FRP strengthening of concrete structures: new inventions and applications

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Summary
The advantages of FRP strengthening have been shown time and again during the last decade. All over the world several thousand structures retrofitted with FRPs exist. There are various reasons why the retrofit is needed, but since buildings and civil structures usually have a very long life, it is not uncommon that the demands on the structure change with time. The structures may have to carry larger loads at a later date or fulfill new standards. In extreme cases, a structure may need repair, owing to an accident, or to errors made during the design or construction phase, such that the structure needs to be strengthened before it can be used. Over the past decade, the issue of deteriorating infrastructure has become a topic of critical importance in Europe, and to an equal extent in North America and Japan.

The deterioration of bridge decks, superstructure elements and columns can be traced to reasons ranging from ageing and environmentally induced degradation, to poor initial construction and lack of maintenance. Added to the problems of deterioration are issues related to the need for higher load ratings and increased numbers of lanes to accommodate the ever-increasing traffic flow on major arteries.

As a 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 economic issues related to time and resources caused by delays and detours. As we move into the twenty-first century, the renewal of our lifelines becomes critical. Here, FRP strengthening may be a tool in the overall toolbox to be used to overcome some of the problems related to repair and strengthening of structures.

In this paper a short historical background to plate bonding is presented. The paper focuses on the possibility of improving the existing technology and how drawbacks can be overcome.

Key words: retrofitting; concrete; FRP; NSMR; mineral bonding agents

Introduction
The motivation for research and development into repairing, strengthening and restoration of existing structures, particularly concrete systems, is increasing. If consideration is given to the capital that has been invested in the existing infrastructure, it is not always economically viable to demolish and rebuild a deficient structure. The challenge must be to develop relatively simple measures such as restoration, repair and strengthening that can be used to prolong the life of structures. This challenge places a great demand on both consultants and contractors. Also, there could be difficulties in assessing the most suitable method for an actual repair; for example, two identical columns within the same structure can have totally different lifespans, depending on their individual microclimate.

At the end of the 1980s, Luleå University of Technology commenced research into the repair and strengthening of existing concrete structures utilizing the plate bonding technique. Initially steel plates were used to strengthen members. Currently, however, all research is focused on plate bonding using fibre-reinforced polymer (FRP) composite materials in which, carbon fibre composite is the favoured material.
Historical background

Apparently humans learned early on how to join together different materials. In nature there are many materials with adhesive properties, for example clay, mud, resin and egg white. They were used for various purposes, producing scrolls or ornaments in early households. Natural adhesives such as starch, animal glues and plant resins have been used for centuries and are still used widely today for packing and for joining wood. However, these adhesives are not very good for structural bonding, where polymer adhesives such as epoxies and polyesters are used. These are also known as synthetic adhesives. Such adhesives are widely used today, but were first used in Germany at the beginning of 1930s. The first synthetic adhesives were sold in the form of hard processing films. Owing to the expansion of the aircraft industry during the Second World War, adhesives were developed to be more easily handled. The construction of wooden wartime aircraft was facilitated by the availability of phenol resorcinol and ureaformaldehyde-based adhesives. Since then, reactive formaldehyde-based adhesives continue to be used in the manufacture of timber-based building elements, such as plywood and laminated timber beams[1].

Over the past four or five decades natural adhesives have been improved, and there has been an intensive development of synthetic adhesives to meet demanding technical applications. These synthetic polymers, which include thermoplastic and thermostetting types, have been developed to possess a balance of properties that enable them to adhere readily to other materials, to have an adequate cohesive strength and appropriate mechanical characteristics when cured, to ensure good durability, and to fulfil various applications and manufacturing requirements.

The method of strengthening existing concrete structures with the use of epoxy adhesives originated in France in the 1960s[2-4], where tests on concrete beams with epoxy bonded steel plates were conducted. There is also reported use of this strengthening method in South Africa in 1964[5]. Since then, the application of epoxy bonded steel plates has been used to strengthen bridges and building in several countries over the world; Switzerland[6,7], the former Soviet Union[8], the United Kingdom[9], Australia[10], the United States[11], Japan[12] and Sweden[13], just to mention a few.

Even though the method was used widely, it was not considered very successful. The drawbacks such as corrosion, the need of overlap joints, the heavy working loads during installation and the need for pressure on the adhesive during hardening could not be overcome. In 1995, one of the last applications to strengthen bridges with steel plates was carried out in Sweden, and this is shown in Fig. 1. This project was considered successful, but the disadvantage of the technique—heavy plates, need of joints, bolting and pressure during curing of the adhesive—still remained. An inspection after 8 years shows no corrosion or degradation of the strengthening system.

