IMPROVEMENT OF THE LOAD-BEARING CAPACITY OF EXISTING BRIDGES

-A Review of Literature-

Anders Carolin
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**PREFACE**

In this report a review of the literature is presented in the area of improvement of the load-bearing capacity of existing bridges. The work has been done at the request of the Swedish Road Administration (BY 20A 98:7699) at the Division of Structural Engineering at Luleå University of Technology.

The treated subject is extensive and spans over a large area. This report gives only a short summary and should be seen as a first inventory of essential methods that are worth further studies. Comments and suggestions are gratefully welcomed.

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Anders Carolin
SUMMARY
Improvement of the load-bearing capacity of bridges is a large subject. Many methods have been developed for strengthening and for increasing the bearing capacity. Two examples are the use of post-tensioning reinforcement and externally bonded carbon fibre products. There is an accelerated increase in the number of objects being strengthened. Especially the method by bonding of carbon fibre is a fast growing technique.

SAMMANFATTNING
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1 INTRODUCTION

1.1 General

A large part of the existing infrastructure is rapidly getting towards its structural lifetime. This leads to a need for methods for strengthening and repair. Reasons for strengthening can be changed use, structural faults, accidents, new demands in codes and absence of maintenance. In some cases an older structure needs to be replaced with a new one. In many cases it can be economic to take measures to the existing structure. The cheapest and easiest way can be an administrative upgrading where refined calculation methods are used in connection with exact material parameters to show that the existing structure has a higher load-carrying capacity than what has earlier been assumed. This can in some cases be used to still show that the structure can fulfil new demands. If an action needs to be taken there are some different methods that can be used. General presentations on this area are given in Mallet (1994), Raina (1994), Sasse (1998) and Davis (1998). The methods have their different advantages and disadvantages. Further, some of the methods are only suitable for special types of applications.

In the future it will probably be even more common with strengthening as new methods are developing and as the knowledge on environmental aspects and life cycle cost are increasing.

1.2 Scope of the Report

This report aims to clarify which methods that are suitable for improvement of existing bridges. Improvement can involve a lot of things, for example strengthening, widening, sealing of cracks, repairing, replacing of deficient parts and preventing corrosion. In Mallet (1994) improvement stands only for operations, which raises the service level above what was intended in the original design. Restoration of the service level intended in the original design is there called rehabilitation, refurbishment or renovation. The method for improvement, when it comes to structural changes, are in fact in many cases the same whether it is for restoration to an old level or amelioration for higher levels. There is no need to make a difference between restoration and betterment especially since in many cases there is a combination that is needed.

This report mainly focuses on improvement of the load bearing capacity, which is also the definition of improvement in Bro94: 4, 5 (1994). The report will focus on concrete bridges since it is the most common type of bridge. However, the presented methods can also be applied to bridges of wood, steel and combinations of materials.

Chapter 2 gives an introduction to the following three chapters where different strengthening methods are studied. Each chapter begins with a general description of a method followed by some special properties and it then ends with some examples where the method is used.

In Chapter 6 some glimpses of the history are presented together with some thoughts regarding probable development in the future.
2 PROBLEMS AND DEMANDS

2.1 General
As earlier mentioned bridges can have too low service levels due to many reasons. Before any actions are taken on a bridge it is necessary to study the bridge thoroughly. The extent of damages and the reasons for them must be investigated and analysed, Bro 94:7 (1994). This is done by a bridge inspection. The aim of a bridge inspection is to establish if the bridge needs to be strengthened or repaired. It can also in some cases give answers to what have caused the problems. Approaches for bridge inspection are presented in Vägverket (1994), Fleuriot (1996) and Raina (1994). Bro 94:7 (1994) include some demands for bridges and criteria of damages. Further Xanthakos (1995) gives a good procedure for detecting defects and deterioration mainly regarding substructures but the method can be applied to other structures as well. The static mode of action of the bridges and its bearing capacity shall be studied with regard to the actual repairing or strengthening method, Bro 94:7 (1994).

In some cases there are problems with durability in regard to fatigue. This can be solved by an increase of the bearing capacity, which may decrease stress and strain levels.

