Strengthening structures with externally prestressed tendons

Laboratory tests

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Technical Report
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PREFACE

In this report the laboratory tests with externally prestressed concrete beams is presented. The tests were carried out at Testlab, Luleå University of Technology.

The study has been supported by my supervisor Prof. Dr. Björn Täljsten.

The financial support was given by the Development Fund of the Swedish Construction Industry (Svenska Byggbranchens Utvecklingsfond, SBUF).

A special thanks to Testlab at Luleå University of Technology, for their help and support during the tests.

Luleå December 2004

Håkan Nordin
SUMMARY

The need of rehabilitation and strengthening of concrete structures has increased considerably the last decade. The causes for repair and/or strengthening can be many, but normally change of use, increased demands on the structure, errors in the design or/and construction phase or accidents are governing. Many methods to repair or/and strengthen concrete structures exists such as concrete overlays, shotcrete, external prestressed cables etc.

This report presents laboratory tests where concrete T-beams with a length of 6 meters have been strengthened. External prestressed cables and epoxy bonded CFRP (Carbon Fibre Reinforced Polymer) rods have been used. Three beams had external tendons, two with steel tendons and one with CFRP. Three beams were strengthened with epoxy bonded CFRP Near Surface Mounted Rods (NSMR). On one of those beams the rods were prestressed before bonding. One beam had post-stressed internal steel tendons and also a non strengthened reference beam was tested.

The results showed that all tested strengthening techniques increased the load carrying capacity of the beams. The beam with external tendons of CFRP obtained problems with the anchor and could therefore not be prestressed to the desired level, which also then had effect on the strengthening level. The other strengthened beams recorded for a strengthening level from 81% to 107% depending on the technique used.

The tests scores show that prestressing is a very effective strengthening method to increase the load carrying capacity of existing concrete beams.
SAMMANFATTNING

Behovet av återställande och förstärkning av betongkonstruktioner har ökat markant det senaste deceniet. Orsaken till reparation och/eller förstärkning kan vara många, men normalt är förändrat nyttjande, ökande krav på konstruktionen, fel i design och/eller byggandet eller olyckor bidragande. Det finns många metoder att genomföra reparation och/eller förstärkning som till exempel betong påbyggnad, shotcrete, utanpåliggande spännkablare etc.


Resultaten visar att alla testade förstärkningstekniker ökade lastkapaciteteten för balkarna. Balken med utanpåliggande kablare av CFRP fick problem med förankringen och därför kunde inte önskad förspänning uppnås, vilket också fick följdeffekt på förstärkningseffekten. De övriga förstärkta balkarna hade en förstärkningseffekt på från 81% till 107% beroende på använd teknik.

Försöksresultaten visar att förspänning är en effektiv förstärkningsmetod för att öka bärförmågan hos befintliga betongbalkar.
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1 INTRODUCTION

1.1 General

External prestressing was initially developed for strengthening of bridges, but is today used for both strengthening of existing as well as for new built structures. Prestressed concrete bridges with external prestressing are becoming popular because of their advantages, like simplicity and cost-effectiveness. External prestressing is when unbonded tendons are placed, and prestressed, outside the structure anchored at the ends and sometimes with one or several deviators during the length of the structure. This method is advantageous for strengthening of a structural member to obtain improved load carrying capacity.

The external tendons can be made of steel, but also fibre reinforced polymer (FRP) materials have been used. They provide one of the most efficient solutions to increase the load carrying capacity of existing bridges when the infrastructures are in need of renewal and made of all structural materials, such as concrete, steel and timber.

1.2 Scope of the study

The scope of this report is to present the laboratory tests that have been conducted at Luleå University of Technology during the spring of 2004 concerning strengthening of concrete structures with external tendons.

The tests aim to compare the strengthening techniques of prestressed external tendons and steel and CFRP and strengthening with Near Surface Mounted Reinforcement (NSMR), both with and without prestress. The tests are an initial study that will be complemented in future test series.

