Use of Carbon Fibers", IABSE Symposium, San Francisco, 1995

Meier U., Deuring H. and Schwegler G. (1992) "Strengthening of structures with CFRP laminates: Research and application in Switzerland" Advanced composites materials in bridges and structures, Edt. Neale K.W. and Labossiére P., 1992

Meier U (2001a), "CFRP tensile members in structural engineering" ACUN-3: Technology Convergence in Composites Applications, Sydney 6-9 February 2001

Mutsuyoshi H., Machida A. and Sano M., (1991), "Behavior of pretressed concrete beams using FRP as external cable" Japan Concrete Institute, Vol. 13, 1991

Nanni A., Bakis C.E., O´Neil E.F. and Dixon T., (1996) "Performance of FRP tendon-anchor systems for prestressed concrete structures" PCI Journal, January-February 1996

Nordin H, Carolin A and Täljsten B (2001), "Concrete beams strengthened with prestressed near surface mounted reinforcement (NSMR)", International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 1067-1075

Pisani M.A. (1997), "A numerical survey on the behavior of beams prestressed with FRP cables" Construction and Buildning Materials 12, 1998, pp 221-232

Quantrill R.J., Hollaway L.C. (1998), “The flexural rehabilitation of reinforced concrete beams by the use of prestressed advanced composite plates” Composites Science and echnology 58 1998, pp 1259-1275

Sen R., Shahawy M., Sukumar S. and Rosas J. (1998), “Durability of Carbon Pretensioned Elements in a Marine Environment”, ACI StructuralJournal, V.95, No.6, November-December 1998

Stoll F., Saliba J.E. and Casper L.E. (2000), “Experimental study of CFRP-prestressed high-strength concrete bridge beams“ Composite structures 49, Elsevier Science Ltd. 2000, pp 191-200

Teng J.G., Chen J.F., Smith S.T. and Lam L. (2001), “FRP Strengthened RC Structures” John Wiley & Sons, LTD, ISBN –0471-48706-6

Toutanji H. and Saafi M. (2001) “Durability studies on concrete columns encased in PVC-FRP composite tubes”, Composite Structures 54, 2001, pp 27 - 35

Triantafillou T.C., Deskovic N. (1991) “Innovative Prestressing with FRP Sheets: Mechanics of Short-Term Behavior” Journal of Engineering Mechanics 1991, Vol. 117 pp 1652-1672

Triantafillou T.C., Deskovic N, Deuring M (1992): “Strengthening of Concrete Structures with Prestressed Fiber Reinforced Plastic Sheet” ACI Structural Journal, May-June 1992, Vol. 89 No 3 pp 235-244

Täljsten B., (1994), “Plate Bonding, Strengthening of Existing Concrete Structures with Epoxy Bonded Plates of Steel or Fibre reinforced Plastics” Doctoral Thesis 1994:152D, Div. of Structural Engineering, Luleå University of Technology, Sweden, ISSN 0348 – 8373, 308 pp.

Täljsten B., (1996), “Strengthening of concrete prisms using the plate-bonding technique”, International Journal of Fracture 82: 253-266, 1996, 1996 Kluwer Academic Publishers, Printed in the Netherlands.

Täljsten B., (1997), “Strengthening of Beams by Plate Bonding”, Journal of Materials in Civil Engineering, November 1997, pp. 206-212.

Täljsten B., (1998), ”Förstärkning av betongkonstruktioner med stålplåt och avancerade kompositmaterial utsatta för vridning”, Forskningsrapport, Luleå tekniska universitet, Avdelningen för konstruktionsteknik, Institutionen för Väg- och vattenbyggnad, 1998:01, ISSN 1402-1528 (In Swedish)

Täljsten, B. and Carolin, A, (1999), “Strengthening of a concrete railway bridge in Luleå with carbon fibre reinforced polymers - CFRP: load bearing capacity before and after strengthening”, Technical Report 1999:18, Luleå: Luleå University of Technology, Structural Engineering. 61 pp

Täljsten B., (2000), “Förstärkning av befintliga betongkonstruktioner med kolfiberväv eller kolfiberlaminat, Dimensionering, material och utförande”, Teknisk Rapport, Luleå tekniska universitet, Avdelningen för Konstruktionsteknik, 1999:12, ISSN 1402-1536, 1999, p 122 (In Swedish).

Täljsten B. and Carolin C., (2001), "CFRP strengthening, Concrete beams strengthened with Near surface mounted CFRP laminates", to be presented at FRPRC-5 in Cambridge UK, July 2001.

Täljsten B., (2001), "Design guidelines – a Scandinavian approach", to be presented at International Conference on FRP Composites in Civil Engineering CICE 2001. Hong Kong.

Täljsten B., (2002), "FRP strengthening of existing concrete structures – Design guidelines" ISBN: 91-89580-03-6

Wight R.G., Green M.F., Erki M.A. (1995a) "Post-strengthening conrete beams with prestressed FRP sheets" Non-metallic (FRP) Reinforcement for Concrete Structures 1995, ISBN 0 419 20540 3

Wight R.G., Green M.F., Erki M.A. (1995b) "Tapered transfer zones using prestressed FRP sheets for post-strengthening concrete beams" 1995 Annual conference of the Canadian society for Civil engineering

PAPER A

TESTING OF HYBRID FRP COMPOSITE BEAMS IN BENDING

Håkan Nordin[1] and Björn Täljsten[1,2]

[1] Division of Structural Engineering
Luleå University of Technology
97187 Luleå, Sweden

[2] Skanska Teknik AB
16983 Solna, Sweden

Submitted to *Composites part B: Engineering*

TESTING OF HYBRID FRP COMPOSITE BEAMS IN BENDING

Håkan Nordin and Björn Täljsten

ABSTRACT

This paper presents tests where hybrid composite beams have been investigated. The hybrid beam consists of a glass fibre I-beam with carbon fibre strengthened bottom flange and a rectangular concrete block in the compressive zone. The interaction between the concrete and composite beam were obtained in two ways; casting in steel dubs and bonding by epoxy adhesive. As a reference, a beam without concrete in the compressive zone was also tested. The idea of combining carbon, glass and concrete was to utilize the stiffness contribution from the carbon and the compressive strength from the concrete. The glass fibre I-beam would then take up the main part of the shear force. The results from the test showed that a good composite action could be achieved between carbon, glass and concrete. However, it could also be noticed, as expected, that an I-beam is not the ultimate form due to stability problems. In the tests, problems arose due to lateral instability, but this was solved by placing stiffeners manufactured from wood between the flanges of the FRP beam over the supports. With a few modifications of the hybrid beam it is believed, that it would be possible to create both a technical and economical hybrid profile that benefits from carbon, glass and concrete.

KEYWORDS

FRP, Glass fibre, Carbon fibre, Concrete, Composite action, Hybrid composite

INTRODUCTION

We live in a world of change where the industries often have to rethink their plans due to environmental, technical as well as economical demands. For the construction industry this may imply faster, better, safer and cheaper structures, not always easy demands to combine. One way to achieve these goals might be to develop new and innovative building parts, for example by using new materials. Here FRP (Fibre

Reinforced Polymer) materials could play an important role for the construction industry of tomorrow.

So far, FRP has mostly been used for strengthening concrete structures, Täljsten [1],[2] and Teng et al [3]. Due to the relatively low weight and high strength of FRP girders and decks it has proven to be efficient to replace old bridges that no longer meet today's requirements with FRP alternatives. The low weight makes it often possible to build most of the bridge nearby the existing bridge and then lift it in to place, thus minimizing the effect on traffic. In USA a number of road bridges have been replaced with FRP alternatives, Alampalli et al. [4], and in Western Europe the first road bridge was replaced with a FRP bridge during the summer of 2002, Luke et al. [5].

It is no doubt, that there is a great potential for, and economic interests in FRP for construction elements. 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 materials. For engineers designing and construction workers handling the material, the physical properties and workability need to be understood. It is also important to know the limitations of the material used. Just because FRP's have good potential, they cannot be used in every structure. One thing that needs to be considered is the beam-to-column connections; Mottram and Zheng [6] have tested both connections consisting of FRP materials and those of steel. The conclusions from this test were that the steel option worked better and was recommended in the article.

For I-beams it is important how the connection between the web and flange is designed. That area is often the location of failure that reduces the stiffness of the beam, Gan et al. [7]. Increasing the radius between the web and flange could help to improve the stiffness of a pultruded FRP I-beam.

FRP BEAMS IN CONSTRUCTION

Fibre Reinforced Polymers are not a new innovation; these materials were developed after the Second World War. However, the quality and the cost for using FRPs in various applications have improved and decreased respectively. The pultrusion technology of today, gives both the manufacturer and the designer possibilities to manufacture structures with various forms and shapes. The structural part may be optimised for its use, for example a beam. Analysis and design of FRP girders and decks have been investigated by several researchers around the world; see for example Qiao et al. [8] and Upadyay and Kalyanaraman [9].

Ideas that have proven to be efficient are hybrid beams where FRP materials are combined with concrete resulting in a stiffer structure. Mainly two ways are possible when concrete is combined with FRP. The first is where concrete is cast in a U-shaped FRP-profile on top of the beam, Ribeiro et al. [10], and the second when the concrete is cast on a flat surface in the same way as on a traditional steel girder, Sekijima et al [11].

GFRP (Glass Fibre Reinforced Polymer) beams with CFRP (Carbon Fibre Reinforced Polymer) in the tension zone and concrete in the compression zone have not been commonly tested. Deskovic and Triantafillou [12] tested an interesting design where a GFRP box girder had CFRP bonded to the lower flange and concrete cast to the upper flange. The tests also included a theoretical investigation and a finite element analysis. The conclusions from those tests were that a combination of different FRP materials with concrete appears to be a feasible way of producing technically efficient and cost-effective hybrid structural members.

EXPERIMENTAL PROGRAM

The laboratory tests presented in this paper shall be considered as pilot tests. The tests have been carried out at Luleå University of Technology in Sweden, Lindgren and Nordin [13]. The tests were made to investigate the behaviour of hybrid FRP beams consisting of GFRP, CFRP and concrete. The idea was to benefit from each material, using the tensile strength from the CFRP, the low cost of the GFRP and the compressive strength of the concrete.

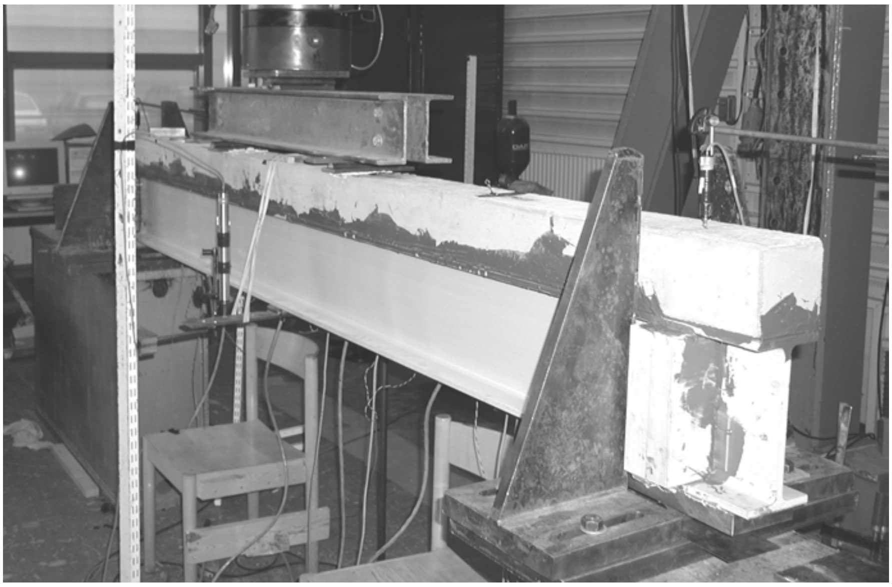


Figure 1 *Laboratory set-up*

The glass fibre reinforced polymer beams used in the tests were pultruded I-profiles with carbon fibre in parts of the lower flange. The beams were 240 mm in height and 120 in width with a thickness of flanges and web of 12 mm. The lower flange consisted of 9 mm of GFRP and 3 mm CFRP. Material properties for the FRP are shown in table 1. Fiberline Composites A/S in Denmark manufactured the beams and the profile is one of their standard profiles with the exception for the CFRP in the lower flange. In figure 1 a photo of the test set-up is shown.

Table 1 *Material properties for the glass fibre and carbon fibre composite*

	GFRP		CFRP
	Fibre direction	Perpendicular	Fibre direction
Density (kg/m^3)	1700	1700	1600
Tensile strength (MPA)	240	50	2400
Module of elasticity (GPa)	23	8.5	150

The concrete used had a cross section of $b \cdot h = 120 \cdot 115$ mm. The cross-section was chosen with consideration to the width of the upper flange of the FRP beam. The composite action between the hybrid FRP beam and the concrete were achieved in two different ways; on Beam B the upper flange had no: 72, 90 mm high steel dubs drilled through the flange and concrete cast upon it. Beam C had hardened concrete bonded to the FRP with an epoxy-based adhesive, BPE® Lim 465, with a thickness of 1 mm controlled by spacers, the material properties of the adhesive are recorded in table 2. Tests with steel beams have shown that bonding concrete to an I-beam with epoxy adhesive is possible, Täljsten [14]. The concrete used in the tests had a compressive strength of 80 MPa. No steel reinforcement bars were used in the concrete. In figure 2 the profile of the beams is shown.

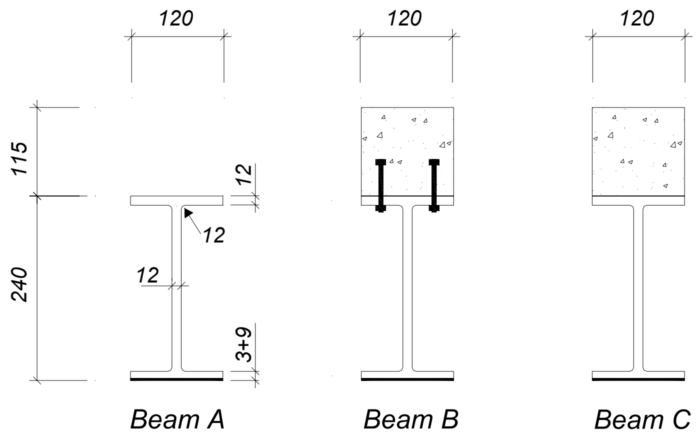


Figure 2 *Cross section of the three beams*

Table 2 *Material properties for adhesive used*

	Density [kg/m^3]	Compressive strength [MPa]	Tensile strength [MPa]	Modulus of elasticity [MPa]
BPE 465	1498	103	31	7

The 3-meter long beams were subjected to a four-point bending load, as shown in figure 3, with a free span between the supports of 2700 mm. A total of three beams were tested, one reference Beam A without concrete and two beams, Beam B and Beam C, with concrete on the upper flange.

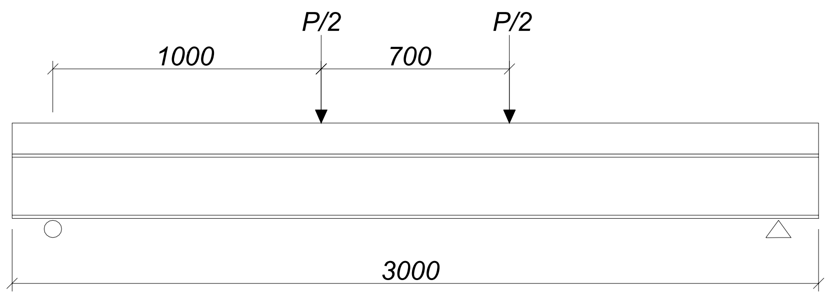


Figure 3 *Set-up for four point bending*

During the tests the beams were monitored in several points. Strain gauges were attached at the top of the beam as well as the bottom, five gauges at each side giving ten strain gauges per beam. Two rosette gauges were placed on the web and the mid span displacement was measured. The placement of the gauges can be seen in figure 4.

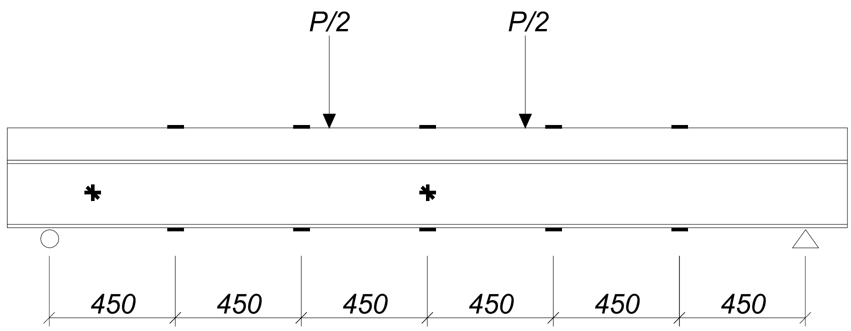


Figure 4 *Placement of the gauges*

Beam A

Beam A was a FRP beam without concrete, see figure 5. It was tested to study the FRP beam behaviour and was also used as a reference to the hybrid beams. The loading was set to 0.1 mm/second and the loading was to be made in 5 steps with complete unloading between the steps. The loading levels chosen for the steps were 25, 50, 75 100 and 125 kN, the beam was visually inspected before every unloading. At about 80 kN the first noises from the beam, in the form of snapping sounds, could be heard. After 100 kN the top flange started to twist and at 125 kN the twist was clearly visible. At this point it was decided not to unload, instead the loading was increased after inspection of the beam. Directly after the loading began again the top flange experienced increased twist and strong snapping sounds were heard at about 130 kN. The twisted top flange created instability in the beam causing it to slip from its support at 133 kN.