2.2 Steel Bridges
Steel bridges need improvement when they have to carry larger loads or after an accident. Steel bridges can also have problems with corrosion and fatigue in some of the elements.

2.3 Concrete Bridges
Concrete bridges are the most common bridges due to low costs. Concrete also gives long lives for bridges with only small needs for maintenance. The long lives implies that the traffic load will change over the life time i.e. the bridges will often need to carry larger loads then what they were designed for.

Concrete is a building material with high compressive strength and poor tensile strength. A structure without any form of reinforcement will crack and fail for a relatively small load. Concrete’s compressive strength increases in most cases over time due to maturing, Rådman (1998). Unfortunately, the tensile strength does not increase in the same way over time. This means that increasing of concrete bridges load bearing capacity can in most cases be done by use of more reinforcement.

Concrete bridges can also have problems with corrosion of the old steel reinforcement. Since iron enlarge when it corrodes it often leads to cracking, see Noghbai (1998), Ohtsu (1998) and Raina (1994), which can lead to concrete spalling. The problem with corrosion is not studied in this report. There are anyhow many ways to decrease the corrosion of the reinforcement, for example with different types of coatings see Zemajtis and Weyers (1996) and Cheaitani et al (1996). Another way can be re-alkalisation of the concrete, Banfill (1996) and Mattila and Pentti (1996).
2.4 Other bridges

Bridges can also be made by masonry, wood et cetera. These bridges can have problems with wood that become rotten and stones drifting apart. Since these bridges are not so common as steel and concrete bridges they are not further studied, even if some examples are given in the following chapters.

2.5 Different Methods

Bridges are special structures since they have to withstand heavy loads and de-icing salt as well as large and many changes in humidity and temperature over a long time. These demands must be kept in mind when a bridge is built and also when it is strengthened or repaired. Further, environmental and aesthetic aspects must be kept in mind when bridges or bridge repair work is designed. Many different methods and variants of methods for strengthening work are available, Al-Aieshy (1997), Mallet (1994) and Trinh (1990). The methods can be different variants of concrete castings, post tensioning, externally bonding of carbon fibres or steel plates and insertion of external beams. Another way to improve structures is to replace only some part with newer ones. The different methods will be described in the following chapters, where some examples of applications also are presented. In some cases only few of them are possible to use due to aesthetics and durability. In Allen et al (1996) and Raina (1994), many methods are described with some examples of undertaken objects. Some of them will be related in the following.

When a bridge is going to be modified it is important to do a close scrutiny to be able to pick the right method with regard of economical, structural and durability aspects.

In Mallet (1994) and Raina (1994) there are several examples of bridges with problems and how the problems can be solved. Since these books are some years old they do not consider the latest techniques for example externally bonded carbon fibre products. External bonding with carbon fibre products can instead be found in several proceedings from recent conferences, for example Mihashi and Rokugo (1998) Dhir and Jones (1996), Nordic Concrete Research (1999) and Forde (1999).

2.6 Common Strengthening Materials

Different materials can be used for strengthening purposes. The applied material is often chosen because of its special characteristics. In Table 2-1 some material data for the most common materials are presented. Further information about materials can be found in Betonghandboken (1994), Andersson et al (1992) and Hull and Clyne (1996).

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<td>Concrete</td>
<td>20–40</td>
<td>5–60</td>
<td>1–3</td>
<td>2400</td>
<td>0.2–0.4</td>
<td>1</td>
</tr>
<tr>
<td>Steel</td>
<td>200–210</td>
<td>240–690</td>
<td>240–690</td>
<td>7800</td>
<td>3–5</td>
<td>≈3</td>
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<tr>
<td>Carbon fibre*</td>
<td>200–800</td>
<td>-</td>
<td>2500–7500</td>
<td>1750–1950</td>
<td>100–250</td>
<td>3–4</td>
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*) Given values are for plain carbon fibre. The characteristics of the composite will vary with amount and property of the used matrix.
3 INCREASED DIMENSIONS

3.1 General
This is the oldest technique for strengthening and the principle works for almost every material. The method has been used for almost just as long as structures have been built. By adding extra material to critical parts of the structure, the cross-sectional areas are increased as well as the moments of inertia. The added material can be designed to fit the requirements of the improved structure. The technique is often used to strengthen chosen parts of a structure but can also be used to unload old parts of the structure by adding new elements. This technique also includes insertion of extra beams and elements.