The tests have been limited to concrete T-beams. The strengthening methods that were chosen were external tendons with steel and CFRP. During the initial face of the study it was decided to include internal post-tensioned tendons of steel and Near Surf ace Mounted Reinforcement (with and without prestress).
2 LABORATORY TESTS

2.1 Test set-up
The tests were carried out at Luleå University of Technology during spring of 2004. The test specimens were concrete T-beams with a length of 6 meters. The flexural steel reinforcement was three Ø16mm bars in the lower part of the beam and four Ø10mm bars in the upper part, see figure 2.1. The shear reinforcement were designed to ensure flexural failure, stirrups Ø12mm were placed with a 100mm distance over the whole length of the beam. The tensile strength of the steel reinforcement was \( f_y = 496 \text{MPa} \). The strength of the concrete for each beam is presented in table 2.1.

![Figure 2.1 Cross-section of the beams, in mm](image)

The beams were loaded under four-point bending as can be seen in figure 2.2 and figure 2.3. The load was applied with deformation control at 0.2mm/s until failure or to a point where the beam no longer could carry any more load.
2.2 Measuring

The beams were measured with both strain gauges and displacement gauges. During prestressing the tension in the midsection was measured by the use of strain gauges in the upper part of the concrete beam and in the internal steel reinforcement, see figure 2.2. The prestressing force in the strengthening material was controlled differently; it is described for each beam in the coming sections.

During testing the strain, midpoint and support displacement was measured as well as the load.
2.3 Beams tested.

A total of eight beams were tested during the series. The strengthening techniques used were externally prestressed steel rods, externally prestressed CFRP rods and Near Surface Mounted Reinforcement (NSMR) with CFRP rods with and without prestress.

For complete view of the beams tested see table 2.1 and the material properties for the reinforcement see table 2.2. The material properties for the strengthening material are those provided by the supplier. For the concrete 6 cubes were made for each beam and tested, 3 in compression and 3 in splitting.

<table>
<thead>
<tr>
<th>Beams</th>
<th>$f_{ce}/f_{et}$</th>
<th>Strengthening technique</th>
<th>Strengthening material properties</th>
<th>Prestressing force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>E</td>
<td>A_{tot}</td>
<td>f</td>
</tr>
<tr>
<td>Ref</td>
<td>47/3.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel 1</td>
<td>54/3.4</td>
<td>External steel</td>
<td>195 300 1760 180</td>
<td></td>
</tr>
<tr>
<td>Steel 2</td>
<td>52/3.3</td>
<td>External steel</td>
<td>195 300 1760 180</td>
<td></td>
</tr>
<tr>
<td>Steel 3</td>
<td>40/2.7</td>
<td>Internal steel</td>
<td>195 300 1760 180</td>
<td></td>
</tr>
<tr>
<td>CFRP</td>
<td>42/2.8</td>
<td>External CFRP</td>
<td>150 301 2600 110</td>
<td></td>
</tr>
<tr>
<td>NSMR 1</td>
<td>53/3.5</td>
<td>NSMR</td>
<td>150 300 2600 -</td>
<td></td>
</tr>
<tr>
<td>NSMR 2</td>
<td>50/3.6</td>
<td>NSMR</td>
<td>150 300 2600 -</td>
<td></td>
</tr>
<tr>
<td>NSMR 3</td>
<td>49/3.4</td>
<td>Prestressed NSMR</td>
<td>150 300 2600 150</td>
<td></td>
</tr>
</tbody>
</table>
Three beams had grooves sawn in the sofit for use of the NSMR technique. The groves were sawn with a two-blade concrete saw and was then chiselled with an air pressure driven chisel, and finally cleaned by high pressure air. In figure 2.5 the sawing and chiselling is shown and in figure 2.6 the size of the grooves are shown.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_t$ [GPa]</th>
<th>$f_{fu}$ [%]</th>
<th>$f_y$ [MPa]</th>
<th>$f_s$ [MPa]</th>
<th>$f_{ac}$ [MPa]</th>
<th>$f_{at}$ [MPa]</th>
<th>$E_a$ [GPa]</th>
<th>Visc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel bars, Ks500</td>
<td>210</td>
<td>-</td>
<td>500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel tendons, 7 wire</td>
<td>200</td>
<td>53</td>
<td>-</td>
<td>&gt;1760</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CFRP tendons</td>
<td>160</td>
<td>17.5</td>
<td>-</td>
<td>2800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sto BPE® NMSR 101S</td>
<td>160</td>
<td>17.5</td>
<td>-</td>
<td>2800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sto BPE® Lim 465/464</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>103</td>
<td>31</td>
<td>7</td>
<td>Tix</td>
</tr>
</tbody>
</table>

Table 2.2 Data of the steel reinforcement, tendons, CFRP and the adhesive used
2.3.1 Reference beam

The reference beam had no external reinforcement, strengthening, and was used for comparison to evaluate the strengthening effect that each technique would provide, see figure 2.7 and 2.8.