In the last decade the plate bonding method has gone through a revival. The reason for this is mainly the increased need for retrofitting of our existing buildings and bridges. However, another very important factor is the introduction of advanced composites to the civil engineering arena. Fibre composites and reinforced plastics offer unique advantages in applications where conventional materials cannot supply a satisfactory service life[14]. The high strength-to-weight ratio and the excellent resistance to electrochemical corrosion of composites make them attractive materials for structural applications. In addition, composites are formable and can be shaped to almost any desired form and surface texture. One interesting application of currently available advanced composite materials is the retrofitting of damaged or structurally inadequate building and bridges. In Switzerland[15], one of the first applications with the use of carbon FRP (CFRP) was carried out at the end of the 1980s, and since then several thousand applications have been carried out worldwide.

Clearly there is a great potential for, and considerable economic advantages in, FRP

Fig. 1 Underside of a concrete bridge in Sweden strengthened by steel plates in the mid-1990s
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 to know the practical limits of any proposed strengthening method.

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 now continuing with FRP materials. Both comprehensive experimental work and theoretical work have been carried out. The laboratory tests have included strengthening for bending as well as for shear[16] and torsion[17]. Full-scale tests on strengthened bridges have also been performed[18–20]. In particular, the theory behind the development of peeling stresses in the adhesive layer at the end of the strengthening plate has been studied, as has been the theory of fracture mechanics to explain the non-linear behaviour in the joint[18,21,22].

In Sweden the FRP strengthening methods have been used in the field for almost 10 years now, and both laminates and wrap systems are used. Sweden is also one of the first countries in the world where a national code exists for FRP strengthening[23].

Advantages of using FRP in construction

There exist many technical solutions for structural problems and deficient concrete, and the final decision is always based on many factors. Some of these factors include: material cost, demand for mechanical strength and stiffness, impact resistance and resistance to vandalism, resistance against environmental effects, long-term properties such as relaxation and creep, application, and production methods. In addition, in some cases, the client may not be familiar with the purposed solution and, therefore, chooses a more conventional method. However, FRP strengthening poses a number of potential advantages.

Handling and transportation

The composite materials used for strengthening are very light and easy to handle. In comparison with steel plate bonding where plates not longer than 2–3 m can be handled, here almost infinitely long plates or sheets can be handled. In addition, no overlap plating is necessary. Also, compared with traditional concrete overlays or shotcrete, much less material has to be transported when FRP strengthening is used.

Durability and maintenance

Carbon fibre composites have especially good durability, long-term fatigue properties, and do not need to be maintained over time.

Thin strengthening layers

In many situations, thin strengthening layers can be advantageous. Thin layers will not change the dimension of the existing structure and can also be combined with thin concrete overlays or surface-protecting materials. Here low underpasses for road traffic can be an application where otherwise complicated methods of strengthening would be needed.

Construction time

Time is always a critical factor in the construction industry. If time can be reduced, money can be saved. FRP strengthening can often be done during short periods without stopping the traffic, and little time is needed for hardening of the bonding agents.

Prestressing possibilities

During the last few years, products have been introduced to the market that can be prestressed in combination with bonding. This gives a higher utilization of the strengthening product, at the same time reducing existing cracks, and increasing the yield load of the existing steel reinforcement. It is also possible to use prestressing to increase the shear capacity of concrete structures.

Design

The possibility to optimize the FRP materials in the direction most needed is a benefit for design. In addition, compared with many other strengthening techniques, few methods have undergone such thorough investigation regarding testing, design and application as FRP strengthening. Therefore, the consultant can rely on existing design guidelines.

Cost

The cost of a strengthening work with composites compared with traditional methods is often lower, even though the material costs are higher.

Disadvantages

Mechanical damage

Since the FRP materials themselves are brittle, they can be damaged by vandalism or by other types of attack. If this is a concern, the FRP should be protected. Fortunately, if damage should occur, repairs can be easily undertaken.
LONG-TERM PROPERTIES
Carbon fibre composites with an epoxy matrix are said to have very good long-term properties. However, since the materials have been used for only about 10 years in the building industry, not enough data exist to verify this. However, the main concern is probably not the composite itself, but rather the adhesive layer. Nevertheless, the experience from older steel plate bonding projects shows that many of these structures are still in use with no visible deterioration of the bond layer. If the right type of material is used, and if the strengthening work is carried out carefully, 30 years of use can be guaranteed.

