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STRENGTHENING OF CONCRETE BRIDGE OVER THE RIVER NOSSAN

New pre-stressing method - evaluation and development

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FÖRORD

Denna studie finansierades av SBUF (Svenska Byggbranschens Utvecklingsfond) och har genomförts som ett samarbetsprojekt mellan Chalmers och NCC. Rapporten skrevs på engelska med en sammanfattning på svenska under tiden februari till april 2014.

Projektet är samfinansierat av SBUF och Trafikverket. Trafikverket genom Tekn. Dr Anders Carolin, hjälpte oss med finansieringen för detta demonstrationsprojekt inom ramen för EU-projektet PANTURA. Demonstrationsprojektet omfattade för Trafikverkets del att förarbeta med att tillhandahålla en bro, organisera upprättning och etablering på bron, ansvara för trafikavstängningar och bekosta ställningen. Tekn. Dr Anders Carolin har föreslagit Nossansbro som ett lämpligt objekt för denna studie.

Simon Dahlberg, Strong Solution AB, har hjälpt till med det praktiska arbetet på bron och Fredrik Olsson, Trafikverket, med etableringen på bron. Överslagsberäkning i mittsnitt av bro över Nossan utfördes av Tekn. Dr Joosef Leppänen, Chalmers, och redovisas i bilagan. Till alla som hjälpt till vill vi framföra vårt varma tack. Till slut vill vi speciellt tacka Tekn. Dr Thomas Blanksvärd, Skanska, för hans engagemang, värdefulla synpunkter och diskussioner för att lösa olika problem som har dykt upp.

Göteborg, april 2014

Robert Kliger, Reza Haghani, Valbona Mara (alla från Chalmers) och Alexandre Mathern (NCC)

SAMMANFATTNING

Forskargruppen ”Stål- och träbyggnad” vid Chalmers tekniska högskola har under de senaste sex åren arbetat aktivt med att ta fram en ny förstärkningsmetod för äldre broar. Den nya metoden möjliggör ett fullt utnyttjande av den mycket höga draghållfastheten hos kolfiberlaminat (CFRP) genom förspänning. Metoden utvecklades för att åstadkomma ett snabbt utförande och en minimering av trafikstörningar på bron samt att helt kunna ta bort mekaniska förankringar i ändarna på kolfiberlaminaten. Arbetet har resulterat i en ny förspännings- och förankringsmetod speciellt anpassad för förstärkning med förspänt CFRP-laminat. Det teoretiska arbetet gjordes redan 2007, vilket resulterade i patentansökan No. 0701574-6 “Anchoring pre-stressed FRP laminates”. Idén blev också ett projekt kallat TENROC Technologies för Encubator, Chalmers Entreprenörsskola (CSE) 2008. Inom EU-projektet *PANTURA* mellan 2011 och 2013 har Chalmersgruppen verifierat förspänningsmetoden i labbmiljö genom att utföra provningar på ett antal betongbalkar förspända med olika mängder kolfiberlaminat och med olika förspänningsnivåer. . Trafikverket (TRV) som var en partner i *PANTURA* blev ombedd att tillhandahålla en lämplig bro för att demonstrera en ny förstärkningsteknik. I april 2013 föreslog Trafikverket en bro över Nossan vid S. Härene kyrka (nr. 15-376-1), som en fallstudie och demonstration som blev en liten insats i *PANTURA.* Förstärkningsarbetet av denna bro utfördes av Chalmers och entreprenören Strong Solution med NCC som partner i *PANTURA*. Förstärkning utfördes mellan 10 och15 september 2013.

Syftet med detta projekt är att redogöra för en genomförd förstärkning samt att vidare utvärdera och utveckla utförandemetoden med hänsyn till planering, förberedande arbete, montering av förspända laminat på bron, miljöpåverkan och LCC-analys. Materialåtgången och anpassningen av laminaten för förspänningsarbetet, säkerheten för entreprenören före och under förspänningen av laminaten på en betongbro och hanteringen av epoxin som blev kvar redovisas i rapporten. Tider som krävs för olika arbetsmoment redovisas också. Dessa aspekter är mycket viktiga vid utvärdering av nya tekniker.