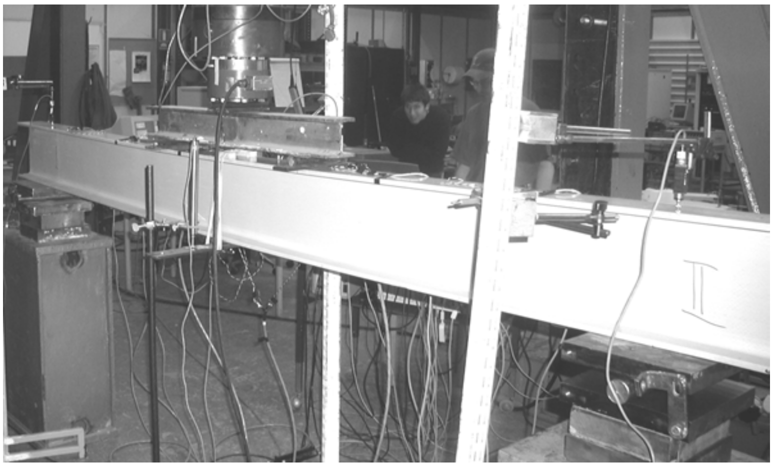


Figure 5 *Beam A during test*

Beam B

Beam B was the first hybrid beam tested. The concrete was cast on to the flange and the bond between the FRP and concrete was achieved with steel dubs. There were 72 steel dubs with a total length of 90 mm. To avoid any risks of obtaining the same failure as in Beam A, wood stiffeners were used over the supports in between the flanges. Beam B was tested in three steps, 25, 50 and 75 kN with unloading between the load steps. After that the beam was loaded until failure. At the first step it became clear that the speed of loading was too high when the stiffness of the beam was increased, therefore the speed was lowered to 0.02 mm/second. After 75 kN snapping sounds were heard from the beam all the way until failure. The failure occurred at 275 kN when the concrete crushed outside one of the loading points, see figure 6. There was no visual failure in the connection between the FRP and the concrete; this indicates that mechanically fastening the concrete with dubs is an efficient method.

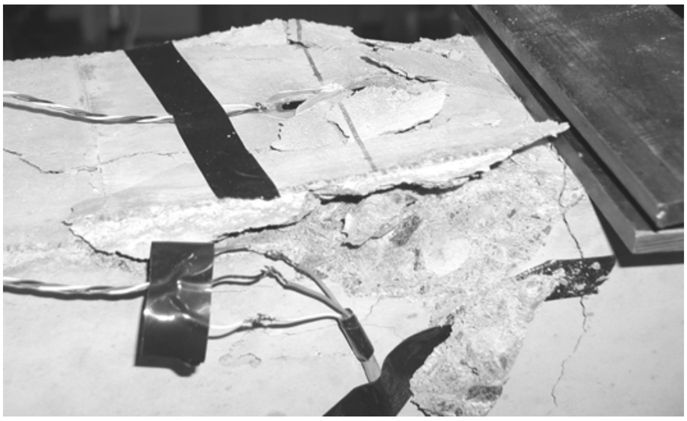


Figure 6 *Concrete crushing on Beam B*

Beam C

As with Beam B, wood stiffeners in between the flanges over the supports, were also used for Beam C. For Beam C the concrete was cast and allowed to cure for 28 days before it was epoxy bonded to the FRP beam. The load rate was the same as for Beam B. The loading was made in the steps of 25 and 50 kN with unloading and after that loaded up to failure. The first sounds from the beam were heard at 90 kN and at 150 kN cracks was visible just above the bond area at the ends of the beam. Just below 250 kN tensile cracks in the lower part of the concrete were noticed. The failure came at 292 kN when two thirds of the concrete was sheared off just above the bond area. The bond itself was strong enough but the shear forces in the concrete were too large.

Figure 7 *The concrete was thrown off the beam when the stresses became too high for the adhesive*

TEST RESULTS AND DISCUSSION

Beam A was only used to compare the stiffness with the hybrid beams and to gain the bending stiffness, *EI*, of Beam A. In figure 8 a comparison of the load-displacement between all three beams is made; the figure clearly shows that the stiffness is considerably higher when using concrete on the upper flange. The bending stiffness from the tests, EI_{test}, is calculated by:

$$EI_{test} = \frac{PL^2 a}{48\delta_{test}}\left(3 - \frac{4a^2}{L^2}\right) \tag{1}$$

Where P is the total load on the beams, L is the distance between the supports, a the distance from the support to the point-load and δ_{test} is the midpoint displacement.

In table 3 the calculated results are presented with a percentage comparison between the beams. The beams with concrete on the upper flange have a threefold bending stiffness compared to Beam A.

Table 3 *Calculated average* EI *from tests*

	Beam A	Beam B	Beam C
P [kN]	100	200	200
L [mm]	2700	2700	2700
A [mm]	1000	1000	1000
δ_{test} [mm]	23	17.4	14.3
EI [Nmm^2]	$1.6\cdot10^{12}$	$4.3\cdot10^{12}$	$5.2\cdot10^{12}$
% of Beam A	100	271	325

There is a slight difference in the bending stiffness from the tests between Beam B and C. It is most likely that both connection techniques used give a very good composite action between concrete and the FRP beam. When using steel dubs (bolts) some settlement could be noticed in the beginning of the loading patch, see figure 8. However, this effect vanished when the loading continued. For Beam C when the concrete was epoxy bonded to the FRP beam no movements could be noticed. In the calculations of the bending stiffness from the test the linear part of the curves for Beam B and C have been considered.

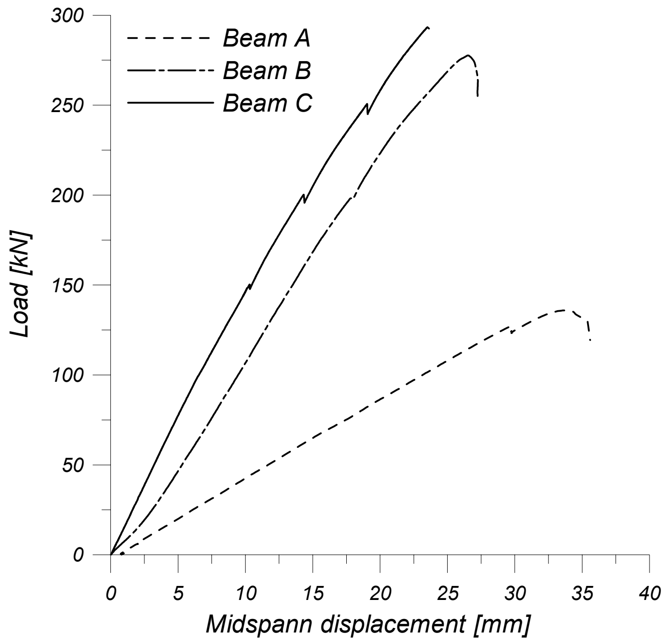


Figure 8 *Midspann displacements for the three beams*

THEORY

The theoretical calculations are based on a linear behaviour for a beam with concrete. It assumes perfect bond between the concrete and the FRP. The displacement consists of a flexure contribution and from shear deflection. With the total displacement a theoretical bending stiffness, EI_{theory}, can be calculated and compared to the bending stiffness calculated from the laboratory tests, EI_{test}.

A transformed section can be calculated, where the CFRP and concrete are transformed to GFRP. By introducing a transformation factor it is possible to write:

$$\alpha_c = \frac{E_c}{E_{GFRP}} = \frac{4700\sqrt{f_{cc}}}{E_{GFRP}} = \frac{4700\sqrt{80}}{23 \cdot 10^3} = 1.83 \tag{2}$$

$$\alpha_{CFRP} = \frac{E_{CFRP}}{E_{GFRP}} = \frac{150 \cdot 10^3}{23 \cdot 10^3} = 6.52 \tag{3}$$

where E_c is the modulus of elasticity of the concrete, E_{GFRP} for the GFRP and E_{CFRP} for the CFRP. F_{cc} is the compression strength of the concrete. With the transformed section and the parallel-axis theorem the moment of inertia for the beam can be calculated as:

$$I_{trans} = \alpha_c I_c + \alpha_{CFRP} I_{CFRP} + I_{GFRP} = 351 \cdot 10^6 \text{ mm}^4 \tag{4}$$

$$EI_{flex} = E_{GFRP} I_{trans} = 8.07 \cdot 10^{12} \text{ Nmm}^2 \tag{5}$$

The flexural displacement is calculated using traditional beam theory.

$$\delta_{flexure} = \frac{PL^2 a}{48 EI_{flex}} \left(3 - \frac{4a^2}{L^2} \right) \tag{6}$$

The displacement due to the web shear is given by, Fiberline Design Manual [15]:

$$\delta_{shear} = \frac{k_{\delta V} PL}{G_{GFRP} A_{web}} \tag{7}$$

Where $k_{\delta V}$ is a constant provided by the manufacturer, G_{GFRP} the shear modulus and A_{web} the cross-sectional area of the web.

The total theoretical mid-displacement is then derived from:

$$\delta_{theory} = \delta_{shear} + \delta_{flexure} \tag{8}$$

From equation (8) the mid-displacement can be calculated for different loads. Results from this are shown in table 4. To calculate the theoretical bending stiffness, EI_{theory}, with some rewriting revision equation (1) can be used:

$$EI_{theory} = \frac{PL^2 a}{48 \delta_{theory}} \left(3 - \frac{4a^2}{L^2} \right) \tag{9}$$

Using the values from table 4 gives $EI_{theory} = 4.2 \cdot 10^{12}$ Nmm^2 for Beam B and C.

Table 4 *Theoretical displacements*

Load (P) [kN]	δ_{shear} [mm]	$\delta_{flexure}$ [mm]	δ_{theory} [mm]
50	2.17	2.01	4.24
100	4.34	4.15	8.49
150	6.51	6.23	12.73
200	8.68	8.30	16.98
250	10.84	10.38	21.22

By assuming linear behaviour of the beams it is possible to calculate the stress distribution.

$$\sigma = \frac{M}{I_{trans}} e \tag{10}$$

With e as the value of the distance from the zero-strain level to the studied level of the beam the stress for that level can be calculated, using the transformed moment of inertia.

$$\sigma = \varepsilon E \Rightarrow \varepsilon = \frac{\sigma}{E} \tag{11}$$

Now the strain can be calculated using equation (11) with the values from equation (10). The distribution over the section for the load 100 kN is shown in figure 9, the theoretical values are calculated using the modulus of elasticity from the GFRP, since it was used for calculating the transformed moment of inertia, and the values from Beams B and C are measured from the tests. Linear behaviour is assumed.

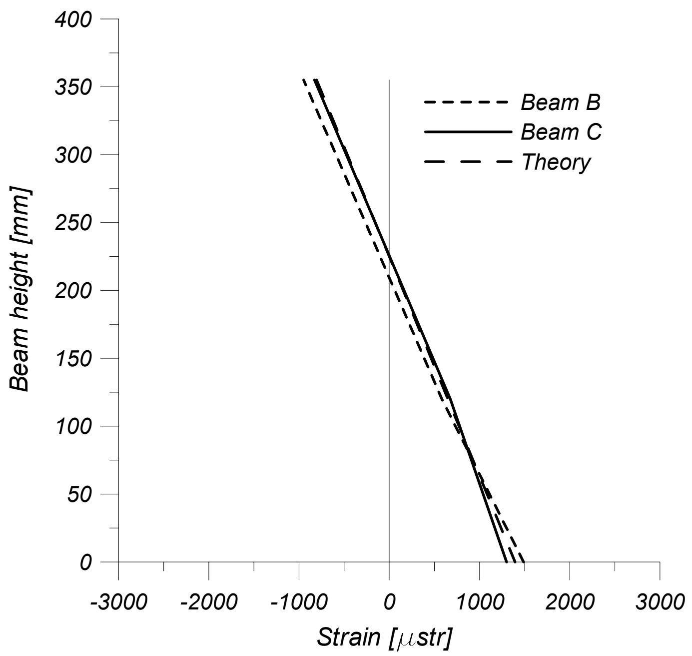


Figure 9 *Strain distribution at the load P=100kN, linear behaviour is assumed*

COMPARISON TESTS AND THEORY

The comparison from the tests and the theory are made on Beams B and C. In figure 10 the theoretical displacement is plotted together with the displacements from the tests on Beam B and C. The theory proves to be fairly correct compared to the tests although Beam C differs more than Beam B when studying mid-displacement. The initial behaviour of Beam B is not linear and depends most likely on movements in the connection zone between FRP and concrete.

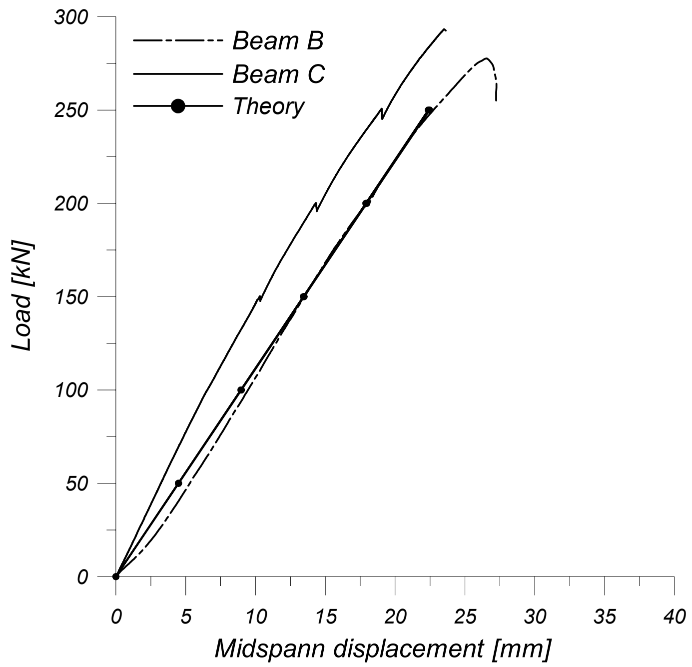


Figure 10 *Comparison between theory and tests for Beam B and C*

In figure 9 theoretical values calculated with equation (11) are plotted with the strain measured from the tests for Beam B and C. The theory fits the results from the tests very well.

When comparing the calculated bending stiffness *EI*, from equation 1 and equation 9, the theoretical values are fairly comparable to the tests, see figure 11. Here, as in the comparison of displacements, the theory is closer to Beam B than to Beam C.

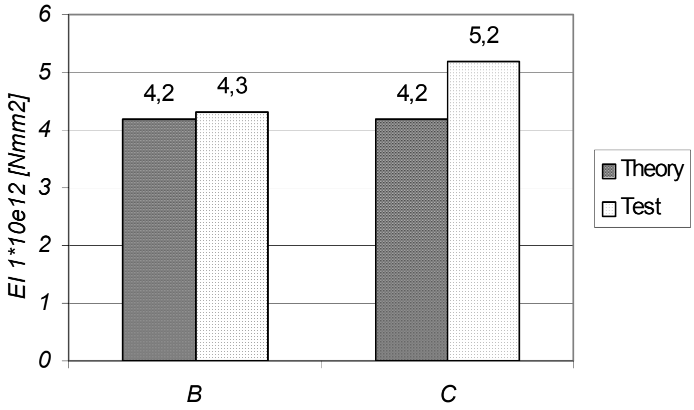


Figure 11 *Comparison of EI between theory and tests*

From these comparisons it can be concluded that the theoretical stiffness works well, although the stiffness calculated from the tests somewhat higher. This indicates that fairly simple analytical equations can used to calculate linear behaviour for the beams, however more tests should be done before too wide conclusions can be drawn from the linear theory used.

CONCLUSIONS

The tests presented in this paper show, in a short-time perspective, that a hybrid FRP-girder could be a promising load-carrying element. The low weight combined with high strength is an excellent alternative to traditional steel and concrete beams. It is, however, important to understand the materials and their strengths and weaknesses, for example the stability issue is of tremendous importance. The tests presented in this study, show that it is possible to manufacture a beam combining GFRP, CFRP and concrete for use in structures, i.e. hybrid beams.

The results from the tests show that it is possible to manufacture a FRP hybrid beam with concrete that can have excellent stiffness and be able to bear heavy loads. However, concrete is needed in the compressive zone to achieve sufficient stiffness.

If FRP I-beams are to be used efficiently, stiffeners have to be used. However, unlike steel it is not possible to weld these to the FRP, but epoxy bonding gives a good force transfer. A better alternative though would be to manufacture more optimal cross-sections, for example beams with double webs.

The steel dubs used worked well as a mechanical connection between the concrete and FRP. In production, traditional production techniques will therefore be possible. An advantage compared to steel and concrete beams would not only be better durability but also less weight, which will make the working procedure simpler and faster. The epoxy-bonded concrete connection worked somewhat better then the steel dubs in the laboratory. However, this technique would be more complicated since it would require extensive lifting of the pre-cast concrete on site. Here, using a FRP deck might be a solution to replacing the concrete.

The analytical theory used in the paper, based on linear behaviour, has proven to work well with the laboratory tests. To be able to predict the behaviour of the beam should therefore be fairly simple to calculate. It is however, important to take in consideration the different material properties that the FRP have in different directions.