WORKING ENVIRONMENT
Since epoxies are used for bonding the sheets or laminates to the structure, the working environment is very important. If these materials are not handled as prescribed, a risk for injuries to the labourers exist. However, with correct handling, the risk for injuries is very low.

TEMPERATURE AND MOISTURE DEPENDENCE
The hardening process of thermosetting adhesives is moisture and temperature dependent. It can be necessary, therefore, in some environments to heat to the structure.

LACK OF EXPERIENCE
Lack of experience is of course a large disadvantage. However, this can be overcome with education. Importantly, the knowledge must reach the consultants and the clients.

CONSERVATISM
The well-known conservatism of the construction industry towards something new can be difficult to overcome. Again, the solution is education and the dissemination of knowledge.

DESIGN
The lack of experienced building consultants who understand composites and how they should be used is a big drawback. Since it is the consultant that recommends a solution, if s/he does not know that a certain method exists or how to handle it, s/he will of course suggest another method.

COST
The carbon fibre sheets or laminates are much more expensive compared with traditional building materials, at least per m² or per kg. In some contexts this is a factor and other methods will be used. Nevertheless, as mentioned earlier, the whole strengthening project needs to be considered to get a fair comparison.

Near-surface-mounted reinforcement
Near-surface-mounted reinforcement (NSMR) is a further development for plate bonding with FRPs. The method implies that rods mainly of CFRP are bonded in sawn grooves in the concrete cover. As opposed to external strengthening techniques, the use of NSMR will better protect the strengthening material from external damage, such as vehicle impact. In some cases, it may also be easier to work with than traditional CFRP laminates. Another advantage, compared with fabrics, is that the concrete surface will not be completely covered, thus preventing the trapping of moisture in the structure and possible freeze–thaw problems. However, it has to be remembered that this technique can be used only on structures with sufficient concrete cover, since the rods are mounted in this cover. In Fig. 2 the principles for NSMR are shown. It is also possible to achieve increased bond surface with NSMR compared with traditional laminate plate bonding, thereby avoiding a normal concrete surface failure as seen with laminates.

Plate bonding of a larger volume of the concrete will fracture at failure, i.e more energy is needed to fracture a NSMR strengthened concrete structure than a laminate strengthened structure. Not many tests with NSMR have been reported in the literature. However, tests with circular rods[24] and with rectangular rods by[25] have been carried out. The method was developed in Sweden during the 1940s[26], but at that time with steel bars instead of FRP. This method has now been developed to using square-section CFRP rods, which are bonded either by epoxy polymer or a cementitious bonding agent. The reason for using rods with square cross-section is that the sawn groove will have parallel vertical sides and a uniform adhesive thickness around the rod is desirable; this may be seen Fig. 2. The research with NSMR covers traditional tests of flexural capacity, but also tests with live loads acting during the

Fig. 2 Plate bonding with different types of NSMR
strengthening process and behaviour in a cold climate[27,28].

For flexural strengthening with NSMR, the same design equations as for traditional FRP strengthening may be used, see Equation (1). Equations for anchorage and peeling failure need to be somewhat modified, see for example[29–31].

\[ M_d = A'_s \sigma'_s (\beta x - d'_s) + A_s f_y (d_s - \beta x) + \epsilon_l E_t A_t (\beta - \beta x) \]  

(1)

where \( M_d \) is the designed bending moment; \( A'_s, A_s \) and \( A_t \) are the cross-sectional areas of compressive reinforcement, tensile reinforcement and composite, respectively; \( E_t \) is the Young’s modulus of the composite; \( \sigma'_s \) is the stress in compressive reinforcement; \( f_y \) is the yield stress in the tensile reinforcement; and \( d_s \) and \( d'_s \) are the level arm distances to the tensile and compressive reinforcement, respectively. The distance to the neutral axis is denoted \( x \), \( \beta \) is a factor to take account of the simplification of the compressive stress block of concrete, and here \( \beta \) is set to 0.4. CFRP composites may be prestressed to achieve an effective utilization of materials. There are several reasons why a prestressing force should be applied to a concrete structure. One reason is that the applied axial load induces a bending moment that opposes the self-weight of a concrete structure[32]. Another reason is that the first crack load is considerably increased compared with non-prestressed strengthened beams and beams without strengthening. This can increase the durability of the concrete structure. However, the ultimate load is approximately the same as for non-prestressed strengthened concrete structures[33]. Tests on concrete beams prestressed with CFRP sheets at room and low temperatures have also been carried out[34].