Concrete bridges can for example be strengthened by extra reinforcement covered by different kinds of castings.

3.2 Castings
Concrete castings can be used for force distribution to extra mounted reinforcement and for protection of the structure. The technique is only used for concrete bridges. Normally good bond between the substrate concrete and the new one is required. Through that a composite action between the two materials is reached. Granju (1998) has studied debonding and peeling and found that the tensile stresses perpendicular to the interface are critical in contrast to shear stresses for bonded plates. It is difficult to get good bond between the new layer of concrete and the old concrete. Wittman (1998), Kono et al (1998), Lim and Li (1998) and Li (1998) have studied this interface. Özturan and Cecen (1996) have studied freeze and thaw. Etebar (1996), have studied concrete repaired with concrete under repeated loading conditions.

The castings, except for normal concrete, are high-strength concrete, self-compacting concrete, shotcrete and so on. The mortars can also contain fibres of steel or polymer materials. Dristos (1996) has found that the behaviour of a beam strengthened by using a non-shrinking grout can be better predicted than a beam where conventional concrete is used for strengthening.

One problem with this method is shrinkage and thermal cracking of the hardening concrete, Nilsson (1995). Kunieda (1998) has investigated the shrinking and cracking behaviour of the repair and found that the surface condition of the substrate concrete effects the result. This means that essential parameters are the roughening treatment of interface and the selection of suitable repair materials. Thermal cracking and shrinkage are studied by Decter et al (1996), with two examples of strengthening.

The upper side of bridge decks is quite easy to repair by this method since form works only need to be built along the edges of the cast area. The bottom side and the vertical sides are more complicated. These areas can instead be sprayed with shotcrete, Al-Aieshy (1998). Before a casting is undertaken aggregates must be exposed and old damaged concrete must be removed. This can be done by several methods, Raina (1994) and Al-Aieshy (1998). For example chipping, blasting, milling and grinding can be used to remove old concrete.
3.2.1 Shotcrete
Shotcrete is often used as a repair material for concrete structures. It is good for improving a deteriorated surface. With an addition of fibres into the shotcrete it also gives a certain structural enhancement. A common technique of repairing and strengthening concrete structures is the addition of steel reinforcement bars covered with a layer of sprayed concrete, Wiberg (1998). The most advantageous feature with shotcrete is that it can be applied to big areas in a short time. Because the skill of the nozzleman is all-important it is recommended to use experienced specialist contractors, Mallet (1994). In Figure 3-1 spraying of shotcrete over additional steel reinforcement is shown.

![Bridge strengthening with supplementing reinforcement covered by shotcrete, Raina (1994)](image)

3.2.2 Fibre Reinforced Concrete
By adding fibres to the concrete several positive qualities can be achieved, Al-Aieshy (1998). The fibres gives functions as stretchability, crack control and increased tensile strength, Betonghandboken (1992).

3.3 D-RAP
There exist a method that means increasing of dimensions by bonding prefabricated panels to the structure using an epoxy resin. The method is used for the compression side of concrete elements. Matsushima et al (1998) has studied the effect of the method in combination with different panel arrangement, imperfection of gluing and different wet conditions. They found by test that the method increased the load-bearing capacity for new beams to a level as high as newly constructed beams of the same depth as the strengthened one.

3.4 Wood
The method can also be applied for wood bridges by means of insertion of elements and bolting or nailing more material to the existing beams.
3.5 **Steel**

The method with increased dimensions is effective also for steel bridges. Increasing a cross-section with steel is often quite simple to undertake. If it is possible to weld, it is very easy to achieve a good composite action between the two materials and the method is then also very cost effective. If it is not possible to weld, bolting is a good alternative.

3.6 **Advantages and Disadvantages**

**Advantages**

- This method is cheap for large horizontal upper areas. (concrete bridges)
- Well-known and tested technique.
- The used material and method is quite similar to current execution of normal concrete works.
- For steel bridges the method is quite simple to undertake.