During the test the strain was measured by the gauges, also the midpoint displacement measured. The support displacement was also controlled via displacement gauges.

The concrete started to crack at 24kN and the steel to yield at 108 kN. The test was aborted at 115kN when the load had levelled out.
2.3.2 Steel 1

The first strengthened beam was strengthened with external steel tendons. The tendons were placed as can be seen in figure 2.10. At the ends the tendons was placed at the equilibrium point of the cross-section going down to the lower part of the beam at the middle where a deviator fixed the tendons in vertical direction. This is an effective way to place the tendons and the tendons are always fixed at the endpoints and the middle, regardless of deflections as long as there is no rupture in the tendons.

The tendons were a bundle of 7 twinned steel wires with an anchor plate at each end. Steel wedge anchors were used to secure the tendons to the steel plates.
The tendons were prestressed using wedge anchors and a hydraulic pump. Each tendon was partially stressed and then the pump was shifted to the other. This was repeated until the required force was achieved. As the tendons were of twinned wires it was not possible to have strain gauges on the tendons of that reason the stress in the tendons was measured via the force applied from the hydraulic pump.

During the loading it was not possible to measure the strain or force in the external tendons. The loading started with a rapid increase in the load and only a small displacement was noticed before cracking of the concrete. At approximately 75kN the concrete started to crack and the displacement increased. This load corresponds to 200% higher load then the reference beam. The load-displacement is shown in figure 2.13.
At 215kN the internal flexural reinforcement in the lower part of the beam started to yield, causing the beam to lose stiffness. The placement of the tendons helped the beam to increase the load with almost 100kN from steel yielding, followed by large displacement.

The beam proved to be able to carry both large loads and displacements with the steel tendons, as can be seen in figure 2.14. The ropes around the beam in figure 2.14 were to prevent the tendons to snap out in case of failure in the tendons. The test was aborted after 314kN when the load started to decrease although the displacement still increased.

Figure 2.13 Load-displacement for beam Steel 1 compared to the reference beam

Figure 2.14 The beam during the end of the test
2.3.3 Steel 2

As it would not be possible to place the CFRP tendons in the same way as beam Steel 1, a second beam with steel tendons was tested. The tendons were placed in the lower part of the beam as can be seen in figure 2.15 and the tendons were only fixed at the ends. Opposite to beam Steel 1 the tendons will always remain at the same level as the endpoints, regardless of displacement of the middle of the beam.

The same type of tendons was used as in beam Steel 2 and the pre-stressing force was applied in the same way.

The beam behaved as beam Steel 1 in the beginning. A rapid increase in load until the concrete started to crack at 74kN and then reinforcement started to yield at 207kN, see figure 2.17.
As the beam started to get larger displacements after steel yielding the active cross-section at the middle of the beam changed. Although the beam got larger displacement the tendons remained at the same level as the endpoints causing the effective height of the beam to decrease. In figure 2.18 it is possible to see that the tendons is placed much higher up on the beam when the displacement of the beam increased.
The decreased cross-section caused a much smaller increase of load after steel yielding compared to beam Steel 1, the load increased to 246kN and then the beam started to loose load and the test was aborted.

2.3.4 Steel 3

Beam Steel 3 is not a strengthened but a beam with post-stressed internal steel tendons. The tendons are placed in steel pipes that are installed before casting of the concrete. Apart from the steel pipes the beam is exactly the same as the other beams in the serie.

After the concrete has cured the tendons were placed in the pipes and the prestressing force was applied in the same way as the previous beams. After prestressing the pipes were filled with cement paste according to the Swedish code, in figure 2.20 and 2.21 the steel pipes and the pipes for filling can be seen. The tendons used had the same material properties as the external tendons.