One of the most important advantages when strengthening a structure with pre-stressing members is the reduction of stress in existing tensile steel reinforcement. This should lead to an increase of the fatigue behaviour of the members in the structure[32,35].

The research on NSMR in progress at Luleå University of Technology is mostly focused on prestressed NSMR[36,37]. Tests have shown that very high stresses can be transferred into the concrete structure, and in the ancillary tests, so far, no mechanical anchor system has been used. Long-term applications utilizing this technique are currently being investigated, and a mechanical anchorage system for this purpose is under development.

The theoretical stress and strain distribution of a rectangular prestressed beam with NSMR is shown in Fig. 3; Fig. 3(b) shows the strain distribution where it has been assumed that plain sections remain plain during loading. In Fig. 3(c) and 3(d) the stress distribution due to the bending moment and the prestressing force is shown.

From Fig. 3(c), the stress at level \( z \) from the bending moment is:

\[ \sigma_M = \frac{M}{I} z \]  

(2)

Correspondingly the stress from the compressive force at level \( z \) is:

\[ \sigma_P = -\frac{P}{A} - \frac{P e}{I} z \]  

(3)

The combination of these stresses gives the total stress at level \( z \):

\[ \sigma_z = (\sigma_M + \sigma_P)_z = \frac{M}{I} z + \left( -\frac{P}{A} - \frac{P e}{I} z \right) \]  

(4)

where the bending moment, \( M \), acts on a cross-section together with a prestressing force \( P \). Here, \( e \) is the level arm distance from the centre of gravity to the prestress force, \( z \) is the distance from the centre of gravity to a given level. \( A \) and \( I \) are, respectively, the cross-sectional area and moment of inertia for an uncracked section.

Laboratory tests with non-prestressed and prestressed rectangular NSMR rods show that with prestressing an increase of both the concrete cracking and the steel yielding loads can be achieved (Fig. 4).

In this case, the prestressing level was approximately 20% of the ultimate strain for the NSMR rod, which corresponds to approximately 2000 \( \mu \). In Fig. 5 the test set-up is shown. In Table 1 the

![Fig. 3 Stresses and strains acting on a prestressed cross-section](image-url)
data from test are reported, where $f_{cc}$ and $f_{ct}$ are, respectively, the compressive and splitting strength of concrete. The failure load is denoted $P_f$, and the deflection at failure, corrected for the camber, is $\delta_f$.

The tests reveal that considerable strengthening can be obtained with rectangular NSMR rods. Also, the same cross-section of rod gives approximately the same maximum increase in strength, irrespective of the prestressing force.

It can also be noticed that the deflection at failure for the prestressed beam is substantially smaller than that of the non-prestressed beam. The explanation for this is that when a linear elastic material, such as the NSMR rod, is prestressed a part of the strain is ‘consumed’ in the prestressing. Since both the non-prestressed and the prestressed rods reach the ultimate strain at failure, in this case $>10000 \mu\text{s}$, the prestressing strain, $2000 \mu\text{s}$, was already used. Consequently the prestressed beam reached a smaller deflection at failure. Both the prestressed and the non-prestressed beam obtained failure in the rod when the ultimate strain was exceeded.

Testing is also ongoing on larger concrete beams. Here, three rectangular, 10 mm, NSMR rods have been used, with no prestressing. The rods were bonded in a rectangular saws groove with a cross-section of $15 \times 15$ mm. Comparisons are made with a reference beam without strengthening, and with a concrete beam strengthened with externally prestressed steel cables. The load-deflection curves from the test are shown in Fig. 6, and in Fig. 7 the test set-up is shown. The material data, test configuration and results from test are recorded for in Table 2 and in Figure 7.

The test is designed so that the NSMR-strengthened beam and the beam strengthened with external cables fail at the same load. However, it can be found from the load–deflection diagram in Fig. 6 that the beams strengthened with prestressed external cables had a more ductile failure envelope. The next tests in this series will be with rectangular prestressed NSMR rods.