**Disadvantages**

- Require careful execution with vibration of concrete and applying of shotcrete.
- Changes of cross-section influence the aesthetic appearance. The surface will be different, especially when shotcrete is used.
- The increase in dimensions and the weight of the retrofitted part are not negligible. They influence the natural frequency of the bridge, Kobatake et al (1993).
- Restricted traffic load at the time for concrete hardening.
- Heavy and large amount of material is used.

3.7 **Executed Projects**

South Muskoka River Bridge, a two-span deck type steel bridge, was strengthened by insertion of a new truss beam besides the two old ones, Farago (1990). This method was selected on preliminary cost-estimation in comparison with prestressing and replacement of the bridge. In hindsight, perhaps the bridge should have been replaced considering the long time for the project when the traffic had to detour.

The Tam–Shui River Bridge in Taiwan was built in 1975 and was strengthened in 1996 due to heavier traffic loads, Lu and Wu (1996). The bridge was strengthened by insertion of two posttensioned diaphragms in the bridge cross direction and with a casting of 7 cm steel fibre reinforcement concrete on the top-slab. The new concrete layer covered some new steel bars and was anchored with dowels.

An old arch bridge in Burton, UK required strengthening to meet the new Euro vehicle weight limit of 40 tonnes, Fellows (1998). A reinforcement grid of high-tensile steel bars were mounted underneath the arches and then covered with 8 – 9 cm of shotcrete. The mortar used was a single-component polymer modified designed for dry spraying. The reinforcement grid was anchored with dowels.

The columns of Öland Bridge have been strengthened with a surround casting with thickness of approximately 45 cm that alone will carry the loads, Nilsson (1995). A lot of effort where invested to make the new construction free from cracks. This means
slipping interfaces and cooling of the young concrete. Figure 3-2 show a model of how the work was undertaken.

![Figure 3-2](image)

Figure 3-2  Strengthening of the columns of Ölands Bridge was done under dry conditions inside a caisson, Nilsson (1995).

Other structures that have successfully been strengthened with fibre reinforced shotcrete are for example a lighthouse and a chimney (Sweden), a stormwater drain (Australia) and some marine structures (Canada), Balaguru and Shah (1992).
4 EXTERNALLY BONDED REINFORCEMENT

4.1 General

For concrete structures, it is often the amount of reinforcement that determines the bearing capacity. This is because of that fact that concrete has a very low tensile strength.

By bonding a material with high tensile strength and relative high stiffness to the tension side of an element the new material will carry a part of the tensile forces in the cross-section. The bonded material can be a plate of steel or a product of fibre reinforced polymer, FRP. The most effective is carbon fibre reinforced polymer, CFRP, in form of sheets or laminates. The externally bonded material becomes reinforcement in the same way as the steel bars in reinforced concrete. The method is also very effective in increasing shear capacity of structural members. In those cases the bonded sheets become stirrups. For the bonding an adhesive, normally epoxy, is used. Because of the flexibility and effectiveness of the method it has grown fast and is now used worldwide. The method is also very suitable and effective for wrapping of columns that need to be strengthened.

This method has been evaluated for concrete structures but is practised for structures of other materials as well. For instance the method also works for wooden beams or elements.

The method is further described in Täljsten (1994). Täljsten (1998) has studied both bending shear and torsion capacity for beams strengthened by steel and advanced composites.

4.2 Advanced Composites

Nowadays, externally bonding of reinforcement is mostly done with sheets or laminates of fibre reinforced polymers. The fibres can be carbon, aramid or glass but it is carbon fibres that have the most suitable qualities. This material has the advantages of a high strength to weight ratio, not corroding, easy to handle and can be cut with ordinary knives or pair of scissors. Figure 4-1 shows mounting of carbon fibre sheets to the bottom side of a concrete railroad bridge.

![Bridge strengthening with carbon fibre sheets, Täljsten and Carolin (1999)](image)

Figure 4-1 Bridge strengthening with carbon fibre sheets, Täljsten and Carolin (1999)


4.3 Steel Plates
In mid 70-ties, steel plates began to be used as external reinforcement. Steel plates work well and are still used as a strengthening method. Working with steel plates involves some heavy work moments and further it is necessary with external pressure under the curing of the adhesive. By the fact that steel has the disadvantage of corroding it is now more common to use fibre reinforced polymers.