Since there are many possibilities to manufacture different shapes for FRP beams it would be better to manufacture beams more adapted to the material properties of the FRP, and not be bound to the traditional shapes used for steel structures. By doing that it should be possible to avoid such weak spots as the flange-web intersection as occurred with the beams presented in this paper. With today's pultrusion technology, there are many possibilities for manufacturing tailor-made hybrid composite beams.

ACKNOWLEDGEMENTS

The authors would like to thank Jesper Lindgren for his part in accomplishing the tests. The authors acknowledge the financial support that has been provided by SKANSKA AB and The Development Fund of the Swedish Construction Industry (SBUF). Also Håkan Johansson and Georg Danielsson at Testlab, Luleå University of Technology shall be acknowledged for their help and support during these tests.

REFERENCES

1 Täljsten B., (1994), “Plate Bonding, Strengthening of Existing Concrete Structures with Epoxy Bonded Plates of Steel or Fibre reinforced Plastics” Doctoral Thesis 1994:152D, Div. of Structural Engineering, Luleå University of Technology, ISSN 0348 – 8373, 308 pp.

2 Täljsten B., (2002), “FRP Strengthening of Existing Concrete Structures – Design Guidelines”, Luleå University of Technology, Division of Structural Engineering, ISBN 91-89580-03-6, p 230

3 Teng J.G., Chen J.F., Smith S.T. and Lam L. (2001), “FRP Strengthened RC Structures” John Wiley & Sons, LTD, ISBN –0471-48706-6

4 Alampalli S., O´Connor J. and Yannotti A.P., (2002), “Fiber reinforced polymer composites for the superstructure of a short-span rural bridge”, Composite Structures 58, 2002 Elsevier Science Ltd, pp 21-27

5 Luke S., Canning L., Collins S., Knudsen E., Brown P., Täljsten B. and Olofsson I., (2002), “Advanced Composite Bridge Decking System - Project ASSET”, Structural Engineering International, Journal of the International Association for Bridge and Structural Engineering (IABSE), Vol. 12, Number 2, May 2002, pp 76-79

6 Mottram J.T. and Zheng Y. (1999) “Further tests of beam-to-column connections for pultruded frames: Flange-cleated”, Journal of composites for construction, August 1999, pp 108-116

7 Gan L. H., Ye L. and Mai Y.W. (1999), “Simulations of mechanical performance of pultruded I-beams with various flange-web conjunctions”, Composites Part B, 1999, Elsevier Science Ltd, pp 423-429

8 Qiao P., Davalos J.F. and Brown B., (2000), “A systematic analysis and design approach for single-span FRP deck/stringer bridges” Composites Part B 31, 2000 Elsevier Science Ltd, pp 593-609

9 Upadyay A. and Kalyanaraman V., (2003), “Simplified analysis of FRP box-girders” Composite Structures 59, 2003 Elsevier Science Ltd, pp 217-225

10 Riberio M.C.S., Tavares C.M.L., Ferreira A.J.M and Marques (2001) “Static flexural performance of GFRP-polymer concrete hybrid beams”, International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 1355-1362

11 Sekijama K., Ogisako E., Miyata K. and Hayashi K. (2001), “Analytical study on flexural behavior of GFRP-concrete composite beam”, International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 1059-1066

12 Deskovic N. and Triantafillou T. C. (1995), “Innovative design of FRP combined with concrete: Short term behavior”, Journal of Structural Engineering, July 1995, pp 1069-1078

13 Lindgren J. and Nordin H., (2000), “Samverkanskonstruktion av fiberkomposit och betong, en experimentell och teoretisk analys”, Master Thesis 2000:318 CIV, Div. of Structural Engineering, Luleå University of Technology, ISSN 1402-1617, 101 pp.

14 Täljsten B., (1997), “Replacement of stud connectors with epoxy adhesive in composite structures of steel and concrete”, FIP 97, The Concrete Way to Development, International Conference, South Africa, Johannesburg, March 1997, p 12.

15 Fiberline Design Manual (1995), ”Design Manual for Structural Profiles in Composite Materials”, Fiberline Composites A/S, Denmark

PAPER B

CONCRETE STRUCTURES STRENGTHENED WITH NEAR SURFACE MOUNTED REINFORCEMENT OF CFRP

Björn Täljsten[1,2], Anders Carolin[1] and Håkan Nordin[1]

[1] Division of Structural Engineering
Luleå University of Technology
97187 Luleå, Sweden

[2] Skanska Teknik AB
16983 Solna, Sweden

Published in Advances in Structural Engineering, International Journal

CONCRETE STRUCTURES STRENGTHENED WITH NEAR SURFACE MOUNTED REINFORCEMENT OF CFRP

Björn Täljsten, Anders Carolin and Håkan Nordin

ABSTRACT

The need of maintenance, repair and upgrading of concrete structures has increased considerably over the last decade and will most likely continue to do so. There can be several reasons for this, but it can often be attributed to normal change of use, increased demands on the structure, errors in the design and/or construction phase or in the worst case, accidents. Different methods have been developed over the years for solving different rehabilitation problems. Recently, advanced composites used for external bonding in the form of fabrics or laminates have become an accepted method. Several thousands of objects around the world have been upgraded with advanced composites bonded to its surface. In most cases, this method is very competitive regarding both structural behaviour and economy, but there are also some drawbacks. The surface bonded composite material is relatively sensitive to fire, accidents or vandalism. In addition, the pre-treatment is relatively intensive and time consuming. However, if the composite material is placed in slots in the concrete cover some of these drawbacks can be overcome. This paper presents work carried out on near surface mounted reinforcement (NSMR) at Luleå University of Technology in Sweden.

KEYWORDS

NSMR, CFRP, concrete, strengthening, epoxy, composite, pre-stressing

INTRODUCTION

Concrete is a building material with a high compressive strength and a poor tensile strength. A structure without any form of reinforcement will crack and fail when subjected to a relatively small load. The failure occurs in most cases suddenly and in a brittle manner. To increase a structure load carrying capacity and ductility it needs to be reinforced. This is mostly done by reinforcing with steel bars that are placed in the structure before the concrete is cast. Since a concrete structure usually has a very long life the demands on the structure will normally change over time. The structures may have to carry larger loads at a later date or meet new standards. In extreme cases, a structure may need to be repaired due to accidents. Another reason includes errors made during the design or construction phase so that the structure needs to be strengthened before it can be used. 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. For example, the deterioration of decks, superstructure elements and columns of bridges can be traced to reasons ranging from ageing and environmentally induced degradation to poor initial construction and lack of maintenance. 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.

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 may 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 paper, mainly strengthening is discussed.

Maintenance, repair and strengthening 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 to keep or increase a structure performance level through its life. This places a great demand on both consultants and contractors. There are difficulties in identifying the most suitable method for an actual subject; for example, two identical columns within the same structure can have totally different life spans depending on their individual microclimate. Because of this, it is important to analyse the problem thoroughly to be able to select the most suitable method. The choice of an inappropriate repair or strengthening method can even worsen the structure's function. In comparison to building a new structure, strengthening an existing one is often more complicated since the structural conditions are already set. In addition, it is not always easy to reach the areas that need to be strengthened, often there is also limited space. Traditional methods such as different kinds of reinforced overlays, shotcrete or post tensioned cables placed on the outside of the structure normally need much space.

In recent years the development of the plate bonding repair technique has been shown to be applicable to many existing strengthening problems in the building industry. 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 two-component epoxy adhesive. The old structure and the new bonded-on material create a new structural element that has a higher strength and stiffness than the original.

The basic ideas related to the use of FRPs (Fibre Reinforced Polymers) 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; Benmokrane and Rahman, 1998; keynote lectures (Maruyama, 1997; Neale and Labossiére, 1997) and journal articles (Täljsten, 1997, Thomas, 1998). There are also tests reported where NSMR rods were used (De Lorenzis et al, 2000, Blaschko, 2001, Rizkalla and Hassan, 2001 and Nanni, 2001). In spite of the research carried out no one has earlier reported tests on pre-stressed NSMR.

The most common way to strengthen structures has been for flexural strengthening and confinement but shear strengthening is also often needed. The most common method is 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 Near Surface Mounted Reinforcement (NSMR).

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 is placed in slots in the concrete cover or in additional concrete cover that is cast onto the structure (Asplund, 1949). Here steel bars are placed in slots in the concrete structure and then the slots are grouted. It has also been quite common to use steel bars, fastened to the outside of the structure, covered with shotcrete. However, in these applications it is often difficult to get a good bond to the original structure, and in some cases, it is 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 is still needed. For these applications, epoxy coated steel bars have also been used. However, it has been shown that over time, epoxy coated steel bars are not always corrosion resistant for various reasons that will not be discussed here. The use of steel NSMR cannot be said to have shown great success. Nevertheless, by using CFRP NSMR some of these drawbacks that steel NSMR possess can be overcome.

Firstly, CFRP NSMR does not corrode, so thick concrete covers are not needed. Secondly, the CFRP laminate can be tailor-made for near surface applications and moreover, the lightweight of the CFRP laminates makes them easy to mount. Finally, 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 slots in the concrete cover, with the depth depending on the product used and the depth of concrete cover.
- Careful cleaning of the slots after sawing using high-pressurised water, approximately; 100 - 150 bars is recommended. No saw mud is 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 generally 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.

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 energy required to remove NSMR is in many cases much larger than that for bonded laminates.

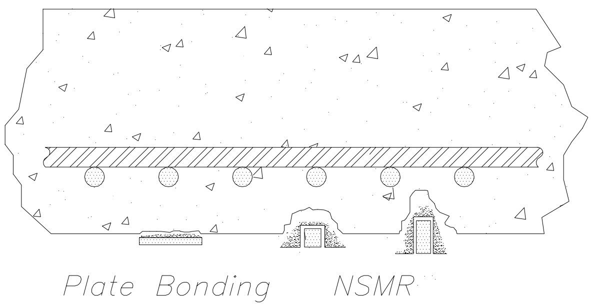


Figure 1 *Comparison between laminate Plate Bonding and NSMR*

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 and bending 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

Furthermore, NSMR resists end peeling much better than bonded laminates and is 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. Also, see (FIB Bulletin 14, 2001) and (Täljsten, 2002).

THEORY

Theory derived for the ultimate bending capacity of concrete beams strengthen with NSMR can be found in Täljsten (2000, 2002), Nordin et al. (2001), Täljsten and Carolin (2001) and so will only be described shortly here. However, in design for strengthening with NSMR the following assumptions are made:

- Bernoulli's hypothesis applies, i.e. linear strain across the cross-section varies rectilinearly. This implies that linear strain in the concrete, steel reinforcement and laminate that occurring at the same level is of the same size. Composite action applies between all the materials involved.
- Concrete stresses are obtained from the material's characteristic curve. Concrete compressive strain is limited to an approved failure strain of ε_{cu} = 3.5 ‰.
- For a cracked cross-section, the concrete's residual tensile strength is ignored.
- The stresses in tensile and compression steel reinforcement are taken from the reinforcement's characteristic curve corresponding to the total strain. The total strain may not be greater than the failure strain.
- The laminate stress is obtained from the characteristic curve of the material. The total strain in laminate may not exceed the failure strain.
- The laminate is assumed to be linearly elastic until breakage, i.e. Hooke's law applies.

In addition 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. In figure 2(b) 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. A calculation is then made to determine whether the concrete is uncracked. The studied section can be considered uncracked if the tensile capacity of the concrete is not exceeded. 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:

$$M = \frac{x - d_s^{'}}{h - x}\left(\varepsilon_{fu} + \varepsilon_{uo}\right) A_s^{'} E_s \left(0.4x - d_s^{'}\right) + A_s f_s \left(d_s - 0.4x\right) + \varepsilon_{fu} E_f A_f \left(h - 0.4x\right) \tag{1}$$

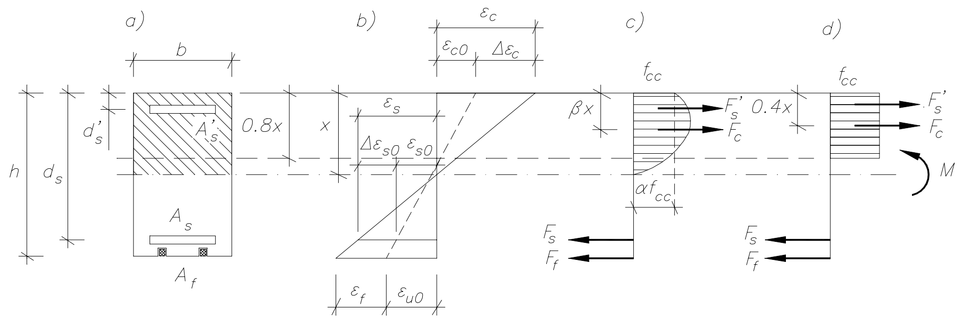


Figure 2 *Principles for strengthening in bending*

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

$$0.8 f_{cc} b x + \frac{x - d_s^{'}}{h - x}\left(\varepsilon_{fu} + \varepsilon_{u0}\right) A_s^{'} E_s = A_s f_s + \varepsilon_{fu} E_f A_f \tag{2}$$

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

$$C_1 x^2 + C_2 x + C_3 = 0 \tag{3}$$

where

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

If a pre-stressing force can be applied to the structure, the effect of 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 such there is a small tensile force at the top of the beam.

Anchorage is not covered here, however, it is shown by ongoing research at Luleå University of Technology that the anchorage is better for inserted CFRP compared to surface bonded CFRP reinforcement.

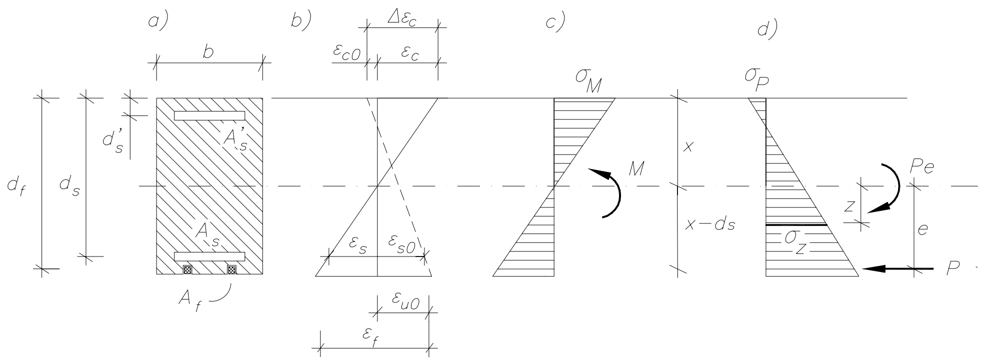


Figure 3 *Application of pre-stressing by using NSMR*

LABORATORY TESTS

Since 1996 several laboratory tests with NSMR have been carried out at Luleå University of Technology, Division of Structural Engineering. Here, two different test series will be presented, Series I and Series II. First, a test where epoxy bonded and grout bonded rectangular NSMR rods have been tested in four point bending. Second, tests with pre-stressing will briefly be discussed. A more thoroughly presentation of the tests can be found in Täljsten and Carolin (2001), and Carolin et al. (2001).

In the static four point bending test, Series I, four rectangular concrete beams were manufactured, three were strengthened and one served as a reference beam. The geometry and loading conditions are shown in Figure 4. Also the placement of the slots for Series I can be seen in Figure 4. The size of the slots for epoxy bonded rods is 15 x 15 mm and for the cement grout bonded rods 20 x 20 mm. The slots were sawed 55 mm from the side of the beam, and symmetrically placed. 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-span, settlement at the support and strains in the laminates. Crack distributions and widths were recorded at every 10 kN. The NSMR laminates were manufactured by vacuum infusion at SICOMP AB and measurements after tests showed a fibre content of 50 % in the laminates, which then give a Young´s modulus of 115 GPa. The corresponding strain at failure is 1.8 %. Both epoxy bond and cement grout bond NSMR 10 mm square rods were used. Before the grout bonded rods were placed in the pre sawn slots the surfaces was pre-treated by bonding quartz sand to them. The material data for the steel reinforcement, concrete and carbon fibre used can be found in Table 2. The adhesive used, BPE® Lim 465, had the following material properties; Young´s modulus, E_a = 7.0 GPa, compressive strength, f_{ca} = 103 MPa and tensile strength, f_{ta} = 31 MPa with a viscosity of 28 Pas. The mortar used, Bemix High Tech 305, had the following material properties;

compressive strength f_{cc} = 60 MPa after 28 days, d_{max} = 0.2, with a tixotropic consistency. Recommended application thickness is 0 - 5 mm.