The behaviour of this beam was expected to be different, this due to that the tendons were placed somewhat higher up in the structure but also that the tendons were bonded by the cement paste.
When the loading started the concrete cracking began at 69kN and steel yielding at 224kN. The behaviour of the beam was the same as the beams with external unbonded tendons until before steel yielding. As can be seen in figure 2.22 the behaviour during steel yielding is softer then for the beams with unbonded tendons.

Figure 2.21 The steel pipes and the end zone during manufacturing and after prestressing

Figure 2.22 Load-displacement comparing beam Steel 3 with the reference beam
After the soft behaviour the load started to level out and the test was aborted at 284kN when the load started to decrease.

### 2.3.5 CFRP External

The tendons used could not be placed as beam Steel 1 and therefore was placed in the lower part as can be seen in figure 2.23. The tendons used had a diameter of 8mm, with a modulus of elasticity of 150GPa and ultimate strength at failure of 2600MPa.

![Figure 2.23 Beam configuration](image)

As normal steel wedge anchors would crush the FRP tendons a modified anchor with a plastic wedge was used, see figure 2.24. To get better effect of the anchor the tendons had quarts sand glued on them. As those anchors would not be able to take as high forces as a steel anchor on a steel tendon six tendons were used instead of two.

![Figure 2.24 The placement of the rods and the modified wedge anchors used](image)

Once the anchors were in place they could not be moved as it is possible with steel tendons, therefore using the hydraulic pump as for steel tendons was not possible. Instead the whole anchor plate was used to apply the prestressing force. As the prestressing was applied it became clear that it would not be possible to achieve the same prestressing force as with the steel tendons. Instead the prestressing force stopped at 90kN.
Due to the lower prestressing force the concrete cracking load got lower than the beams with the steel tendons, 51kN. After that the steel reinforcement started to yield at 149 kN, but before that there were some slip between the anchors and the tendons. After steel yielding the slips caused the beam to have just a small increase in load capacity and a slippage in one of the anchors occurred at 173kN.
The concrete cracking load increased with 100% and the steel yielding load with 50% compared to the reference beam.

It is important to keep in mind that the results from this beam would have been other if the anchorage had worked better. The anchor devices consequently needs to be improved before future tests.

### 2.3.6 NSMR 1 and NSMR 2

Two beams were tested with the Near Surface Mounted Reinforcement (NSMR) technique without prestress. The rods used were 10x10mm BPE \textsuperscript{®} NSMR 101S and the adhesive was BPE \textsuperscript{®} Lim 465/464, see table 2.2 for more details.

The slots were placed with the bottom up and the sawed grooves were cleaned with air pressure. The rods were grinded with normal sandpaper and then cleaned with acetone. The grooves were filled with sufficient amount of adhesive and then the rods were placed in the slots and allowed to cure for 5 days in ambient conditions (20±2°C and 50±5% RH).
As there was no prestressing force on the beams the concrete cracking started at the same level as the reference beam, 25kN. But after that the NSMR beam had a stiffer behaviour and the steel reinforcement started to yield at around 295kN. Both beams failed at around 300kN.

![Load-displacement diagram](image)

Figure 2.29 Load-displacement comparing the NSMR beam 1 and 2 with the reference
Both beams failed when the rods were ripped of the concrete due to the high shear stresses between the concrete and rods.

### 2.3.7 NSMR PS
One beam was strengthened with prestressed NSMR. The material and placement of the rods were the same as for the previous NSMR beams, but here a prestressing force of 150kN (50kN per rod) was applied.
During prestressing the beam was placed with the soffit up to make the strengthening work easier. The slots were filled with the adhesive and the rods placed in the slots and then prestressed. The adhesive cured for 5 days and then the prestressing force was released. The prestressing force was then transferred to the concrete via the adhesive.
When testing the beam it was hard to find the concrete cracking load, this may be due to initial cracks in the beam. At 216kN the steel started to yield and at 324kN the concrete in the sofit was ripped off due to high shear stresses.