4.4 Advantages and Disadvantages

Advantages
- The method can in some cases be used without any restrictions of the traffic on the bridge, Täljsten and Carolin (1999).
- Carbon fibres show excellent fatigue and durability properties.
- A low weight of the fibres makes it easy to handle without lifting equipment at the site.
- Effective structural strengthening.
- No changes of cross-section or free height.
- Quick to apply.

Disadvantages
- Relative new method, so long-time experience is still missing.
- Can not be done at low temperatures or in rainy conditions without climate protection from tents combined with hot air blower.

4.5 Examples
From recent years, many examples of this strengthening technique can be found especially when it comes to advanced composites. The Swedish Road Administration has undertaken a pilot project under 1998. A small frame bridge from the 40-ties over Maren outlet outside Kalmar has been strengthened. Approximately 320 meter of carbon fibre sheets with the width 0.3 m were used.

In Luleå a three-span railroad bridge, Figure 4-2, has been strengthened during the summer of 1998, Täljsten and Carolin (1999). The bridge was strengthened because of increased loads on the railway system. The bridge was built in the 60-ties and had mainly a to low moment bearing capacity in the cross-direction. In total 3200 m carbon fibre sheets, 0.3 m wide, were used. The work was undertaken without any restrictions for the train traffic on the bridge. A comprehensive test program was undertaken where strains and deformations were studied. The measurements showed that the stiffness of the bridge had increased with 16 % after that the work was completed.
Figure 4-2  
Bridge in Luleå strengthened with externally bonded carbon fibre sheets

The first application of strengthening with carbon fibre sheets on infrastructure in Scandinavia concerned repair of 18 concrete columns on a bridge outside Sundsvall, Aboudrar and Johansson (1998). The bridge was built in 1939 and the columns had a shortage of stirrups. The repair work started with rebuilding of the concrete cover of the column, which had spalled of due to corrosion of the reinforcement. Figure 4-3 shows the deteriorated column and the final result.

Figure 4-3  
Columns strengthened with CFRP to the left and one column with uncovered corroded steel reinforcement to the right, Aboudrar and Johansson (1998).

Bonding of carbon fibre has strengthened a bridge in Devonshire, Lane et al (1998). The bridge needed strengthening because of some damaged prestressing tendons and the new higher European design loads. The bridge were strengthened in one day and remained fully open during the work.

The method is widely used for retrofitting of concrete columns in USA and Japan, Horii et al (1998), Karbahari (1996) and Katsumata et al (1998). The columns are often strengthened in order to stand higher earthquake loads. Many bridges have been strengthened with carbon fibres in Japan, Busel (1995).
In Germany near Dresden, three 70-year-old r/c frame bridges were strengthened by use of CFRP-plates, Neubauer and Rostásy (1997b). Before strengthening the bridges were deteriorated and had load restrictions. CFRP was chosen from the owner because of corrosion resistance and long-term durability.

The Ibach Bridge in Switzerland was built in 1969. During drilling for installation of new traffic lights in 1991 a number of prestressed tendons were damaged. Before the bridge was strengthened the allowed maximum load was decreased. 6.2 kg of CFRP-laminates was used. In order to obtain the same results with steel, 175 kg would have been necessary, Meier (1994) and Meier et al (1993). The work was undertaken at night since it was preferred to minimise disturbance on the traffic.

The historical wooden bridge from 1807 in Sins, Switzerland was strengthened in 1992 with CFRP-laminates, Meier (1994). The bridge consists of two spans, each of 30.8 m length. The bridge was strengthened because of excessive deflections in the crossbeams of oak. CFRP laminates having a longitudinal modulus of elasticity of 300 GPa successfully limited the deflections without changing the look of the bridge.