Table 2 *Material data of Series I test beams*

	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	18.0

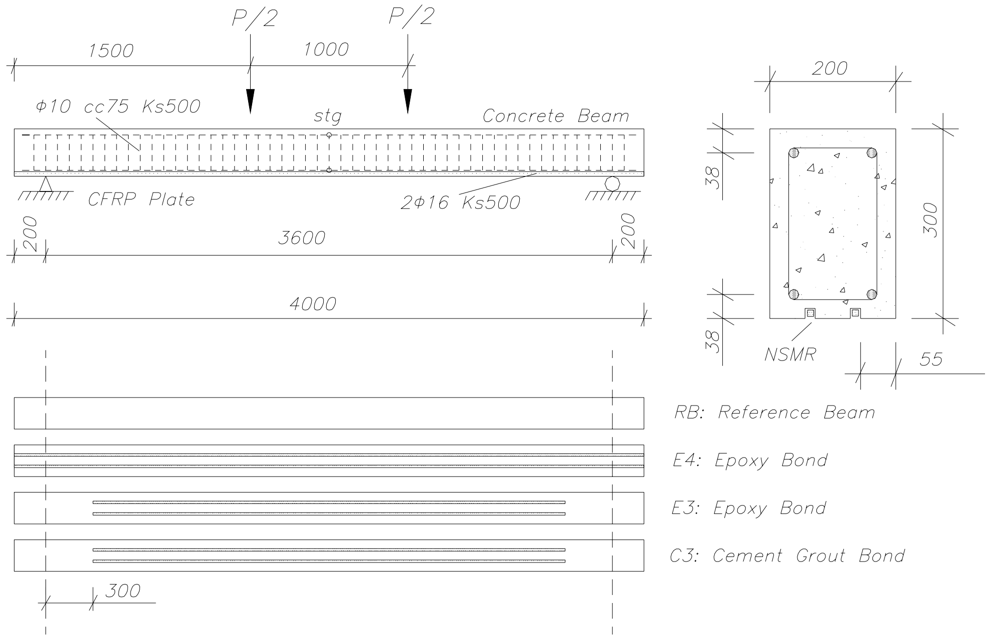


Figure 4 *Test set up and dimensions of the beams of Series I*

The load deflection curves from the tests are presented in Figure 5. The ultimate loads strains in the CFRP rods at mid-span and deflections are given in Table 3. In Figure 5 is a photo of Beam E3 during preparation also shown. It can clearly be noticed in Figure 5 that Beam E4, as expected, has the best failure envelope, where failure was by rupture of 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. In 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 but also suffered an anchorage failure. The anchor failures are not the same type of peeling-off failure noticed for laminate strengthen beams where a sudden and brittle failure often can be noticed. For Beam C3 and E3, the anchor failure was more to be defined as slippage between the rod and the concrete in the slot.

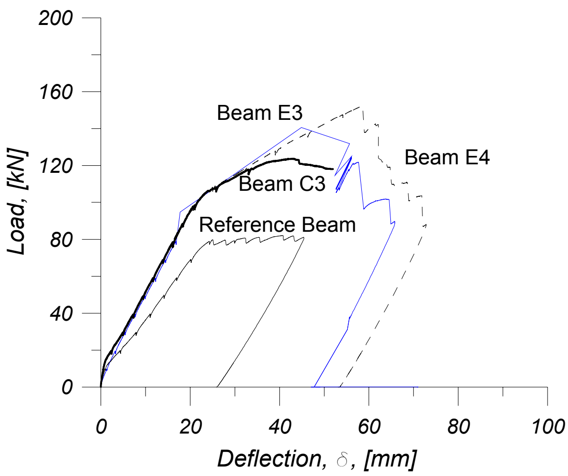
Table 3 *Results from Series I tests*

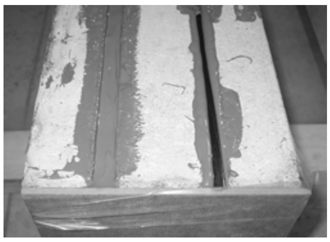
Beam	Ultimate load [kN]	Ultimate deflection [mm]	Strain at failure [%]
C3	123.5	43.0	0.74
E3	140.0	51.5	1.12
E4	152.0	58.5	1.15
Reference	79.0	24.0	---

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

Table 4 *Theoretical calculations compared with loads at failure for Series I tests*

Beam	Ultimate load [kN]	Calculated load [kN]	Ultimate/Calculated	Type of failure
C3	123.5	149.3	0.83	Anchorage
E3	140.0	167.7	0.83	Anchorage
E4	152.0	176.3	0.86	In rod
Reference	79.0	---	---	Steel yielding





10 mm square rods bonded in slots in the concrete cover

Figure 5 *Load- deflection curves for the tested beams of Series I and beam E4 during preparation*

It can be noticed in Table 4 that the theory overestimates the failure load. There can be numerous reasons for this. For Beams C3 and E4 where we had an anchorage failure, the theory described in this paper does not cover this. However, for beam E4, a higher failure load was expected, but it is possible that the strain was higher in the CFRP rod than the one measured by the strain gauges, for example concentrated at a nearby bending crack in the beam. Another more reason could be that the steel yield stress was higher than the one given by the manufacturer.

The next series of tests to be presented, Series II, are on beams strengthen with pre-stressed NSMR rectangular rods. In these tests, several problems were addressed during pre-stressing. Firstly, how to pre-stress the NSMR rods and up to what level? Secondly, how can sufficient anchorage length for the pre-stressed rod be ensured? Moreover, how much loss of pre-stress will occur when the pre-stressing equipment is disconnected? It was decided not to pre-stress higher than 20 % of the ultimate stress in these tests. There are two main reasons for this: in field applications it will most likely be impossible to anchor the NSMR rods for very high stresses; and the shear stresses at the concrete surface will probably be too high for the dimensions of the NSMR rods used. However, this will be investigated in additional tests. The pre-stressing was achieved with the beams on the floor, with the bottom facing up.

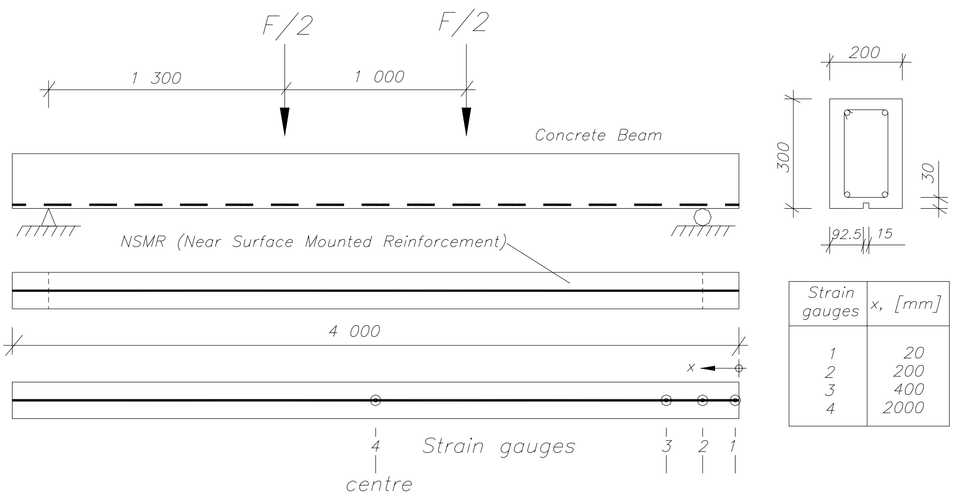


Figure 6 *Test set-up of beams of Series II*

The slots were cleaned by removing all contaminations such as dust and small particles and were then filled with a sufficient amount of adhesive. The rods were then positioned in the adhesive filled slots. Each of the rods had 5 strain gauges bonded to the outer surface, one just outside the end of the concrete beam, three within the last 400 mm of one end of the beam and one in the middle. The placement of the strain gauges are shown in Figure 6 together with the test set up and the dimensions of the beams. The rods were then subjected to a pre-stressing force until a strain of approximately 2000 micro strain was achieved, this corresponds approximately to a stress in the rod of 320 MPa. However, about 5 % of the pre-stress was lost due to problems with the equipment. The epoxy adhesive cured for 5 days before releasing the pre-stressing force, here an additional strain loss of 2 % was recorded in the centre of both beams, BP1 and BP2, see Table 5. The additional loss is most likely a combination of leakage in the hydraulic cylinder, shear deformation of the adhesive in the connection between the CFRP and concrete and strain loss in the CFRP. When the pre-stress was released the gauge closest to the end of the beam, approximately 20 mm from the end, showed more than 70 % strain loss for both BP1 and BP2. The rest of the gauges showed a loss of strain less then 5 % for both beams, which indicated that most of the pre-stress was transformed to the concrete beam as expected. There was no mechanical anchorage used in the test, the adhesive had to take all the shear stresses after curing. Figure 7 shows the test beams during pre-stressing and Figure 8 shows a schematic sketch of the anchorage detail used during pre-stressing.

Table 5 *Strains in the CFRP during pre-stress*

Beam	Initial strain [μstrain]	Strain after curing [μstrain]	Strain after release [μstrain]	Strain loss [%]
BP1 (Strain gauge 4)	1813	1802	1708	5.2
BP1 (Strain gauge 1)	1872	1849	533	71.2
BP2 (Strain gauge 4)	1887	1869	1816	2.8
BP2 (Strain gauge 1)	1951	1932	409	78.8

The purpose of the shape of the anchorage detail, shown in Figure 8, is that a more uniform pressure to the CFRP rod is achieved during pre-stressing. However, it was not possible to verify this through these tests.

Table 6 *Material data of Series II test beams*

Beam	f_{cc} [MPa]	f_{ct} [MPa]	E_f [GPa]	ε_{fu} [‰]	σ_f [MPa]
Reference	61	3.5	---	---	---
BNP	64	3.6	160	17.5	2 800
BP1	68	3.8	160	17.5	2 800
BP2	68	3.8	160	17.5	2 800

The material data of the concrete and CFRP rods are recorded in Table 6. The square 10 mm NSMR rods were delivered by BPE® Systems AB in Sweden and was manufactured by pultrusion, where the Young's modulus was 160 MPa and the strain at failure 1.75 %. For the steel reinforcement the characteristic value, quoted by the supplier, of the steel has been used, i.e. f_{ys} = 500 MPa and E_s = 205 GPa. The adhesive used is the same as for test Series I.

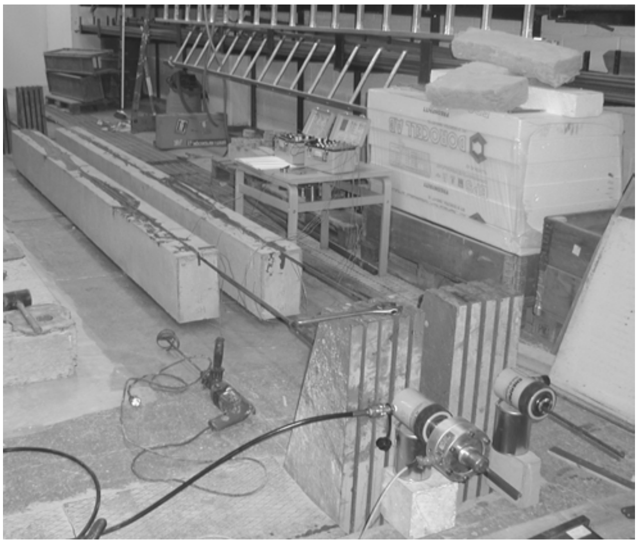


Figure 7 *Pre-stressing setup*

The beams were subjected to four-point loading as shown in Figure 6 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, one beam strengthened without pre-stress and two strengthened with pre-stress. The beams that were strengthened had a slot sawed underneath the beam with a cross section of 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.

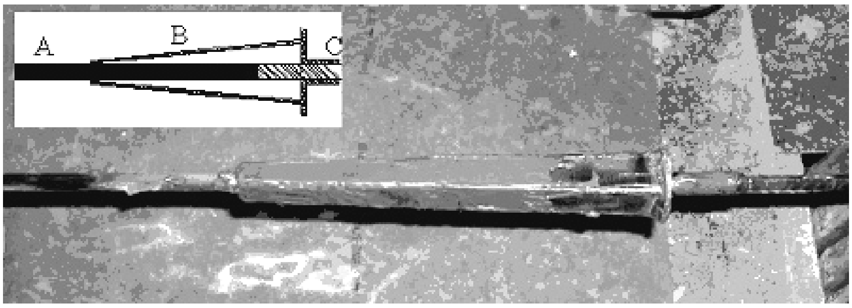


Figure 8 *Details of the connection between CFRP and steel during pre-stressing, A) CFRP rod, B) steel cone filled with adhesive, C) steel bar welded to the cone*

The load-deflection curves for the four beams are shown in Figure 9. All the strengthened beams had fibre fracture as the failure mode. The strengthening increased the ultimate load by almost 70 % compared with the reference beam. Beams BP1 and

BP2 had; a 37 % increase in load before the steel yielded compared with the unstressed beam BNP; and an increase in the cracking load of about 100 % compared with the reference beam; but the same ultimate load as BNP.

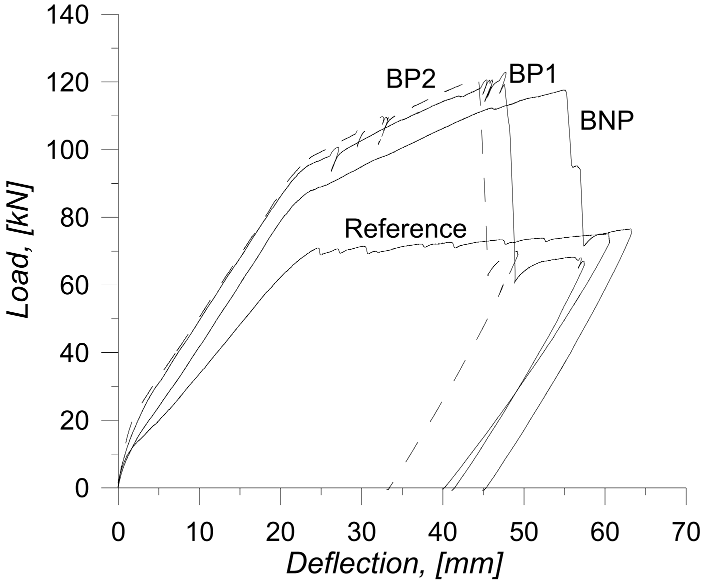


Figure 9 *Results from Series II tests*

Studying Figure 9 shows that the stiffness of the beam was about the same for the non-pre-stressed and the pre-stressed beams but the pre-stress helped in delaying concrete cracking and yielding of the steel reinforcement. It can also be noticed that the non-pre-stressed beam BNP had a larger deflection than the pre-stressed beams BP1 and BP2. In Table 7 the first crack, steel yielding and ultimate load together with the maximum deflection are shown. All strengthened beams failed by fibre failure in the NSMR rod.

Table 7 *Loads and deflections from Series II tests*

Beam	First crack [kN]	Steel yielding [kN]	Ultimate load [kN]	Ultimate deflection [mm]
Reference	10	71	75	60
BNP	16	84	118	55
BP1	19	96	121	46
BP2	21	99	121	44

The increase in load for steel yielding can be very important during the life of the member, the fatigue behaviour will improve and the crack widths will be smaller which will result in increased durability.

Further tests will include different amounts of pre-stressing and a comprehensive theoretical investigation on the technique. Furthermore, efforts will also be focused on the development of methods to apply the technique in the field. No mechanical anchorage was used in the tests and a loss of strain in the end zones was measured, in the field, mechanical anchors would most probably be used.

It must be realised that the study is limited and too many conclusions can not be drawn from the results. However, the tests performed show the promising results worthy of future research. The next step will be an extended test series with NSMR rods of different stiffness, different levels of pre-stressing and a special focus on the end anchorage problem. In these tests, more extensive measurements will be taken.

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 in-situ cast concrete was not sufficient and strengthening was demanded. The reason for choosing NSMR for this application was the resistance to corrosion of CFRP laminates and comparable stiffness and strength to that of 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 of 1.6 %. Furthermore, the main advantage of the NSMR was that the laminates could be placed in the concrete cover and that no great work effort was needed. 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 determined to be very likely. Another concern was the wearing surface, in form of warm asphalt, that was going to be applied.

10a) Slots in front of the worker holding an NSMR laminate

10b) Bonding the NSMR laminates in the cleaned and dry slots

10c) Results after bonding but before sealant and asphalt

Figure 10 *Strengthening of a concrete joint with NSMR.*

First the slots (40 x 8 mm) were sawn 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 10a, the laminates and the slots in the concrete cover can be seen prior to bonding. In Figure 10b the laminates are bonded in the slot and Figure 10c shows the result after strengthening but before the surface is asphalted.

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 has just been 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 at 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 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 finally a full-scale application to strengthen a road bridge for the Swedish Road Authorities will be carried out.

CONCLUSIONS

There is no doubt that strengthening concrete structures with NSMR is an effective method.

The tests presented in this paper show promising strengthening results and a considerable strengthening effect could be noticed. Pre-stressing increased the steel yielding load and delayed concrete cracking. The 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

The authors acknowledge the financial support that has been provided by Skanska AB, SBUF (The Development Fund of the Swedish Construction Industry) and BPE® Systems AB. Also Georg Danielsson and Håkan Johansson at Testlab, Luleå University of Technology are acknowledged for their help and support with the testing.

REFERENCES

Asplund, S.O. (1949), "*Strengthening Bridge Slabs with Grouted Reinforcement*", Journal of the American Concrete Institute, Vol. 20, No. 6, January, pp. 397-406

Blaschko, M. A. (2001), *"Zum Tragverhalten von Beetonbauteilen mit in Schlitze eingeklbten CFK-Lamellen"*, Doctoral Thesis ISSN 0941-925X, pp 150 (In German).

De Lorenzis, L., Nanni, A. and La Tegola, A. (2000). "*Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods*" Advanced Composite Materials in Bridges and Structures, Proc. of 3rd Int. Conf., Ed. Humar, J.L. and Razaqpur, A.G. Ottowa, ISBN: 0-7709-0447-5, pp. 521-528.

Benmokrane B. And Rahman H. Eds., 1998, "*Durability of fibre reinforced polymer (FRP) composites for construction"*, Department of Civil Engineering, Université de Sherbrooke, 1998.