Figure 2.32 Beam NSMR PS after failure
3 RESULTS

3.1 Prestressing

Five beams were strengthened with prestressed tendons or rods. The results from the prestressing is presented in table 3.1 as the measured strain in the concrete on the top of the section and in the lower steel reinforcement.

<table>
<thead>
<tr>
<th>Table 3.1 Strain after prestress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beams</td>
</tr>
<tr>
<td>Steel 1</td>
</tr>
<tr>
<td>Steel 2</td>
</tr>
<tr>
<td>Steel 3</td>
</tr>
<tr>
<td>CFRP 2</td>
</tr>
<tr>
<td>NSMR 3</td>
</tr>
</tbody>
</table>

3.2 Loading

With the exception of the beam with external CFRP tendons all the tested beams behaved as expected. The strengthening effects for the prestressed beams were over 100%, all with a limited addition to the beam.

<table>
<thead>
<tr>
<th>Table 3.2 Loads and displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ref</td>
</tr>
<tr>
<td>Steel 1</td>
</tr>
<tr>
<td>Steel 2</td>
</tr>
<tr>
<td>Steel 3</td>
</tr>
<tr>
<td>CFRP</td>
</tr>
<tr>
<td>NSMR 1</td>
</tr>
<tr>
<td>NSMR 2</td>
</tr>
<tr>
<td>NSMR PS</td>
</tr>
</tbody>
</table>

*Cracking load could not be determined
In table 3.2 the loads for the concrete cracking, steel yielding and ultimate is presented.

When looking at the post-steel yielding behaviour it is interesting to compare the beams strengthened with unbonded tendons and those with bonded tendons (Steel 3 and NSMR PS). The beams with bonded tendons and rods showed a better behaviour after steel yielding than those with unbonded tendons.

In figure 3.1 and 3.2 the loads and displacements are shown.

![Graph](image-url)

Figure 3.1 Load-displacement for the tested beams strengthened with CFRP.
3.3 Strain distribution

During the tests the strain were measured in the middle of the beam, on the top of the beam and on the tensile reinforcement, see figure 2.4. The strains were measured both during prestressing and loading.

In figure 3.3 and 3.4 the strain distribution is presented for four beams at five load levels. For three of the beams the load level of 0 kN includes strains from the prestressing, hence the initial strain. For beam NSMR 2 only three load levels are shown as the steel reinforcement started to yield before 200 kN resulting in a too high strain to be presented in the graph.

When studying the graphs the effect by the prestressing force is clearly shown when comparing the strain at 50kN. The lower strain is due to that the concrete has not yet cracked giving the beam a stiffer behaviour.
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Figure 3.3 Strain distribution for beams Steel 1 and Steel 2

Figure 3.4 Strain distribution for beams NSMR 2 and NSMR PS
4 THEORETICAL CALCULATIONS

4.1 Prestressing
For the prestressing one assumption was taken for the calculations, there is no concrete cracking.

The theoretical stresses in the middle of the beams during prestressing are calculated using:

$$\sigma_z = \frac{M}{I} \cdot z + \left( -\frac{P}{A} - \frac{P \cdot e}{I} \right)$$  \hspace{1cm} (4.1)

In the equation $M$ is the external moment (during prestressing the dead weight of the beam), $P$ is the prestressing force, $I$ the moment of inertia and $A$ the cross-sectional area. Figure 4.1 shows how the values for $z$ are used, from the centre of the cross-section to the top of the concrete for the compression and down to the steel reinforcement for the tensile stress. The lever $e$ depends on what prestressing technique used, as is shown in figure 4.1.

![Figure 4.1 Distances for prestressing calculations](image-url)
When the stress have be calculated for the top of the beam and the tensile steel reinforcement the values are calculated to strains using

\[ \varepsilon = \frac{\sigma}{E} \quad (4.2) \]

The results from the calculations are presented in table 4.1 for the beams that were prestressed.