An impact from a truck damaged the outer girder of a bridge on the Southbound Interstate 95 highway in West Palm Beach, Florida. The truck caused a longitudinal twist in the concrete beam. The owners considered that except for replacement the only alternative was strengthening with carbon fibre due to the twisted shape of the beam. Replacement was not an acceptable alternative since it had required closing of one lane of the bridge at least a month, Busel (1995). Therefor carbon fibre was used and the work was undertaken in three five hour long night shifts.

The deck of Hiyoshikura Bridge in Japan was strengthened 1994 because of demands for higher design loads. Measurements that were undertaken showed that the stresses in the old steel reinforcement decreased with 30–40 % after strengthening, Aboudrar and Johansson (1998).

Even if the method of plate bonding with steel have had retrogression the method is still used. In the summer of 1998 a bridge in Boden was strengthened in shear capacity by use of externally bonded steel stir-ups in form of plates, Figure 4-4.

Figure 4-4 Bridge in Boden strengthened in shear with externally bonded steel plates.
Other structures that recently have been strengthened by bonding of carbon fibres in Sweden are a Chimney in Halmstad 1997, two crane beams in Hojum 1998 and several systems of joists in Stockholm.

A 91 m long, 35-year-old concrete bridge near Salt Lake City has been tested by lateral displacement. For the test a hydraulic ram was constructed beside the bridge, see Figure 4-5. Using a loading plate and cables wrapped around the bridge deck, the ram pushed and pulled the bridge laterally, simulating the displacement of a magnitude 7.0 earthquake. The ram first tested the strength and ductility of the bridge to the yield point. Then carbon fibre sheets wrapped the bridge columns and deck supports before shaking the bridge to the yield point again. The carbon fibre restored the damaged bridge to nearly its original strength and ductility and actually increased its load-carrying capacity by 25%, Geopier (1998).

![Figure 4-5](image.png)

**Figure 4-5** Full-scale-testing of earthquake loads on a bridge strengthened by carbon fibre sheets, Geopier (1998).

In Japan, bonding unidirectional carbon fibre sheets to the surface has retrofitted many chimneys, Kobatake et al (1993).
5 Post Tensioned Reinforcement

5.1 General
This method works in the same way as prestressed or post tensioned concrete except that the tensioning is done afterwards when it is time to strengthen the structure. By introducing a compressive force to the concrete from a steel or composite tendon, the cross-section tensile forces are decreased and the high compressive strength of the concrete is used. The method is limited by the compressive strength of the concrete and can therefore only be used when the compressive strength of the concrete is sufficient. The method also works for steel and wood bridges. The tensile forces that can arise, on the normally compressed side, when the structure has its minimum load also limit the method.

Strengthening of prestressed concrete beams by external post tensioning is presented in Ionel (1996). Former, tendons consisted of steel or steel wires but advanced composites as carbon fibres can also be used for this purpose, Nakai et al (1994) and Meier et al (1993). Leeming (1997) has tested carbon fibre plates in full-scale experiments and Ando et al (1998) have done creep rupture tests on tendons of carbon and aramid fibre. Shehata et al (1996) has found that external prestressing can be an effective way to strengthening the shear capacity in beams.

5.2 Advantages and Disadvantages

Advantages
- Well-known and tested method.
- Calculation models exist.
- Effective in some cases.
- Can often be used with only small restrictions of the traffic.
- Contributes to the shear capacity.

Disadvantages
- Special devises for prestressing are required.
- Corrosion sensitive when externally mounted, in case of steel tendons.
- Need very stiff and powerful anchorage.
- Cause large extra moments that make strengthening of other parts necessary.
- Not economical for shorter spans.
- Need space for tendons, diaphragms and anchorage devises.

5.3 Examples
In Nottingham a concrete box girder bridge has been strengthened with external prestress during 24 weeks in 1997, Driver and Haynes (1998). The bridge needed strengthening for bearing of the support moments. Roughly 1m³ of concrete were used for each anchorage block. Traffic ran on the bridge deck continually throughout the project.
A bridge Southwest of London, the A3/A31 flyover, was built with post-tensioning between 1973 and 1976. The bridge showed in 1978 growing cracks and therefore a need for strengthening. The bridge was externally re-post-tensioned and showed problems again in 1994, Robson et al (1997). This time it was found that two strands had completely failed and there were a lot of wire failures in many other strands. The failures were due to corrosion and traffic restrictions were taken. In the 1996 the bridge were strengthened by replacement of the tendons during use of temporary prestressing devices.