Carolin, A., Nordin, H. and Täljsten, B. (2001): *"Concrete beams strengthened with near surface mounted reinforcement of CFRP"* International Conference on FRP Composites in Civil Engineering, Volume 2, J.-G. Teng (Ed). ISBN: 0-08-043945-4 pp 1059-1066

FIB, 2001, Bulletin 14, *Externally bonded FRP reinforcement for RC structures*, Technical Report, Task Group 9.3 FRP (Fibre Reinforced Polymer) reinforcement for concrete structures, ISBN 2-+88394-054-1, p 130, July 2001.

Maruyama K., 1997, "*JCI activities on continuous fibre reinforced concrete, Non-Metallic (FRP) Reinforcement for Concrete Structures"*, Japan Concrete Institute, pp 3-12, 1997.

Meier U. And Betti R. Eds., 1997, "*Recent advances in bridge engineering – Advanced Rehabilitation, durable materials, non-destructive evaluation and management"*. EMPA Switzerland.

Nanni A., (2001), *"North american design guidelines for concrete reinfrocement and strengthening using FRP: Principles, applications and unresolved issues"*, International Conference of FRP Composites in Civil Engineering, Volume 1, J-G. Teng (Ed.), ISBN 0-08-043945-4, pp 61-72.

Neale KW. And Labossiére P., (1997), *"State-of-the-art report on retrofitting and strengthening by continuous fibre in Canada"*, Non-Metallic (FRP) Reinforcement for Concrete Structures, Japan Concrete Institute, pp 25-39.

Nordin, H., Täljsten, B. and Carolin, A., (2001), *"Concrete beams strengthened with prestressed near surface mounted reinforcement (NSMR)"* International Conference on FRP Composites in Civil Engineering Volume 2, J.-G. Teng (Ed). ISBN: 0-08-043945-4, (2001), pp 1067-1075.

Rizkalla S. and Hassan T. (2001), *"Various FRP strengthening techniques for retrofitting concrete structures"*, International Conference on FRP Composites in Civil Engineering, Volume 2, J-G Teng (Ed.), ISBN 0-08-043945, pp 1033-1040.

Thomas J., (1998), "*FRP strengthening – Experimental or mainstream technology?",* Concrete International, ACI, pp57-58.

Triantafillou T. C., (1998), "*Shear Strengthening of Reinforced Concrete Beams Using Epoxy-Bonded FRP Composites*," ACI Structural Journal, Vol. 95, No. 2, March-April, pp 107-115.

Täljsten B., (1997), "*Strengthening of Beams by Plate Bonding",* Journal of Materials in Civil Engineering, November, pp. 206-212.

Täljsten, B. (2000): *"Förstärkning av befintliga betongkonstruktioner med kolfiberväv eller kolfiberlaminat – Dimensionering, material och utförande"* In Swedish. Technical report. Luleå University of Technology, Division of structural engineering, 119 pp

Täljsten, B. and Carolin, A. (2001): *"CFRP - Strengthening. Concrete Beams Strengthened with Near Surface Mounted CFRP Laminates"* Fibre reinforced plastics for reinforced concrete structures, FRPRCS-5, Cambridge (Edited by Chris Burgoyne), pp 107-116.

Täljsten, B. (2002): *"FRP Strengthening of Existing Concrete Structures - Design Guidelines".* Luleå University of Technology, Division of structural engineering, ISBN 91-89580-03-6, p230.

NOTATIONS

A_f	cross-sectional area of FRP	[m^2]
A_s	area of tensile steel reinforcement	[m^2]
A_s'	area of compression steel reinforcement	[m^2]
C_1	constant	[N/m]
C_2	constant	[N]
C_3	constant	[Nm]
E_a	modulus of elasticity of adhesive	[Pa]
E_f	modulus of elasticity of FRP	[Pa]
E_s	modulus of elasticity of steel	[Pa]
F_C	normal force, concrete	[N]
F_f	normal force, FRP	[N]
F_S	normal force, tensile steel	[N]
F_s'	normal force, compressive steel	[N]
M	bending moment	[Nm]
b	width	[m]
d_f	effective height to FRP	[m]
d_{max}	maximum aggregate size for grout	[mm]
d_s	effective height to tensile reinforcement	[m]
d_s'	effective height to compression reinforcement	[m]
f_{cc}	compressive strength, concrete, grout	[Pa]
f_{ca}	compressive strength, adhesive	[Pa]
f_{ct}	splitting strength, adhesive	[Pa]
f_{cu}	failure stress, FRP	[Pa]
f_s	yield stress in tensile reinforcement	[Pa]
f_s'	yield stress in compression reinforcement	[Pa]
f_{ta}	tensile strength, adhesive	[Pa]
h	height	[m]
x	inner lever arm	[m]
ε_c	strain in concrete	[--]
ε_{c0}	compressive strain, unconfined concrete	[--]
$\Delta\varepsilon_c$	additional strain in concrete	[--]
ε_{c0}	compressive strain in concrete, upper side, remaining strain	[--]
ε_{cu}	compressive strain in concrete, upper side, ultimate strain	[--]
ε_f	strain of FRP	[--]
ε_{fu}	failure strain of FRP	[--]
ε_s	strain of tensile steel reinforcement	[--]
ε_{s0}	strain of ensile steel reinforcement, remaining load	[--]

$\Delta\varepsilon_{s0}$	additional strain in tensile steel reinforcement	[--]
ε_{u0}	strain in underside concrete, remaining load	[--]
σ_f	Tensile strength of FRP	[Pa]
σ_M	normal stress due to bending moment	[Pa]
σ_P	normal stress in concrete	[Pa]

PAPER C

CONCRETE BEAMS STRENGTHENED WITH PRESTRESSED NEAR SURFACE MOUNTED CFRP

Håkan Nordin[1] and Björn Täljsten[1,2]

[1] Division of Structural Engineering
Luleå University of Technology
97187 Luleå, Sweden

[2] Skanska Teknik AB
16983 Solna, Sweden

To be submitted

CONCRETE BEAMS STRENGTHENED WITH PRESTRESSED NEAR SURFACE MOUNTED CFRP

Håkan Nordin and Björn Täljsten

ABSTRACT

Strengthening concrete structures with fibre reinforced polymer materials have grown to be a widely used method over most parts of the world today. As a way of higher utilization of the FRP (Fibre Reinforced Polymers) prestressing of the FRP could be an interesting path to follow. Most of the research done with prestressing Carbon Fibre Reinforced Polymers (CFRP) for strengthening has been with surface bonded laminates. However, in this paper prestressed CFRP quadratic rods are placed in the concrete cover in sawed grooves. This have proven to be an advantageous way of bonding CFRP to the concrete, and will also transfer the shear forces between the CFRP and the concrete more efficient, compared to surface bonded laminates. No mechanical device has been used to keep the prestress during testing, which then means that the adhesive has to transfer all shear stresses to the concrete. Tests show that the prestressed beams exhibit a higher first crack-load as well as a higher steel-yielding load compared to non-prestressed strengthened beams. The ultimate load at failure is also higher, compared to non-prestressed beams, but in relation not as large as for the cracking and yielding. All strengthened beams failed with fibre rupture.

KEYWORDS

NSMR, NSM, prestress, FRP, 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 probably 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 replacement 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 may 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 Fibre Reinforced Polymers (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 (Meier, 1995).

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 (Täljsten, 1994). The laboratory tests have included strengthening for bending as well as for shear (Täljsten, 2003a) and torsion (Täljsten, 1998). Full-scale tests on strengthened bridges have also been performed (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; in addition the theory of fracture mechanics introducing non-linear behaviour in the bond has also been investigated, (Täljsten, 1994, 1996, 1997).

In Sweden FRP strengthening have been used in the field for almost 10 years now and both laminates and wrap systems have been and are used. Sweden is also one of the countries where a national code exists for FRP strengthening (Täljsten, 2003b).

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. Flexural strengthening with unstressed laminates has been the most common way to increase the load-bearing capacity of a concrete structure, while in comparison only limited research has been undertaken for beams strengthened in bending with prestressed laminates.

STRENGTHENING WITH PRESTRESSED CFRP

There are four main advantages to prestress the CFRP strengthening material.

- Better utilisation of the strengthening material
- Decreased crack size and mean crack distance
- Unloading of the steel reinforcement
- Higher steel yielding loads

In the service limit state decreased crack size will be very beneficial for a concrete structure. Smaller crack sizes and distance between the cracks will most likely increase the durability as well as the stiffness of the structure. The largest advantage with prestressing the strengthening material is probably the increased steel-yielding load. Studies has shown almost 50% increase in steel yielding compared to unstrengthen structures and up to 25% compared to not prestressed strengthened structures (Wight et al 1995; Nordin et al 2001).

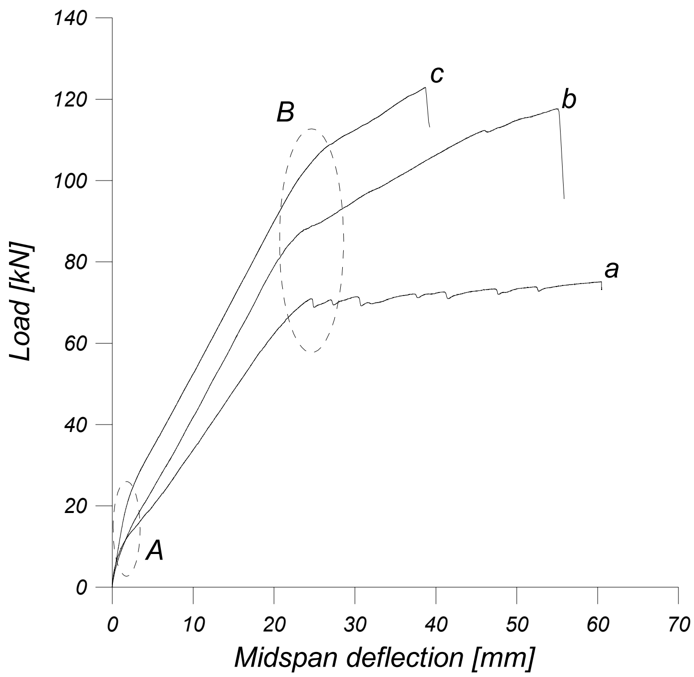


Figure 1 *Beams strengthened with CFRP, (a) not strengthened, (b) strengthened without prestress and (c) strengthened with prestress*

Figure 1 shows the typical behaviour of beams loaded with four-point bending. The values are from one study (Nordin et al 2001) but other studies show the same behaviour (El-Hacha et al 2001a; Wight et al 1995). The figure shows three important stages, concrete cracking, steel yielding and the ultimate load at failure. A non-prestressed strengthened beam has about the same cracking load as a non-strengthened beam, where the beam with prestressed strengthened FRP has about twice the load depending on the prestress. For steel yielding the strengthening effect is almost double for prestressed strengthening compared to not prestress (Wight et al 1995), this effect is of course also dependent on the level of prestress applied.

When strengthening with non-prestressed CFRP it is often the strain in the steel reinforcements or the compressive stress in the concrete that are the limiting factors. Even if the strengthening material carries larger parts of the load, the steel reinforcement may yield or the concrete may be crushed. This also imply a low utilisation of the FRP laminate, NSMR or sheet used. A low utilisation of the CFRP product implies higher costs for the client. It would therefore in many situations be beneficial if the structure could be unloaded before strengthening. This is not always possible, however, if the CFRP material can be prestressed the stress on the steel and the concrete will be decreased, which gives better utilizations of the FRP material and in addition lower deflections of the structure.

In Figure 2 a theoretical stress and strain distribution for a concrete beam with prestress, but without external loads, is shown. In Figure 2b is the strain distribution of a strengthened beam without prestressed FRP (continuous line) and with prestressed FRP (dotted line). Shown in Figure 2c is the stress distribution for a beam strengthened without prestress and in Figure 2d a beam with prestressed FRP is shown.

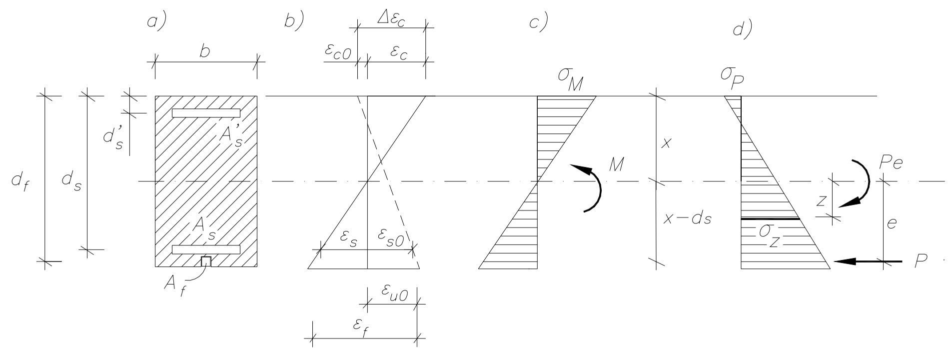


Figure 2 *The theoretical stress distribution, c) is without prestress and d) is with prestress, Nordin et al (2001)*

When prestressing for strengthening purposes there is also a reduction of crack widths. Research in the area of strengthening with prestressed FRP has mainly been carried out with FRP plates, such as failure modes (Garden and Hollaway 1998), short-time behaviour of prestressed FRP (Triantafillou and Deskovic 1991; Triantafillou et al. 1992), flexural rehabilitation (Quantrill and Hollaway 1998), prestressing system (El-

Hacha et al 2003) etc. Tests have been carried out tests on concrete beams prestressed with CFRP sheets at room and low temperatures (El-Hacha et al. 2001b). EMPA in Switzerland has also done research in the area of prestressed laminates (Meier, 2001). The results from these tests show a significant increase in flexural stiffness and ultimate capacity compared to unstrengthened control beams. They also point out that the flexural behaviour of the strengthened beams is not adversely affected by reduced temperature (-28 ºC), and prestressed CFRP sheets could be used to increase and restore the original strength of damaged concrete beams under extreme environmental conditions. Tests reported on severely damaged concrete slabs strengthened with CFRP shows that both higher load capacities and reduced deflections could be achieved with prestressed CFRP sheets in comparison with non-prestressed sheets (Wight and Erki 2001a). A prestressed 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 then prevent initialising failures 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 prestressing 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).

Anchoring of the end zones has been one of the biggest problems when concrete structures are strengthened with prestressed FRP sheets. It have been necessary to mechanically anchor the strips at the ends to prevent peeling failures. Different techniques using bolted metal plates have been tested as well as decreased thickness of the FRP at the ends to lower the stresses in the concrete-FRP interface. The results have proven efficient. Multi-layer application of FRP has been tested to achieve a different prestressing profile on the concrete beam (Wight et al 2001).

PRESTRESSING WITH NSMR

The idea of Near Surface Mounted Reinforcement is to insert the added reinforcement into sawed grooves in the concrete cover. The idea of placing reinforcement in the concrete cover for strengthening is not new. The first application was made in northern Sweden in 1940's where a bridge slab had to be strengthened in the negative moment zone (Asplund 1949). Steel bars where placed in the concrete cover and bonded with a cement grout. Before the actual strengthening was carried out, four test slabs were loaded until failure, strengthened with the same technique. The results proved that the method could work and by March 1948 more then 600 meters of steel bars were bonded in the concrete cover. However, in these applications it is often difficult to get a good bond to the original structure, and in some cases, it is not always easy to cast the concrete around the whole steel reinforcing bars.

Researchers have tested NSMR with CFRP circular rods, (De Lorenzis et al 2000 and Hassan and Rizkalla 2001). A pilot study with rectangular rods has earlier been undertaken at Luleå University of Technology with the first tests done in 1996 (Täljsten and Carolin 2001). The sawing of grooves is only possible on structures with enough "depth" to the steel reinforcement. One should remember that the thickness of the concrete cover is depending of the workmanship when the structure was built rather then the code that design was based upon. Anyhow, it is easy to believe that the method is more suitable for outdoor structures such as bridges then indoor structures with normally less concrete cover.

Opposite to external strengthening techniques the use of NSMR will, in a better way, protect the strengthening material from external damage such as vehicle impact. Another advantage is that the concrete surface will not be completely covered as in some cases with CFRP wraps, which can lead to built-in moisture in the structure with possible freeze-thaw problems in the future. In Figure 3 are the principles for NSMR shown. It can be noticed in Figure 3 that it is possible to achieve increased bond surface with NSMR compared to traditional laminate plate bonding since more energy is needed to introduce failure in the concrete. This assumes sufficient bond between the CFRP and the concrete, which is mostly dependent on workmanship during strengthening but also on the quality of the constituents.

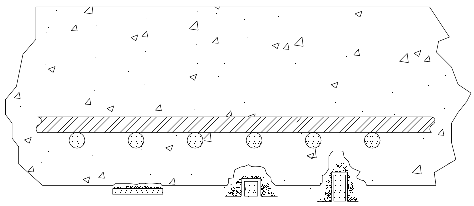


Figure 3 *Schematic sketch of NSMR*

The insertion of the reinforcement should vouch for a more efficient force transfer between the concrete and the composite. The bonded area will change and be dependent of the geometry of the inserted reinforcement. If the rods are placed too close to each other, the failure may occur from interaction between the two rods and maybe also by interaction from the existing steel reinforcement. Even though no creep in the bond zone between the NSMR rod and the concrete has been noticed during laboratory tests, creep can be anticipated over long time and in field conditions. Therefore is it most likely necessary to use mechanical anchorage devices at the end of the rods.