### Mineral-based bonding systems

It would be, from several points of view, very beneficial and interesting if the epoxy adhesive could be replaced with a mineral-based bonding agent, such as modified concrete. One of the drawbacks with

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**Table 1** Data from tests with concrete beams strengthened with NSMR

<table>
<thead>
<tr>
<th>Beam</th>
<th>Configuration</th>
<th>Failure</th>
<th>$f_{cc}$ (MPa)</th>
<th>$f_{ct}$ (MPa)</th>
<th>$P_f$ (kN)</th>
<th>$\delta_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reference</td>
<td>Bending/yielding</td>
<td>64.2</td>
<td>5.7</td>
<td>75.0</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Non-prestressed NSMR</td>
<td>Failure in rod</td>
<td>65.4</td>
<td>5.8</td>
<td>117.7</td>
<td>55.1</td>
</tr>
<tr>
<td>3</td>
<td>Prestressed NSMR</td>
<td>Failure in rod</td>
<td>68.2</td>
<td>6.1</td>
<td>122.9</td>
<td>38.7</td>
</tr>
</tbody>
</table>

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epoxy is that it is considered toxic; on the skin, thermosetting components can cause irritations and eczema. Inhalation of epoxy resins should be also avoided. The hardeners have, as a rule, a pungent smell that can cause temporary irritation of the respiratory tract.

Inhalation of amines does not normally cause any poisoning. The risk of swallowing thermosetting components is deemed minor. In order to avoid problems with epoxy work, the work should be well planned in advance, and personal protective equipment should be used.

Another area where it would be beneficial to replace epoxy is when retrofitting work is carried out on areas where the concrete needs to be open to diffusion, i.e. wrapping of columns or similar applications. Low temperatures might also cause problems for thermosetting adhesives, where most formulas need at least $10^\circ C$ to get the exothermic hardening process started. Here it would be possible to apply the cement-based bonding agent at temperatures as low as $0^\circ C$. That means that if the epoxy adhesive could be replaced with a mineral-based bonding agent a more environmentally friendly, diffusion-open and less temperature-sensitive strengthening system could be obtained. However, these systems will most likely also have drawbacks. For example, laminates or dry fabrics will be complicated to bond, the laminate owing to low adhesion to the composite and the fabric because of inferior wetting of the fibre. Research with the use of short FRP fibres has been going on for some time now,[38–40].

However, research with the use of long FRP fibres is limited. Research studying cement overlays with textiles of carbon fabrics embedded in cement-based matrix to strengthen masonry walls has been carried out[41]. The strengthening system prevents partial or complete collapse of masonry walls in the critical out-of-plane direction during a seismic event.

![Fig. 6 Load–deflection curves for concrete beams strengthened with NSMR](image)

![Fig. 7 Test set-up](image)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Configuration</th>
<th>$f_{cc}$ (MPa)</th>
<th>$f_{ct}$ (MPa)</th>
<th>$P_f$ (kN)</th>
<th>$d_f$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Reference</td>
<td>47.0</td>
<td>3.9</td>
<td>114.2</td>
<td>42.5</td>
</tr>
<tr>
<td>B</td>
<td>Prestressed steel</td>
<td>54.0</td>
<td>4.0</td>
<td>315.3</td>
<td>149.0</td>
</tr>
<tr>
<td>C</td>
<td>Non-prestressed NSMR</td>
<td>53.0</td>
<td>4.0</td>
<td>302.0</td>
<td>74.0</td>
</tr>
</tbody>
</table>

A study to improve the bond between carbon fibres and cementitious matrices has been carried out \cite{42}, where dry fibre fabrics were used. It was found that a pretreatment with silica fume and high amounts of polymers improved the bond behaviour of carbon fibre to the cement. However, it was also stressed that more research is needed in this field.

Some very interesting pioneering work has been carried out \cite{43} in which large-scale tests of ordinary concrete beams strengthened with a cementitious fibre composite were reported. The composite used was made of polymer-modified mortar and a unidirectional sheet of continuous dry carbon fibres applied by hand. Both flexural and shear strengthening were tested. From the tests it was concluded that the method works, and that considerably strengthening effects can be achieved. In comparison with epoxy bonded carbon fibre sheets, the amount of carbon fibre needed to reach the same strengthening effect for the cementitious strengthening system was more than double. The reason for this is mainly due to problems with wetting the carbon fibre. This is also emphasized by Badanoui & Holmgren \cite{44}, where it was found that the load capacity of the cementitious carbon fibre composite is influenced by the amount of fibres in the tow. If the cementitious matrix can penetrate into the interior of the carbon fibre tow, a higher number of filaments will be active during loading, and this will lead to the increase in load-carrying capacity.