The steel and concrete Friarton Bridge in Scotland, Slater (1997), needed strengthening over the supports due to higher design loads. The bridge was strengthened with insertion of prestressing cables and stiffeners of steel at the compression flange.

Burlington Skyway bridge, a steel truss bridge located in Canada, needed to be strengthened due to an increased number of lanes and heavier design loads. The bridge was strengthened in 1990 by external post tensioning using Dywidag bars, Farago (1990). The method was chosen after investigation of prestressing, individual replacements, addition of new elements and replacement of whole beams. Some vertical and diagonal members were also strengthened due to local prestress forces from the strengthening system.

A bridge over Mosel in Germany was built in 1963. At the beginning of the 1980s, the bridge showed a heavily corrosion of an anchorage link and deflection of the hinge at centre of the main span, see Figure 5–1. The bridge was repaired in 1986 by supplementary prestress, closing of the hinge and removal of the defected anchorage, Mallet (1994).

![Diagram](image_url)

**Figure 5–1** Strengthening of Mosel Bridge at Thörnich with supplementary prestress, Mallet (1994)
A three-span, steel-beam, concrete-deck, bridge in Iowa, USA, was strengthened in 1988 in all spans with post tensioning, Klaiber et al (1990).

A curved bridge built 1973 in Switzerland consisting of two prestressed girders were posttensioned 1988 because of lost prestressing forces which led to too big deformations, Fuzier (1990).

A viaduct over the River Cam in England was built 1926. It was strengthened in 1974 by prestressing of Macalloy bars and a 50 mm galvanised mesh covered with a layer of shotcrete, Mallet (1994).

Hythe Bridge was constructed 1874. The decks comprise 8 inverted tee section cast iron beams. Three of the beams were found badly cracked. 1998 it was decided to strengthen the bridge. The cracks were first stitched together by the ‘Metalock’ system and additional plating was then applied to do local strengthening. Prestressed carbon fibre laminates were used to strengthen the beam globally, Darby et al (1999).

Mallet (1994) further presents several examples of bridges strengthened by post tensioning.

A two-span post-tensioned concrete A31 overbridge with the A3 at Guildford. This glued segmental bridge needed temporary post-tensioning to be applied before it was safe to cut the existing corroding tendons. The temporary prestress was provided by two differing tendon types above and below the deck. Anchorages for the temporary tendons were purpose made friction grip devices. The permanent prestress was installed following cutting of the existing tendons. The new tendons consist of 35 strands inside a wax filled plastic sheath, Bennet (1999).
6 TRENDS AND FUTURE

6.1 General
The infrastructure in many industrialised countries is ageing. In the US for instance, the interstate highway system is in disrepair. Almost 40% of US bridges are in some state of serious deterioration, Li (1998). Put in economic terms, the magnitude of our infrastructure need is enormous. Worldwide about 10% of GDP derives from infrastructure construction. In US alone, there are approximately $17 trillion of infrastructures in place, Li (1998). Obviously it is not possible to replace our bridges frequently. Instead the solution must lie in repair, retrofit and rehabilitation technology.

Improvement of concrete structures and especially improvement of bridges is a fast growing area. In the future it is probably going to be even more common with strengthening as new methods and techniques are developing and the knowledge of environmental aspects and life cycle cost are increasing.

6.2 History
Structures have been strengthened as long as structures have been built. In the beginning structures were built by the principle of trial and error. When the structures could not carry the loads they were built for, they were strengthened by use of more materials and larger cross-sections. This is also the first strengthening technique in connection with use of different supporting elements.

By time the structural understanding increased. This means that structures could be built with less extra capacity which earlier had led to longer length of life. The consequences were that the need for repairing and strengthening increased.

When the structures became more refined, the strengthening methods also improved. When prestressed reinforcement was introduced and accepted in structures, post tensioning became a strengthening method.