Full-scale tests and field applications have shown that the pre-treatment when using plate bonding can be work intense and therefore often expensive. In traditional plate bonding the concrete laitance layer must be removed and the aggregates must be exposed before adhesive and the composite can be applied, this to ensure good bond between the composite and the concrete. In the most cases this may be done by sandblasting and is neither complicated nor expensive. However, if the surface has irregularities, from formwork for instance, or if the sand blasting has a small or negligible effect then the surface needs grinding or a more powerful surface treatment. Whichever method chosen, the work will be time consuming and costly.

When placing the strengthening material in pre-sawed slots in the concrete cover no surface treatments are needed, except cleaning with medium pressurised water, approximately 150 bars, immediately after sawing. In addition, if a stiff "rail" is used as support for the saw then the grooves will become straight and are possible to make also on rough surfaces. This is probably also a more advantageous method for the workers to do the pre-treatment compared to grinding, at least from a work environmental point of view.

Another issue regarding execution is the use of thermosetting polymers as epoxy. Epoxy, if it is handled in a wrong way, may be allergenic and harmful. Therefore the possibilities to replace the epoxy by cement grout would be preferable. This will also give possibilities to use NSMR under conditions with high humidity and even in submerged conditions. Another possible way to carry out the bonding works is to use injection or infusion techniques (Täljsten and Elfgren 2000).

Probably, the biggest advantage of NSMR can be found in increased force transfer compared to laminates, but also increased durability and impact resistance are advantages with the technique. Traffic running underneath a bridge with low clearance may, sooner or later, result in damages on the bridge. For a concrete bridge this is not critical but can cause severe damages to an unprotected and badly designed reinforcement, for example traditional plate bonding as well as external post tensioning can be sensitive for vehicle impact.

In addition fire, vandalism and environmental loads may also harm the composite. A damage of the reinforcement can give severe problems and eventually failure of the structure. With NSMR the fragile composite will be more protected from outer damage then traditional plate bonding and external post tensioning systems.

LABORATORY SET-UP

In this study a total of 15 full-size concrete beams have been tested. The beams tested were four meters long and with a cross-section of 200x300 mm. The longitudinal steel reinforcement was 2 Ø16 Ks 500 at the upper and lower part of the beam. The steel stirrups was placed at a spacing of 75 mm and consisted of Ø10 steel bars with the same steel quality as for the longitudinal steel. A 15x15 mm groove was sawn up in the concrete cover in the bottom of the beams see Figure 4. One beam was a reference that was not strengthened, four beams were strengthened without prestressing and the remaining 10 were strengthened with prestressed quadratic CFRP rods. During the tests three variables were changed for the NSMR rods; bond length, modulus of elasticity and the prestressing force.

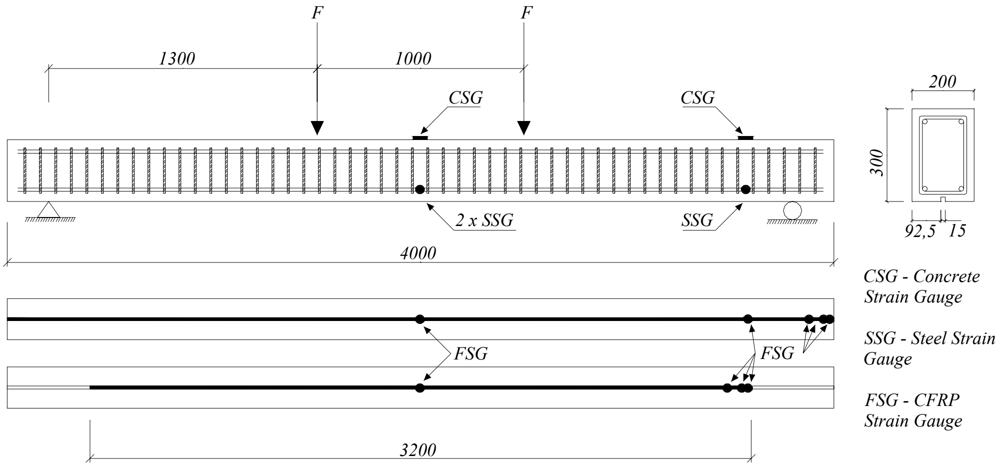


Figure 4 *Beam Set-up*

Two bond lengths were tested, 3200 mm and 4000 mm, in most field applications it is not possible to place the CFRP rod over the whole beam length due to the supports and therefore a 3200 mm rod that not goes beyond the supports was tested. An other aspect is that with four meter rods going beyond the supports a pressure from the supports might beneficial affect the anchorage at the end of the beams.

Two types of NSMR quadratic rods was used; BPE® NMSR 101S and BPE® NMSR 101M. The S rod has a modulus of elasticity of 160 GPa and the M rod 250 GPa. The cross-section for both types of rods used is 10x10 mm. In Table 1 the material data for the rods are recorded.

Table 1 *Data of the CFRP used*

	E_f [GPa]	ε_{fu} [‰]	f_f [MPa]
BPE® NMSR 101S	160	17.5	2800
BPE® NMSR 101M	250	8	2000

In the tests two levels of prestressing force were aimed to be used, 32 kN and 56 kN, those loads corresponding a stress in the rods of 320 MPa and 560 MPa respectively.

In Table 2 the different types of beams tested can be seen. In the table S and M are the two qualities of CFRP rod and P stands for prestressed. The concrete used had an average compressive strength f_{cc} = 65 MPa and an average tensile strength f_{ct} = 3.7 MPa, for each beam three tests were made for both compressive and tensile strength.

During the tests the midpoint displacement, the strain in the CFRP (four gauges), tensile steel reinforcement (three gauges) and the upper part of the concrete (two gauges) was measured. The placement of the gauges is shown in Figure 4.

Table 2 *Beams tested*

Beam	CFRP		Prestress	
	Length [mm]	E [GPa]	Load [kN]	Strain [μstr]
Ref	–	–	–	–
BS1	3200	160	–	–
BS2	4000	160	–	–
BM1	3200	250	–	–
BM2	4000	250	–	–
BPS1 (Pilot 1)	4000	160	29	1800
BPS2 (Pilot 2)	4000	160	30	1870
BPS3	3200	160	33	2060
BPS4	4000	160	34,5	2160
BPS5	3200	160	56	3500
BPS6	4000	160	56	3500
BPM1	3200	250	32	1280
BPM2	4000	250	32	1280
BPM3	3200	250	53,5	2140
BPM4	4000	250	38	1500

The adhesive thickness for all the tests was measured to 2.5 mm on the three bonded sides. In all the tests BPE® Lim 465/464 epoxy adhesive was used. The properties for the adhesive are recorded in Table 3.

Table 3 *Material properties of the epoxy adhesive*

	f_{ac} [MPa]	f_{at} [MPa]	E_a [GPa]	Viscosity
BPE® Lim 465/464	103	31	7	Tix

PRESTRESSING

The prestressing was made with the beams placed on the floor with the bottom face up. The pre-sawed slots were cleaned from all contaminations such as dust and small particles and were filled with sufficiently amount of adhesive at time for bonding/prestressing. The rods were then positioned in the adhesive filled slots. The quadratic rods were then subjected to a prestressing force until the sufficient strain was reached. The epoxy adhesive was then left to cure for 5 days in ambient conditions (19ºC and 50% RH) before releasing the prestressing force. There was no mechanical anchorage used and consequently at releasing the prestress the adhesive had to transfer all the shear stress in to the concrete. In Figure 5 the beams during prestressing are shown.

Figure 5 *Prestressing set-up*

After releasing the prestressing force a compressive force is then introduced to the lower part of the beam and a tensile force to the upper part. At the end of the rods (bonded area) the prestressing force was to a large extent lost during releasing. However the strain loss decreased greatly over the first 100 mm from the end and at a distance of less then 200 mm from the end the strain loss was no higher then 20 % and the loss was decreasing to the centre of the beam. At the centre the strain loss was between 5 to 15 %, see also Table 4 for more detailed information. To be able to keep the strain in the ends a mechanical device will probably be necessary to use and this topic will be studied more in the near future, but are not discussed further in this paper.

One aspect of the strain loss at the ends is that for the beams with four meter rods the area of large strain loss are outside the supports which means that between the supports the strain loss relatively small, this may have a direct influence on the positive contribution for the shear force capacity due to prestressing. However, for these bending tests this will not have any significant impact on the results in bending since the strain is kept in the area where we have the highest bending moment.

Table 4 *The tensile strain on the CFRP, at the middle and the end, before and after release of prestress force*

Beam	Middle			End		
	Initial [μstr]	After [μstr]	Loss [%]	Initial [μstr]	After [μstr]	Loss [%]
BPS1 (Pilot 1)	1802	1708	5.2	1849	533	71.2
BPS2 (Pilot 2)	1869	1816	2.8	1932	409	78.8
BPS3	2095	2003	4,4	2075	1153	44,4
BPS4	2189	2101	4,0	2146	180	91,6
BPS5	3386	3273	3,3	3350	353	89,0
BPS6	3496	3166	9,4	3478	2249	35,3
BPM1	1234	1180	4,4	1166	402	65,5
BPM2	1261	1184	6,1	1350	108	92,0
BPM3	2060	1761	14,5	1960	13	99,3
BPM4	1481	1368	7,6	1529	0	100,0

When studying Table 4 it can be seen that there is no difference in loss between the rods with different modulus of elasticity, the percentage loss is about the same for both. However, the same strain means different stress loss. At the ends, where the strain loss is largest, there is a wide variety of strain loss. This is most likely due to variable quality of the workmanship. Since the ends are most affected to strain loss mistakes in the workmanship will be most apparent here.

For beam BPS6 tensile cracks in the concrete on the upper part of the beam, opposite from the rod, arose during prestressing. This did not happen for any other beam in the tests, it is possible that small cracks existed before the prestressing operation started and that the prestressing force just opened up those cracks.

LOADING

The accomplished test series show interesting and promising results. All beams were tested with four-point bending as shown in Figure 4. The loading was deformation controlled to 0.02 mm/s. The tests were aborted after failure and the beam was unloaded.

In Table 5 the significant loads with midpoint displacement are presented (cracking, yielding of steel reinforcement and ultimate loads). The results show that both an increased cracking load and steel-yielding load can be achieved by strengthening with prestressed CFRP rods in the concrete cover of a beam.

If Figure 6 is studied it can be noticed the stiffness of the beams were about the same for non-prestressed and prestressed strengthened beams but the prestress force has helped in delaying concrete cracking and yielding of the steel reinforcement. It can also be noticed that the non-prestressed beam, NP, had a larger deflection than the prestressed beams. All strengthened beams failed by fibre failure in the quadratic NSMR rod.

Table 5 *The significant values for loads and midpoint displacement*

Beam	Cracking		Yielding		Ultimate	
	Load [kN]	Displ. [mm]	Load [kN]	Displ. [mm]	Load [kN]	Displ. [mm]
Ref	10	1.2	70	32.8	75	60,5
BS1	14	2.0	90	22.2	123	50
BS2	13	1.9	87	23.1	117	55
BM1	11	1,8	105	28	122	40,5
BM2	11	1,8	106	27	122	37
BPS1 (Pilot 1)	20	2.4	97	25	121	45.8
BPS2 (Pilot 2)	21	2	95	22.5	121	44.3
BPS3	23	2.3	105	25.8	120	38
BPS4	23	2.3	108	26.3	123	38.8
BPS5	26	2,2	119	28	122	32,5
BPS6*	N/A	N/A	117	27.6	148	107
BPM1	25	2.5	121	27.9	128	31.6
BPM2	25	2.8	122	27.5	132	33
BPM3	32	3.7	129	28.4	131	29.5
BPM4	23	2.3	121	27.6	123	28.7

* Due to initial cracks in the beam no crack load could be determined

The results from the tests indicate that there is no significant difference in failure load between beams strengthened with 3.2 m rods and 4 m rods when testing bending. It was however noticed that there was cracks in the concrete at the end of the rods when using prestressed 3.2 m rods. The cracks were thin and small with non-prestressed strengthened beams but wider and large with prestressed rods. The prestressing force created tensile stresses in the concrete at the end of the bonded area and in combination with bending cracks opened up. When the crack opened the energy around the end of the rod changed and as a result the outer part of the rod lost strain, a local relaxation. This behaviour will be studied in future research of prestressed NSMR.

There is a significant difference between cracking and yielding loads when comparing the effects of different level of prestressing forces. For concrete cracking loads, the percentage difference is largest. The force that have been introduced to the lower part of the beam when prestressing the CFRP rod increases the loads needed to create cracks in the concrete. Since higher prestressing forces creates higher stresses in the concrete and steel, higher loads are needed to counteract those forces. When it comes to steel yielding the higher prestressing levels helps delaying the steel yielding to higher loads.

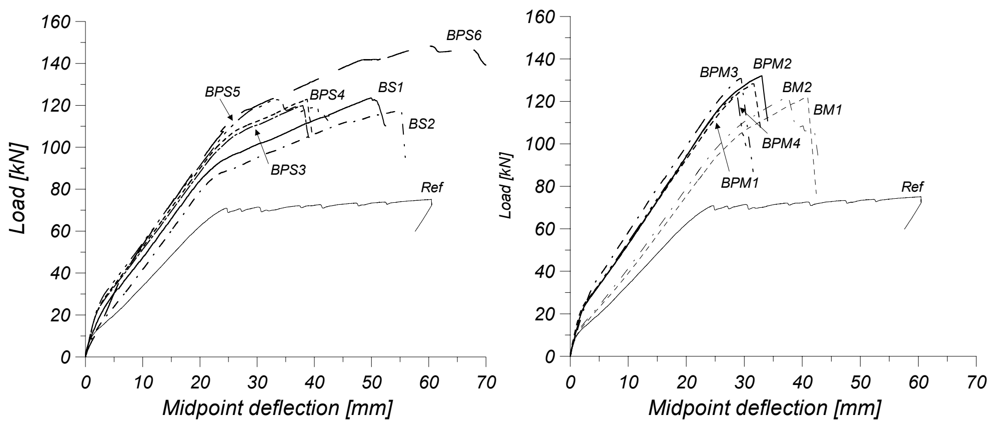


Figure 6 *Results from tests*

The crack patterns in the prestressed beams were different then from those strengthening without prestress. The cracks were smaller all the way up till failure. This should indicate that a better behaviour in the service limit state (SLS) for a prestressed beam. The load needed to open up cracks enough to affect the beam negatively in SLS has been increased significantly.

When comparing the two different CFRP qualities there are two major differences; stiffness of the beams and steel yielding load. The stiffer rod, the M rod, gave the beams a stiffer behaviour, and a higher steel-yielding load. However, it is not possible for these tests to conclude that also the cracking load was higher. The prestressing level has a direct influence on both cracking load and steel-yeilding load, where higher prestress levels increase these loads. In should, though, be mention that the beams with a higher prestress level lose a part of their ductility at failure. The failure mode for all strengthened beams were fibre rupture; BPS5 and BPS6 also had concrete crushing in combination with fibre rupture. There were no indications that there were any problems in the bond at the end of the rods during the bending tests. No indications of slipping or other bond failure were noticed during loading. Although if Figure 6 is studied it clearly shows that BSP6 has different behaviour after steel yielding. This is most likely due to the shortening of the concrete when the concrete crushed; the area of for concrete crushing in BPS6 was much larger than BPS5. This caused larger deflections and a softer failure.

THEORY

The theory presented here is based on the linear elastic theory. The theoretical stress and strain distribution of a rectangular prestressed 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 prestressing force is shown.

Study Figure 2c, the stress at level *z* from the bending moment is:

$$\sigma_M = \frac{M}{I} z \tag{1}$$

Correspondingly the stress from the compressive force at level *z* is:

$$\sigma_P = -\frac{P}{A} - \frac{P \cdot e}{I} z \tag{2}$$

The combination of these stresses gives the total stress at level *z*:

$$\sigma_z = \left(\sigma_P + \sigma_M\right)_z = \frac{M}{I} z + \left(-\frac{P}{A} - \frac{P \cdot e}{I} z\right) \tag{3}$$

where the bending moment, *M*, acts on a cross section together with a prestress force P. Here, e is the level arm from the centre of gravity to the prestress 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. A comparison between theory and test is done in the next section. It is also of great interest to investigate the shear stress at the end of the NSMR rod. First a simplified equation is derived to evaluate the experimental shear stress, see also figure 7:

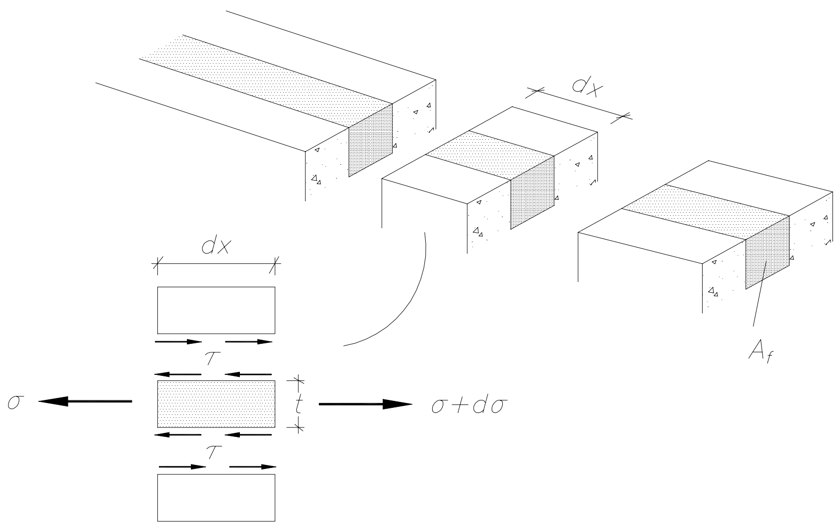


Figure 7 *Shear stresses acting on a small element* dx *of NSMR rod*

Using Hook's law, the stress in the rod can be expressed as:

$$\sigma = \frac{P_f}{A_f} = \frac{P_f}{t^2} \tag{4}$$

and a force equilibrium from Figure 7 gives:

$$\int_{A_f} (\sigma + d\sigma - \sigma) dA_f - \int_{A_\tau} \tau(x) dA_\tau = 0 \tag{5}$$

which may also be written as:

$$d\sigma \cdot t^2 = \int_0^t \int_0^{dx} \tau(x) dx dy \tag{6}$$

And

$$d(E \cdot \varepsilon) \cdot t^2 = t \cdot \tau(x) dx \tag{7}$$

with some simplifications give:

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

Equation (9) applies to one side of the rod; therefore the expression is divided with 3, to take in consideration the three bonded surfaces of the rod, which then give:

$$\tau(x) = E \cdot \frac{t}{3} \cdot \frac{d\varepsilon}{dx} \tag{9}$$

Next, an equation for the theoretical shear stress contribution from bending will be derived; here, the shear stress from the prestress is not included, and only the additional strain in the NSMR rod is considered in the derivation. However, to study the affect of the prestressing load in addition is complicated, not only are high shear stresses introduced at the prestressing phase, but the prestress also varies from the end of the rod to the centre of the beam. However, this effect will be studied in future research.