<table>
<thead>
<tr>
<th>Beams</th>
<th>Stress</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concrete</td>
<td>Steel</td>
</tr>
<tr>
<td>Steel 1</td>
<td>3.5</td>
<td>-6.4</td>
</tr>
<tr>
<td>Steel 2</td>
<td>1.7</td>
<td>-4.6</td>
</tr>
<tr>
<td>Steel 3</td>
<td>1.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>CFRP</td>
<td>0.7</td>
<td>-2.5</td>
</tr>
<tr>
<td>NSMR 3</td>
<td>2.0</td>
<td>-4.4</td>
</tr>
</tbody>
</table>

**4.2 Loading**

For the loading the calculations for the load causing yielding in the tensile steel reinforcement is calculated. To calculate those loads the assumption is made that the tensile stress in the steel reinforcement is 490MPa (steel yielding). Then by using force equilibrium, see figure 4.2 and equation 4.3 the compression zone when steel yields can be calculated.

\[ F_s + F_p = F_c \quad (4.3) \]
Equation 4.3 can then be rewritten as

\[ f_s A_s + f_p A_p = 0.8 x b / f_c \]  

(4.4)

the tensile stress in the prestressed strengthening tendons is calculated by

\[ f_p = f_{p_0} + E_p \Delta \varepsilon_p \]  

(4.5)

Using equations 4.3 – 4.5 the value \( x \) can be calculated and then using equation 4.6 the moment and loads for steel yielding.

\[ M = f_s A_s (d_s - 0.4 x) + f_p A_p (d_p - 0.4 x) \]  

(4.6)

The results from the calculations are presented in table 4.2.

<table>
<thead>
<tr>
<th></th>
<th>( x ) [mm]</th>
<th>( M ) [kNm]</th>
<th>( F ) [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>20</td>
<td>128</td>
<td>111</td>
</tr>
<tr>
<td>Steel 1</td>
<td>36</td>
<td>278</td>
<td>241</td>
</tr>
<tr>
<td>Steel 2</td>
<td>37</td>
<td>271</td>
<td>236</td>
</tr>
<tr>
<td>Steel 3</td>
<td>48</td>
<td>249</td>
<td>217</td>
</tr>
<tr>
<td>CFRP</td>
<td>39</td>
<td>217</td>
<td>189</td>
</tr>
<tr>
<td>NSMR 1</td>
<td>25</td>
<td>181</td>
<td>157</td>
</tr>
<tr>
<td>NSMR 2</td>
<td>25</td>
<td>181</td>
<td>157</td>
</tr>
<tr>
<td>NSMR PS</td>
<td>37</td>
<td>261</td>
<td>227</td>
</tr>
</tbody>
</table>
5 COMPARING TESTS AND THEORY

5.1 Prestressing
For the prestressing a linear equation (equation 4.1) was used as the beams were design not to crack during prestressing. The comparison between the calculated values and the measured can be seen in table 5.1.

<table>
<thead>
<tr>
<th>Concrete</th>
<th>Steel</th>
<th>Calculated</th>
<th>Steel</th>
<th>Compared, $\frac{\varepsilon_{\text{meas}}}{\varepsilon_{\text{cal}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 1</td>
<td>75</td>
<td>-148</td>
<td>95</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.85</td>
</tr>
<tr>
<td>Steel 2</td>
<td>56</td>
<td>-121</td>
<td>46</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.95</td>
</tr>
<tr>
<td>Steel 3</td>
<td>44</td>
<td>-165</td>
<td>32</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.36</td>
</tr>
<tr>
<td>CFRP</td>
<td>28</td>
<td>-97</td>
<td>20</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.31</td>
</tr>
<tr>
<td>NSMR PS</td>
<td>-325</td>
<td>61</td>
<td>-133</td>
<td>-2.44</td>
</tr>
</tbody>
</table>

5.2 Loading
For the loading the state of steel yielding in the flexural reinforcement have bee compared. The loads compared are the total loads of both point loads. The comparison can be seen in table 5.2.

<table>
<thead>
<tr>
<th>Measured [kN]</th>
<th>Calculated [kN]</th>
<th>Compared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>108</td>
<td>111</td>
</tr>
<tr>
<td>Steel 1</td>
<td>215</td>
<td>241</td>
</tr>
<tr>
<td>Steel 2</td>
<td>207</td>
<td>236</td>
</tr>
<tr>
<td>Steel 3</td>
<td>224</td>
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<tr>
<td>CFRP</td>
<td>149</td>
<td>189</td>
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<tr>
<td>NSMR 1</td>
<td>196</td>
<td>157</td>
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<tr>
<td>NSMR 2</td>
<td>195</td>
<td>157</td>
</tr>
<tr>
<td>NSMR PS</td>
<td>216</td>
<td>227</td>
</tr>
</tbody>
</table>
5.3 Comments of the comparison

With simple equations it is possible to get fairly good correspondence with the results from the tests. However, one important thing to remember is the possible variation of the creep in the concrete. As the creep do not vary with the compressive strength it is hard to say how this has influenced the comparison with the theoretical calculations.