In the late sixties the method of plate bonding of steel plates began to be studied and in the seventies a lot of bridges were strengthened mainly in England, Täljsten (1994). When carbon fibre products became cheaper in the eighties the research of using these new materials started. Nowadays, a lot of research has been done and the use of externally bonded fibre reinforced polymers is an accepted and world wide used strengthening method.

6.3 Future
The loads on the infrastructure have up to now increased and in recent decades quite rapidly. It will probably more or less continue to increase also in the future. New methods for strengthening will see the light of the day and the old ones will be further developed.

International conferences, Mihashi and Rokugo (1998) and Dhir and Jones (1996), show that external bonding with advanced composites is a fast growing method. The method will probably be even more common as the price of carbon fibre is decreasing. The method with bonding of steel plates will probably be less used in competition with carbon fibres. Strengthening with carbon fibres will probably outdo post tensioning and
other strengthening methods in some cases. Anyhow these methods will also have an increase due to a larger market for strengthening and repair systems.


The method with post tensioning with tendons of carbon fibre have a great potential but need to be further developed before it will have an extended application.

6.4 Research

Repairing and strengthening are more complicated than building new structures. Many parameters are already fixed and the materials are often in a deteriorated condition. Even if the work is done for strengthening, the failure mode can be the governing factor since a failure is not allowed to be brittle.

Since the strengthening business is a fast growing area a lot of research need to be done. For instance codes and handbooks must be written for this kind of works. There is also some structural muddiness in all techniques that need to be investigated to bring clarity. It is also of interest to investigate how strengthened elements works as a part in a system with other non-strengthened structural elements. For example if a member in a system is strengthened the mode of action for the whole structure will be affected by the local change in stiffness. Some suggestions for research regarding upgrading of concrete bridges can be found in Elfgren et al (1999).

6.4.1 Increased Dimensions

Some problems are not solved in spite of the fact that the method is widely used. Especially the bond between new and old materials can be further investigated. Deterioration mechanisms are not completely explained and creep shrinkage of the new layer must be completely understood. For concrete structures there is a need to investigate the use of carbon or glass fibre (CFRP/GFRP) bars instead of steel bars.

6.4.2 Externally Bonded Reinforcement

Even if the technique is frequently used all around the world there are still some areas that have a need for research. Some of them are:

- Surface treatment before strengthening. It has been found that it is time-consuming to make the surface plain before strengthening. In many cases this is over ambitious but necessary since there are no knowledge about how plain the surface need to be. The method would be more cost-effective with knowledge of a critical level of plainness.

- Dynamic loads during curing of the polymer. During strengthening it is unwanted to interrupt the traffic. It has been showed Täljsten and Carolin (1999), that it is possible with some traffic during the strengthening work but it would be very useful if the relation between dynamical movements and strengthening effect could be clearly stated.

- Milling recesses to inset the composite. In some applications there can be a risk of damage of the composite. This can be avoided with tracks in the concrete that will
protect the composite rods from vehicle impact for instance. This area is very little examined but has a great potential. The technique for milling is well-developed see Figure 6-1, but the mode of action and anchorage lengths of this application needs to be investigated.

![Milled recesses for composite rods. Distance between tracks approximately 7 cm.](image)

Figure 6-1 Milled recesses for composite rods. Distance between tracks approximately 7 cm.

- Prestressing of the composite. Systems with prestressed sheets or laminates can be developed to achieve a higher strengthening effect.
- Calculation models. The calculation models for this technique is well developed for bending, but in shear there are still some work to do to refine the theories.
- Influence on the strengthening effect from climate conditions. The strengthening work is in most cases done at a site where the temperature and humidity is different from normal laboratory environment. Today the restrictions regarding weather can be to hard cause of ignorance of the critical level for those conditions.
- Behaviour in cold climate. It is important to study if the strengthening effect is the same at −35 °C as at +20 °C. The mode of failure may also differ with the temperature.

### 6.4.3 Post Tensioning

With post-tensioning great forces are locally applied to the structure. The anchorage system for these forces can be further developed to improve the method. Corrosion and increased corrosion rate due to high strains is a problem. The service life for this type of structures can be better predicted with more understanding of the mechanisms of the corrosion process.
7 REFERENCES


References