A differential section, *dx*, can be cut out from the beam as shown in Figure 8 and 9. Two assumptions for resolving the equations are that the bending stiffness for the beam is much greater then for the CFRP and the stresses in the adhesive layer do not change with the thickness, i.e. the adhesive layer is very thin and constant. In this derivation no consideration has been taken to the normal stress, perpendicular to the shear stress, in the bond line. The equations are modified equations for surface bonded laminates (Täljsten 1994).

Figure 8 *Beam strengthened inside the supports and with one point load*

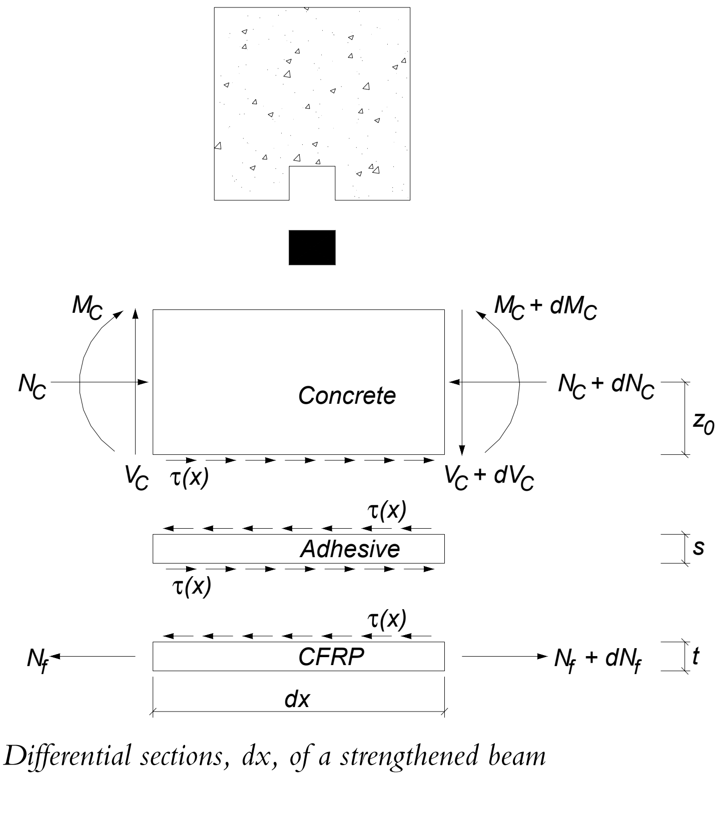


Figure 9 *Differential sections, dx, of a strengthened beam*

The shear stress in the adhesive layer can be expressed as

$$\tau(x) = \frac{G_a}{s}\left[u_f(x) - u_c(x)\right] \tag{10}$$

and following equations are given for the strain in the concrete and the CFRP respectively

$$\varepsilon_c(x) = \frac{du_c(x)}{dx} = \frac{M_c(x)}{E_c W_c} - \frac{N_c(x)}{E_c A_c}\ ;\ \varepsilon_f(x) = \frac{du_f(x)}{dx} = \frac{N_f(x)}{E_f A_f} \tag{11, 12}$$

The next step is to differentiate (10)-(12) with respect to x

$$\frac{d^2\tau(x)}{dx^2} = \frac{G_a}{s}\left[\frac{d^2u_f(x)}{dx^2} - \frac{d^2u_c(x)}{dx^2}\right] \tag{13}$$

$$\frac{d^2u_c(x)}{dx^2} = \frac{1}{E_c W_c}\frac{dM_c(x)}{dx} - \frac{1}{E_c A_c}\frac{dN_c(x)}{dx} \tag{14}$$

$$\frac{d^2u_f(x)}{dx^2} = \frac{1}{E_f A_f}\frac{dN_f(x)}{dx} \tag{15}$$

where

$$\frac{dM_c(x)}{dx} = V(x) - \tau(x)3tz_0 = \frac{F}{2}\frac{2l+a-b}{l+a} - \tau(x)3tz_0 \tag{16}$$

$$\frac{dN_c(x)}{dx} = \tau(x)3t\quad ;\quad \frac{dN_f(x)}{dx} = \tau(x)3t \tag{17}$$

Furthermore, (13) – (17) gives

$$\frac{d^2\tau(x)}{dx^2} = \frac{G_a}{s}\left[\frac{1}{E_f A_f}\frac{dN_f(x)}{dx} - \frac{1}{E_c W_c}\frac{dM_c(x)}{dx} + \frac{1}{E_c A_c}\frac{dN_c(x)}{dx}\right] \tag{18}$$

$$\frac{d^2\tau(x)}{dx^2}=\frac{G_a}{s}\left[\frac{3t}{E_fA_f}\tau(x)-\frac{1}{E_cW_c}\frac{F}{2}\frac{2l+a-b}{l+a}+\frac{3tz_0}{E_cW_c}\tau(x)+\frac{3t}{E_cA_c}\tau(x)\right] \tag{19}$$

$$\frac{d^2\tau(x)}{dx^2}=\frac{G_a}{s}\left[\left(\frac{3t}{E_fA_f}+\frac{3t}{E_cA_c}+\frac{3tz_0}{E_cW_c}\right)\tau(x)-\frac{F}{2E_cW_c}\frac{2l+a-b}{l+a}\right] \tag{20}$$

$$\frac{d^2\tau(x)}{dx^2}-\lambda^2\tau(x)+\frac{G_aF}{2sE_cW_c}\frac{2l+a-b}{l+a}=0 \tag{21}$$

where

$$\lambda^2=\frac{G_a3t}{s}\left[\frac{1}{E_fA_f}+\frac{1}{E_cA_c}+\frac{z_0}{E_cW_c}\right] \tag{22}$$

The solution to (21) and the first derivative with respect to x is given by

$$\tau(x)=C_1\cosh(\lambda x)+C_2\sinh(\lambda x)+\frac{G_aF}{2\lambda^2sE_cW_c}\frac{2l+a-b}{l+a} \tag{23}$$

and

$$\frac{d\tau(x)}{dx}=C_1\lambda\sinh(\lambda x)+C_2\lambda\cosh(\lambda x) \tag{24}$$

The differential equation (23) is valid for $0\leq x\leq b$ since there exists a singularity beneath the point, F. Hence, the following constraints yield

$\tau(x)=0$ when x = b

$$\left.\begin{aligned}N_{c,x=0}&=N_{f,x=0}=0\\ M_{c,x=0}&=\frac{Fa}{2}\frac{2l+a-b}{l+a}\end{aligned}\right\}\quad \text{when x=0 short end}$$

Equations (10) - (12) with the preceding constraints give

$$\frac{d\tau(x)}{dx} = -\frac{G_a F a}{2sE_c W_c}\frac{2l+a-b}{l+a} \tag{25}$$

which gives the following expression if it is specialized, equation (23) can then be written as

$$\tau(x) = \frac{G_a F}{2sE_c W_c}\frac{2l+a-b}{l+a}\frac{a\lambda e^{-\lambda x}+1}{\lambda^2} \tag{26}$$

The maximum shear stress at the short end of the strengthening plates is reached when x=0. It is then possible to write (26) as

$$\tau_{\max} = \frac{G_a F}{2sE_c W_c}\frac{2l+a-b}{l+a}\frac{a\lambda+1}{\lambda^2} \tag{27}$$

Equation (27) is for one point load as in figure 8, if more point loads are present on the beam the shear stress contributed from those loads have to be added.

COMPARISON THEORY AND TESTS

Using equation (3) the theoretical strain for beam BSP4 has been compared to the measured strain at the midpoint of the beam. The comparisons have been done directly after the release of the prestressing force, Figure 10, and at 100 kN load during bending, Figure 11. The strain from the tests have been measured from three points on the beam, at concrete on the top, on the steel reinforcement on the lower part of the beam and on the CFRP rod as shown in Figure 4. When studying Figure 10 and 11 the theory fits the tests very well to the theory. Equation (3) fits the tests well as long as it is possible to predict the moment of inertia. However the theory is no longer valid when the steel reinforcement starts to yield.

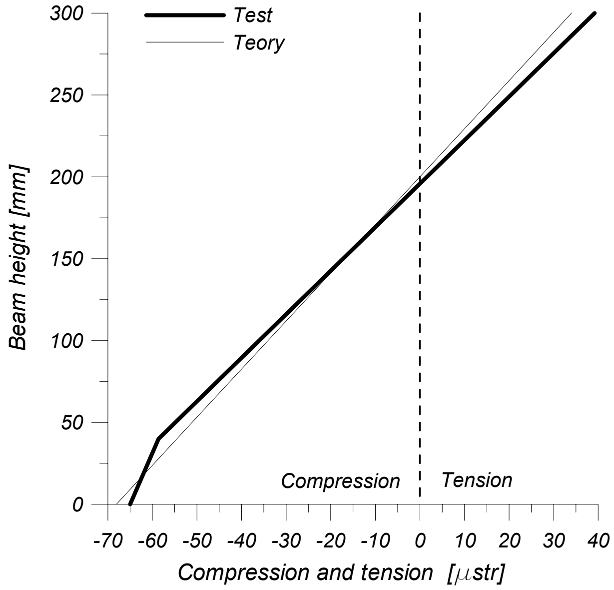


Figure 10 *The strain over the height of the beam after release of prestressing force*

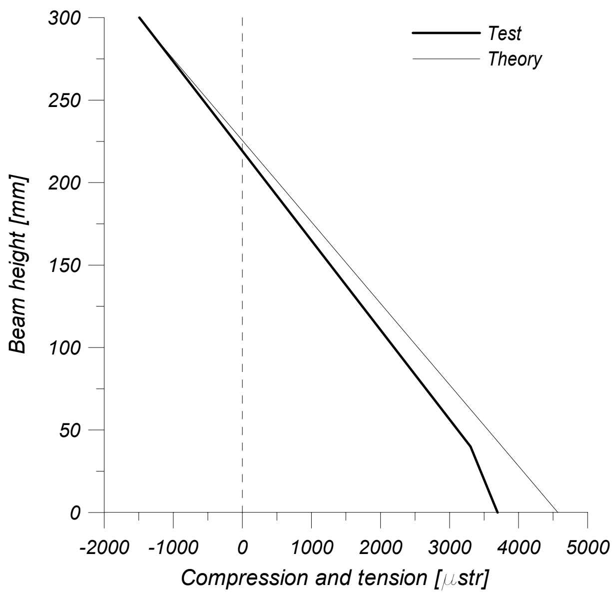


Figure 11 *The strain over the height of the beam at the load 100 kN*

Table 6 *Data used in the theoretical calculations*

Beam	G_a [GPa]	s [mm]	E_c [GPa]	W_c [mm3]	l [mm]	a [mm]	b_1 [mm]	b_2 [mm]
BPS3	2.9	2.5	38	3e6	1600	200	1300	2300

Next a comparison will be made for the maximum shear stress contribution from bending at the end of the rods. Here the strain from the prestressing neglected, only the contribution from bending during loading is considered. The comparison is made for the shorter bond length, i.e. 3.2 m. The tests have been evaluated with equation (9). One beam is presented and compared to the theory using equation (27), important to remember that equation (27) is valid for one point load and in the tests, the beams were loaded with two point, however, this is taken care of in the calculation. In Table 7 the results from the comparison between tests and theory are presented for seven different loads, the loads in the table are the total loads i.e. the sum of the two point loads. It needs to be mentioned that the theory does not consider non-linear behaviour and at higher loads the concrete starts to crack. It was also found that the prestressing force has initiated a crack at the cut of end of the rod, this for the 3.2 m rods. This crack is not considered in the evaluation. The data for the theoretical study with equation (27) can be seen in Table 6 and the comparison can be seen in Table 7. There is a difference between the tests end the theory, one reason is that the theory is linear and does not consider cracking of the concrete.

Table 7 *Comparing test and theory for end shear stresses for two beams*

Load [kN]	BPS5 Test [MPa]	BPS5 Theory [MPa]
10	0.06	0.21
20	0.11	0.42
30	0.19	0.63
40	0.34	0.84
50	0.71	1.05
60	1.02	1.27
70	1.68	1.48

When studying the end shear stresses from bending with equation (27) there are a few factors that affect the results in higher extent then others. These factors are the material properties of the rods and of the adhesive, the thickness of the adhesive and the bonded length of the CFRP. Of those factors the material properties of the rods and adhesive and the bonded length are values that are fairly easy to get correct values. However, the thickness of the adhesive on the other hand may be more difficult to control; here a change of the groove with 1 mm, for example from 15 mm to 14 mm, means a large change of the thickness of the adhesive. But if the beams in this study would have a groove that is 1 mm smaller then expected it would mean a decrease in adhesive thickness with 20 % and increase in shear stress with 10 %. Nevertheless, in these tests measurements of the adhesive thickness and of the sawed slots are fairly constant and in agreement with the theoretical values.

In Figure 12 the tensile strain is presented for beam BPS5, both the total strain with prestress and the strain contribution from the point loads due to bending. As can be seen the strain contribution at the end is small compared to the total strain, even at 100 kN it is still the prestressing strain that has the dominating effect. At the midpoint it is different, here the strain increases considerbly when the load get closer to failure, unfortunately the strain gauge at the midpoint broke just after 70 kN and no higher strains could be recorded for the midpoint.

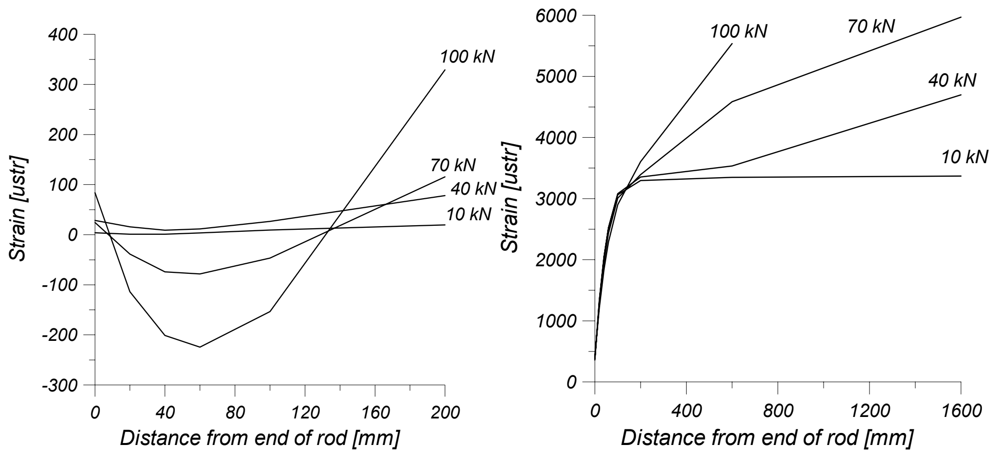


Figure 12 *To the left the strain contribution for the last 200 mm of the rod, to the right the total strain in the rod from the end to the midpoint, this is from beam BPS5*

In the future research the behaviour at the end will be studied more thoroughly, with both laboratory tests and a more detailed theory.

CONCLUSIONS

Fifteen beams have been tested, fourteen with NSMR rods as strengthening. The results from the tests show that strengthening technique using CFRP bonded in the concrete cover is a efficient method to transfer the stresses between CFRP and concrete, both for non-prestressed and prestressed CFRP. The problems with end peeling of the strengthening material that have been a problem when prestressing surface bonded CFRP laminates are minimised with the use of NSMR rods.

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. Together with higher crack loads the cracks also go smaller, this should also indicate a more advantageous behaviour in the service limit state (SLS).

With fairly simple theory it is possible to obtain an estimated value of stresses and strain in the midpoint beam that is, compared with tests, in good agreement. It is also possible to estimate the shear stresses in the bond zone at the end of the bond line for the NSMR rod.