One important thing to remember when studying these comparisons is that the technique with prestressed NSMR is new. The theoretical investigation has to be studied further to achieve better knowledge and more accurate equations for the technique.
6 CONCLUSIONS

Eight beams have been tested, seven strengthened with and without prestress. The results from the tests show that the strengthening techniques used have effective strengthening effect.

As the beam with external CFRP tendons had problems, it is hard to compare that beam with the other. But the technique with prestressed NSMR showed to work very well compared to external steel cables. Although the NSMR technique today is less labour efficient, it should be a competitive method when fully developed.

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 during prestressing. However, the values for the prestressed NSMR beam differed more and should need further studies as the technique is new.
The focus on the future work should be on prestressed FRP. The use of steel tendons, especially practical work, is already well known.

The method with external tendons of FRP materials could, with a more efficient anchor system, give interesting results that could be beneficial.

The method of prestressed NSMR has now been proven to give good results, comparable with external steel tendons. The future work with NSMR should be focused on the following areas:

**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.

**Anchorage 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 possible to use the same technique in the field as have been done in the tests presented. The other reason for having an anchorage device is to try and reduce, or even remove the loss of strain that happens 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, 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 developed. A more thoroughly understanding of the failure modes must be derived. In addition the long-term effects of prestressed NSMR rod should be investigated. It is important to have an complete theoretical investigation for understanding the process of strengthening with prestressed CFRP. But it is also important to develop calculation methods that can be used by engineers working with strengthening works. If engineers can not in a not to advanced way calculate the strengthening and the effect it will have on a structure the strengthening technique will not be used.

It would also be beneficial to have investigated the theory around the anchorage. The stresses in an anchor and fractural mechanics of the concrete in that area has to be investigated to get a full understanding of what happens in that part of the beam.

Field applications
With a developed anchorage system the next step will 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 the strengthening.
Appendix A  Steel details

Deviators for beam Steel 1

Figure A1 Bottom part for the deviator

Figure A2 Side for the deviator
Appendix A

Figure A3 The deviator in 3D

Anchor plate for beam Steel1

Figure A4 Anchor plate from the side
Figure A5 Anchor plate from the back

Figure A6 Anchor plate from the top
Figure A7 Anchor plate in 3D
Appendix B  Beams tested

Reference

Strengthening technique  -
Strengthening material  -
Placement of strengthening (from sofit)  -
Prestressing force  -

Steel 1

Strengthening technique  External prestressing
Strengthening material  7-wire steel tendons
Placement of strengthening (from sofit)  At end: 350mm. At middle: 16mm
Prestressing force  180kN
Steel 2

- **Strengthening technique**: External prestressing
- **Strengthening material**: 7-wire steel tendons
- **Placement of strengthening (from sofit)**: 50mm
- **Prestressing force**: 180kN

Steel 3

- **Strengthening technique**: Internal prestressing
- **Strengthening material**: 7-wire steel tendons
- **Placement of strengthening (from sofit)**: 80mm
- **Prestressing force**: 180kN
Appendix B

CFRP External

Strengthening technique: External prestressing
Strengthening material: 8mm CFRP tendons
Placement of strengthening (from sofit): 0mm, 70mm and 140mm
Prestressing force: 110kN

NSMR 1 and 2

Strengthening technique: Near Surface Mounted Rods
Strengthening material: Sto BPE® NMSR 101S
Placement of strengthening (from sofit): In grooves
Prestressing force: -
Appendix B

NSMR PS

Strengthening technique: Prestressed Near Surface Mounted Rods
Strengthening material: Sto BPE® NMSR 101S
Placement of strengthening (from sofit): In grooves
Prestressing force: 150kN