At Luleå University of Technology a research programme is currently ongoing regarding the use of cementitious bonding agents in combination with carbon fibre composites. In this paper a brief description of pilot tests \cite{45}, carried out on strengthened concrete slabs will be presented. The research at Luleå University of Technology is focused on the use of cementitious bonding agent as a replacement for epoxy adhesive. In light of tests performed by earlier researchers \cite{43}, a different path to overcome problems with wetting the fibres has been chosen. Instead of using dry fibres, a thin composite is chosen. This composite may be in the shape of a small rod (one-dimensional), grid (two-dimensional) or basket (three-dimensional). In the pilot test, a two-dimensional grid has been chosen as reinforcement.

In this particular case, the matrix for the grid consists of epoxy, and the product is manufactured in factory-controlled environment. The test set-up and the test configuration for the pilot tests are shown in Fig. 8. In total, six slabs were tested, one reference slab, one with additional steel reinforcement and three with carbon fibre grids. Here, one of the grids was sanded to increase the bond to the cementitious bonding agent, and for one of the tests the amount of carbon fibre was doubled. In the last slab tested, traditional epoxy-bonded carbon fibre fabric was used for strengthening. In Table 3 the material data and dimensions of the slabs are shown, and in Fig. 9 the load-deflection diagrams for the tests can be seen.
where $f_{cc}$ and $f_{ct}$ are the compressive and splitting strength of concrete, respectively. $P_c$ is the cracking load for concrete and $P_y$ the yield load for the slab. The failure load is denoted $P_f$.

It can be noticed in Fig. 9 that the slab with the highest reinforcement content, i.e. No. 5 with two layers of carbon fibre grid, sustained the highest load at failure. Slabs 2, 3, 4 and 6 were all designed for approximately the same failure load. Slab No. 3 reached failure earlier than the other slabs, owing to breakage of the fibres. The reason for fibre breakage was that the bond between the grid and the cementitious bonding agent was too high, and a failure arose at a crack in the cementitious bonding material. In slab 4 a small slippage between the cementitious bonding material and the grid provided for a higher load. However, in comparison with slab 6, where fabrics had been bonded with epoxy to the slab, a less stiff behaviour could be noticed for the slabs with a single carbon fibre grid. Slabs 2, 4 and 6 reached approximately the same failure load. The slab with extra steel reinforcement, No. 2, showed stiffer behaviour than slabs 4 and 6. Also a theoretical model was developed; however, this model is not presented here. The test was considered promising, and a more comprehensive programme is now running at the University.

### Future aims and needs

There are many areas that need to be further investigated regarding repair and strengthening of existing structures. In the next 4–6 years, focus will, at Luleå University of Technology, be placed on; system thinking, standardisation, long-term behaviour, risk-based design, environmentally friendly strengthening systems, composites in construction in general, and smart materials and structural health monitoring in particular.

In all fields we aim for a strong international collaboration where Luleå University of Technology is one of several important hubs in this research. We believe that more environmentally friendly strengthening systems are essential for long-term success in the area of repair and strengthening—here mineral-based bonding agent could be a very interesting path to follow. In addition, more research needs to be focused on systems, where for example one strengthened part would changes the behaviour of the whole system. Furthermore, a more holistic view of the function of real structures must be built up; here structural health monitoring (SHM) may be one research area to help to obtain this. Risk-based and probabilistic design, where real loads and material values are used, could open up new ways of designing, in particular in regard to repair and strengthening of existing structures.

### Summary and conclusions

In this paper a short summary on past and ongoing research in the area of plate bonding has been reported. The author discusses the development from steel plate bonding to the use of advanced fibre composites for retrofitting of building structures. Two innovative areas within repair and strengthening are discussed more thoroughly: prestressed NSRM (near-surface-mounted-reinforcement) of rectangular carbon fibre rods and the use of cementitious bonding agents in combination with advanced composite materials. Tests are presented briefly in both areas, and it can be seen from the results that by prestressing the rods considerable improvements in flexural behaviour can be achieved, such as increases concrete cracking load and steel yielding load. Slabs strengthened with CFRP grids and bonded to concrete with a cementitious bonding agent are comparable to a slab strengthened with epoxy-bonded carbon fibre fabrics and a slab with increased steel reinforcement. However, the pilot tests
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