Furthermore, it is showed in the tests that the force transfer between the rectangular CFRP rod and concrete works very well, even without mechanical anchorage devices in laboratory conditions.

It is the authors' belief that it in the near future will be possible to use this technique in field applications, however, it would be preferable to use mechanical anchorages at the end to minimise the strain loss due to prestressing.

FUTURE WORK

As the results from the tests presented has shown that the prestressing NSMR technique can be an efficient strengthening method, the next step is to investigate more parameters that may affect the strengthening result. This might be multiple prestressed rods, anchor device for the ends, strengthening of different structural elements, etc. Of utmost importance is to develop a strengthening system that will be practical applicable in the field. Such a system will include a semi-mechanical anchorage system which will be critical for prestressing the rods but also will help maintain the prestressing force, i.e. decreasing the strain loss at the ends.

The long-term behaviour has to be studied. What happens over time with the prestress? For example, how large will the creep in the bond line be?

One interesting aspect is to investigate is integration of fibre optic sensors in the rods. If this is possible, with consideration to prestress and other factors, it would be possible to follow a structure over time, with the fibre optics it might even be possible to see what happens in the entire strengthening material and not only at discrete points as in the case with strain gauges.

In addition, the theory has to be further developed, and the theory must consider the effect of the prestress more accurate. A more thoroughly understanding of the failure modes should be derived; here fracture mechanics may be a way to move forward.

It is also important to undertake field application on real structures, and a field test is planned in the near future.

ACKNOWLEDGEMENT

The authors acknowledge the financial support that has been provided by SKANSKA AB, BPE® Systems AB and The Development Fund of the Swedish Construction Industry. Also Håkan Johansson, Lars Åström and Georg Danielsson at Testlab, Luleå University of Technology, shall be acknowledged for their help and support.

REFERENCES

De Lorenzis L., Nanni A. and La Tegola, A., (2000), "Flexural and Shear Strengthening of Reinforced Concrete Structures with Near Surface Mounted FRP Rods" Advanced Composite Materials in Bridges and Structures, Proc. of 3rd Int. Conf., Ed. Humar, J.L. and Razaqpur, A.G. Ottowa, ISBN: 0-7709-0447-5, pp. 521-528.

El-Hacha R., Gren M. And Wight G. (2001a), "Concrete beams post-strengthened with prestressed carbon fibre reinforced polymer sheets" Conf. Proceedings: Structural Faults & Repair, London June 2001

El-Hacha R., Wight G. and Green M., (2001b), "Long-term behaviour of concrete beams strengthened with prestressed CFRP sheets at room and low temperatures", Conf. Proceedings: Concrete Under Severe Conditions – Environment and Loading, University of British Columbia, Vancouver June 18-20, 2001, Edt. Banthia N., Sakai K. and Gjörv O.E., ISBN 0-88865-782-X, pp 1817 – 1826.

El-Hacha R., Gren M. And Wight G. (2003), "Innovative System for Prestressing Fiber-Reinforced Polymer Sheets" ACI Structural Journal, May-June 2003, pp 305 - 313

Garden H.N. and Hollaway L.C., (1998), "An experimental study of the failure modes of reinforced concrete beams strengthened with prestressed carbon composite plates" Composites Part B, 411-424.

Hassan T. and Rizkalla S. (2001), "Strengtheing of bridgeslabs with FRP systems" Conf. Proceedings: Structural Faults & Repair, London June 2001

Meier U (1995), "Strengthening of structures using carbon fibre/epoxy composites" Construction and Building Materials, Volume 9, Issue 6 , December 1995, Pages 341-351

Meier U (2001), "Poststrengthening with CFRP strips: 10 years of practical experience" ACUN-3 Technology Convergence in Composite Applications, UNSW Sydney 2001

Nordin H, Carolin A and Täljsten B (2001), "Concrete beams strengthened with prestressed near surface mounted reinforcement (NSMR)", International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4, pp 1067-1075

Quantrill R.J. and Hollaway L.C., (1998), "The flexural rehabilitation of reinforced concrete beams by the use of prestressed advanced composite plates" Composites Science and Technology 58 1998, 1259-1275

Triantafillou T.C. and Deskovic N., (1991), "Innovative Prestressing with FRP Sheets: Mechanics of Short-Term Behavior" Journal of Engineering Mechanics 1991, Vol. 117 1652-1672

Triantafillou T.C., Deskovic N. and Deuring M., (1992), Strengthening of Concrete Structures with Prestressed Fibre Reinforced Plastic Sheet. ACI Structural Journal 89:3, 235-244.

Täljsten B., (1994), "Plate Bonding, Strengthening of Existing Concrete Structures with Epoxy Bonded Plates of Steel or Fibre reinforced Plastics" Doctoral Thesis 1994:152D, Div. of Structural Engineering, Luleå University of Technology, ISSN 0348 – 8373, 308 pp.

Täljsten B., (1996), "Strengthening of concrete prisms using the plate-bonding technique", International Journal of Fracture 82: 253-266, 1996, 1996 Kluwer Academic Publishers, Printed in the Netherlands.

Täljsten B., (1997), "Strengthening of Beams by Plate Bonding", Journal of Materials in Civil Engineering, November 1997, pp. 206-212.

Täljsten B., (1998), Förstärkning av betongkonstruktioner med stålplåt och avancerade kompositmaterial utsatta för vridning, Forskningsrapport, Luleå tekniska universitet, Avdelningen för konstruktionsteknik, Institutionen för Väg- och vattenbyggnad, 1998:01, ISSN 1402-1528 (In Swedish)

Täljsten, B. and Carolin, A, (1999), "Strengthening of a concrete railway bridge in Luleå with carbon fibre reinforced polymers - CFRP: load bearing capacity before and after strengthening", Technical Report 1999:18, Luleå: Luleå University of Technology, Structural Engineering. 61 pp

Täljsten B., (2000), "Förstärkning av befintliga betongkonstruktioner med kolfiberväv eller kolfiberlaminat, Dimensionering, material och utförande", Teknisk Rapport, Luleå tekniska universitet, Avdelningen för Konstruktionsteknik, 1999:12, ISSN 1402-1536, 1999, p 122 (In Swedish).

Täljsten B. And Elfgren L, (2000) " Strengthening concrete beams for shear using CFRP-materials: evaluation of different application methods" Composites Part B: Engineering, Volume 31, Issue 2 , March 2000, Pages 87-96

Täljsten B. and Carolin A., (2001), "CFRP strengthening, Concrete beams strengthened with Near surface mounted CFRP laminates", FRPRC-5 in Cambridge UK, July 2001, ISBN: 0 7277 3029 0, 2001, pp 107-116.

Täljsten B. (2003a), "Strengthening concrete beams for shear with CFRP sheets" Journal of Construction and Building Materials 17 (2003), pp 15-26

Täljsten, B. (2003b): "Strengthening of existing concrete structures with externally bonded Fibre Reinforced Polymers – design and execution". Technical report. Luleå University of Technology, Division of structural engineering

Wight R.G., Green M.F., Erki M.A., (1995), "Post-strengthening conrete beams with prestressed FRP sheets" Non-metallic (FRP) Reinforcement for Concrete Structures 1995, ISBN 0 419 20540

Wight R.G., Green M.F., Erki M.A., (2001), "Prestressed FRP Sheets for Poststrengthening Reinforced Concrete Beams" Journal of Composites for Conctruktion, pp 214-220

Wight G. and Erki M.A., (2001a), "CFRP strengthening of severely damaged reinforced concrete slabs", Conf. Proceedings: Concrete Under Severe Conditions – Environment and Loading, University of British Columbia, Vancouver June 18-20, 2001, Edt. Banthia N., Sakai K. and Gjörv O.E., ISBN 0-88865-782-X, pp 2191 – 2198.

Wight G. and Erki M.A., (2001b), "Prestressed CFRP for strengthening concrete slabs in fatigue", International Conference on FRP Composites in Civil Engineering CICE 2001 Ed. J.G. Teng, Hong Kong, ISBN: 0-08-043945-4

NOTATIONS

A	Cross section area	[m^2]
A_c	Area, concrete	[m^2]
A_f	Area, CFRP	[m^2]
E	Modulus of elasticity	[Pa]
E_c	Modulus of elasticity, concrete	[Pa]
E_f	Modulus of elasticity, CFRP	[Pa]
E_a	Modulus of elasticity, adhesive	[Pa]
F	External force	[N]
G_a	Shear modulus, adhesive	[Pa]
I	Moment of inertia	[m^4]
M	Bending moment	[Nm]
M_c	Moment, concrete	[Nm]
N_c	Normal force, concrete	[N]
N_f	Normal force, CFRP	[N]
P	Prestressing force	[N]
P_f	Normal force, CFRP	[N]
V	Shear force	[N]
W_c	Bending stiffness, concrete	[m^3]
a	Distance between short and of rod and support	[m]
b	Distance between short and of rod and force	[m]
f_{cc}	Compressive strength, concrete	[Pa]
f_{ct}	Tensile strength, concrete	[Pa]
f_f	Tensile strength, CFRP	[Pa]
f_{ac}	Compressive strength, adhesive	[Pa]
f_{at}	Tensile strength, adhesive	[Pa]
l	Distance between short and of rod and midpoint of beam	[m]
s	Thickness of adhesive	[m]
t	One side of the rods	[m]
u_c	Local displacement, concrete	[m]
u_f	Local displacement, CFRP	[m]
ε	Strain	[--]
ε_{fu}	Maximum strain, CFRP	[--]
σ	Normal stress	[Pa]
$d\sigma$	Change in normal stress	[Pa]
σ_M	Normal stress due to bending moment	[Pa]
σ_P	Normal stress due to prestressing force	[Pa]
σ_z	Normal stress due at level z	[Pa]
τ	Shear stress	[Pa]

DOCTORAL AND LICENTIATE THESES

Division of Structural Engineering, Luleå University of Technology

Doctoral Theses

Ulf Arne Girhammar (1980): *Dynamic Fail-Safe Behaviour of Steel Structures*. Doctoral Thesis 1980:060D. 309 pp.

Kent Gylltoft (1983): *Fracture Mechanics Models for Fatigue in concrete Structures*. Doctoral Thesis 1983:25D. 210 pp.

Thomas Olofsson (1985): *Mathematical Modelling of Jointed Rock Masses*. Doctoral Thesis 1985:42D.

Lennart Fransson (1988): *Thermal ice pressure on structures in ice covers*. Doctoral Thesis 1988:67D. 161 pp.

Mats Emborg (1989): *Thermal stresses in concrete structures at early ages*. Doctoral Thesis 1989:73D. 285 pp.

Lars Stehn (1993): *Tensile fracture of ice. Test methods and fracture mechanics analysis.* Doctoral Thesis 1993:129D, September 1993, 136 pp.

Björn Täljsten (1994): *Plate Bonding. Strengthening of existing concrete structures with epoxy bonded plates of steel or fibre reinforced plastics*. Doctoral Thesis 1994:152D, August 1994, 283 pp.

Jan-Erik Jonasson (1994): *Modelling of temperature, moisture and stresses in young concrete*. Doctoral Thesis 1994:153D, August 1994, 227 pp.

Ulf Ohlsson (1995): *Fracture Mechanics Analysis of Concrete Structures*. Doctoral Thesis 1995:179D, December 1995, 98 pp.

Keivan Noghabai (1998): *Effect of Tension Softening on the Performance of Concrete Structures*. Doctoral Thesis 1998:21, August 1998, 150 pp.

Gustaf Westman (1999): *Concrete Creep and Thermal Stresses. New creep models and their effects on stress development*. Doctoral Thesis 1999:10, May 1999, 301 pp.

Henrik Gabrielsson (1999): *Ductility in High Performance Concrete Structures. An experimental investigation and a theoretical study of prestressed hollow core slabs and prestressed cylindrical pole elements*. Doctoral Thesis 1999:15, May 1999, 283 pp.

Groth, Patrik (2000): *Fibre Reinforced Concrete - Fracture Mechanics Methods Applied on Self-Compacting Concrete and Energetically Modified Binders*. Doctoral Thesis 2000:04, January 2000, 214 pp.

Hans Hedlund (2000): *Hardening concrete. Measurements and evaluation of non-elastic deformation and associated restraint stresses*. Doctoral Thesis 2000:25, December 2000, 394 pp ISBN 91-89580-00-1.

Anders Carolin (2003): *Carbon Fibre Reinforced Polymers for Strengthening of Structural Members.* Doctoral Thesis 2003:18, June 2003, ISBN 91-89580-04-4. 190 pp.

Martin Nilsson (2003): *Restraint Factors and Partial Coefficients for Crack Risk Analyses of Early Age Concrete Structures*. Doctoral Thesis 2003:19, June 2003, ISBN: 91-89580-05-2.

Mårten Larson (2003): *Thermal Crack Estimation in Early Age Concrete – Models and Methods for Practical Application*. Doctoral Thesis 2003:20, June 2003, ISBN 91-86580-06-0. 190 pp

Licentiate Theses

Lennart Fransson (1984): *Bärförmåga hos ett flytande istäcke. Beräkningsmodeller och experimentella studier av naturlig is och av is förstärkt med armering*. Licentiate Thesis 1984:012L.

Mats Emborg (1985): *Temperature stresses in massive concrete structures. Viscoelastic models and laboratory tests*. Licentiate Thesis 1985:011L, May 1985, rev November 1985, 163 pp.

Christer Hjalmarsson (1987): *Effektbehov i bostadshus. Experimentell bestämning av effektbehov i små- och flerbostadshus*. Licentiate Thesis 1987:009L, October 1987, 72 p.

Björn Täljsten (1990): *Förstärkning av betongkonstruktioner genom pålimning av stålplåtar.* Licentiate Thesis 1990:06L, May 1990.

Ulf Ohlsson (1990): *Fracture Mechanics Studies of Concrete Structures*. Licentiate Thesis 1990:07L, May 1990, 8+12+18+7+21 pp.

Lars Stehn (1991): *Fracture Toughness of sea ice. Development of a test system based on chevron notched specimens*. Licentiate Thesis 1991:11L, September 1990, 88 pp.

Per Anders Daerga (1992): *Some experimental fracture mechanics studies in mode I of concrete and wood*. Licentiate Thesis 1992:12L, 1ed April 1992, 2ed June 1992, 81 pp.

Henrik Gabrielsson (1993): *Shear capacity of beams of reinforced high performance concrete*. Licentiate Thesis 1993:21L, May 1993, 109 pp. 18 June.

Keivan Noghabai (1995): *Splitting of concrete in the anchoring zone of deformed bars. A fracture mechanics approach to bond*. Licentiate Thesis 1995:26L, May 1995, 123 pp.

Gustaf Westman (1995): *Thermal cracking in high performance concrete. Viscoelastic models and laboratory tests*. Licentiate Thesis 1995:27L, May 1995, 125 pp.

Katarina Ekerfors (1995): *Mognadsutveckling i ung betong. Temperaturkänslighet, hållfasthet och värmeutveckling*. Licentiate Thesis 1995:34L, October 1995, 137 pp.

Patrik Groth (1996): *Cracking in concrete. Crack prevention with air-cooling and crack distribution with steel fibre reinforcement*. Licentiate Thesis 1996:37L, October 1996, 128 pp.

Hans Hedlund (1996): *Stresses in High Performance Concrete due to Temperature and Moisture Variations at Early Ages*. Licentiate Thesis 1996:38L, October 1996, 240 pp.

Mårten Larson (2000): *Estimation of Crack Risk in Early Age Concrete. Simplified methods for practical use*. Licentiate Thesis 2000:10, April 2000, 170 pp.

Bernander, Stig (2000): *Progressive Landslides in Long Natural Slopes. Formation, potential extension and configuration of finished slides in strain-softening soils*. Licentiate Thesis 2000:16, May 2000, 137 pp.

Martin Nilsson (2000): *Thermal Cracking of young concrete. Partial coefficients, restraint effects and influences of casting joints*. Licentiate Thesis 2000:27, October 2000, ISSN 1402-1757, 267 pp.

Erik Nordström (2000): *Steel Fibre Corrosion in Cracks. Durability of sprayed concrete*. Licentiate Thesis 2000:49, December 2000, 103 pp.

Anders Carolin (2001): *Strengthening of concrete structures with CFRP – Shear strengthening and full-scale applications*. Licentiate thesis, June 2001, ISBN 91-89580-01-X 2001:01 120 pp

Håkan Thun (2001): *Evaluation of concrete structures. Strength development and fatigue capacity*. Licentiate thesis 2001:25. June 2001, ISBN 91-89580-08-2, 164 pp

Patrice Godonue (2002): *Preliminary Design and Analysis of Pedestrian FRP Bridge Deck*. Licentiate thesis 2002:18, 203 pp

Jonas Carlswärd (2002): *Steel fibre reinforced concrete toppings exposed to shrinkage and temperature deformations*. Licentiate thesis 2002:33. August 2002.

Anders Rönneblad (2003): *Product Models for Concrete Structures - Standards, Applications and Implementations.* Licentiate thesis 2003:22, June 2003

Håkan Nordin (2003): *Fibre Reinforced Polymers in Civil Engineering - Flexural Strengthening of Concrete Structures with Prestressed Near Surface Mounted CFRP Rods* Licentiate thesis 2003:XX, June 2003

Sofia Utsi (2003): *Self-Compacting Concrete - Properties of fresh and hardening concrete for civil engineering applications* Licentiate thesis 2003:19, June 2003