Genomförandet av förstärkningen omfattade (de involverade företagen i parentes):

- Vidare utveckling och tillverkning av specifik utrustning för att ”greppa” laminaten under förspänningen (TENROC)
- Kontroll av betongens hållfasthet och beräkning av förstärkningseffekten (Chalmers och Strong Solutions)
- Anpassning av laminaten för förspänningsarbete genom förstärkning av kolfiberlaminatens ände med glasfiberlaminat med ingjutna muttrar (TENROC)
- Förberedelse, planering och etablering på byggarbetsplatsen (Chalmers, Strong Solutions och TRV)
- Genomförande av förstärkningen och redovisning av alla ingående arbetsmoment inklusive miljöeffekter som hög ljudnivå, tidsåtgången, trafikstörningar, avfallshantering med mera (Chalmers, Strong Solutions och TENROC)
- Mätning av förspänningskraften på laminaten under förstärkningen, utvärdering av säkerheten vid utförande (Chalmers och NCC)
- Utvärderingsprocesser som utfördes utifrån hållbarhetsindikatorer som utvecklades inom *PANTURA*, så kallade KPIs (Key Performance Indicators) för detta projekt
- Livscykelkostnader och jämförelse med andra kända förstärkningsmetoder med förspänd kolfiber (Chalmers).

Resultat

Den teoretiska analysen baseras på numerisk 3D-modellering samt överslagsberäkningar (Bilaga). Dessa beräkningar visade att dragspänningar i armeringen var ganska låga (runt 65 MPa) och att den planerade förstärkningen skulle ha lite inverkan på konstruktionen. Orsaken till sprickbildningen var förmodligen tvångskrafter på grund av temperaturrörelser, då bron är fast inspänd. Två laminat förspända till 100 kN bidrar förmodligen till att de existerande sprickorna inte propagerar. Storleken på den beräknade sprickbredden var mycket liten, ungefär 0,06 mm.

Samtliga arbetsmoment lyckades väl. Hela installationen på plats genomfördes på mindre än en dag. Detta inkluderade ytbehandling och slipning av betongytan, markering av läget där laminat skulle monteras, borrning och installation av förankringsplattor samt ledstänger och domkraft för förspänning, applicering av lim på den slipade betongytan, placering av kolfiberlaminat med förstärkta ändar och slutligen uppspänning med domkraft till 100 kN och låsning av systemet. Ett specifikt arbetsmoment, borrning av 16 hål i betongen för att installera fyra förankringsplattor, tog 2 timmar för 2 personer. Applicering av epoxilim på betongytan, uppspänning av laminaten och säkring av hela systemet tog mindre än en halvtimme per laminat. Trots brons läge med väldigt lite trafik och behov att endast begränsa den tunga trafiken under mycket kort tid, visade denna teknik ändå på stor potential. En jämförelse mellan den nya metoden och en av de existerande metoder som finns på marknaden med hänsyn till flera hållbarhetsindikatorer visade också på många fördelar med den nya metoden. Behov av framtida förbättringar av förspänningssystemet identifierades och dessa var i huvudsak relaterade till att minimera kostnaderna för färdiga laminat. Resultaten från livscykelkostnadsanalysen visade att kostnader för förstärkning av kolfiberlaminat med glasfiberstrimlor som limmas till kolfiberlaminatet i båda ändarna är för dyra. Trots det var utfallet från livscykelkostnadsanalysen positiv för den nya metoden.
Utförandet av detta första förstärkningsarbete med förspänningsmetoden på bron över Nossan ger fog för att vidareutveckla olika arbetsmoment som krävs för att lyckas på bästa sätt med det nya, redan beviljade, SBUF Projekt 12849.

Slutsatser

Den innovativa förstärkningsmetoden (Chalmers/TENROC-metoden) på bron över Nossan har utförts för att få praktisk erfarenhet av produktion och hållbarhetskriterier. Detta är det första förspänningsarbete som utförts på en bro i Sverige med denna teknik. Genomförande, produktion och olika praktiska aspekter bedömdes vara mycket lyckade. Fördelarna med det innovativa förstärkningssystemet i jämförelse med de etablerade systemen som kräver användning av tunga permanenta ankare visade sig vara mycket tydliga. Dessutom visade den utförda livscykelkostnadsanalysen (LCC) en klar fördel för det nya systemet. De specifika kostnaderna, som i framtiden måste minska för att förbättra den innovativa metoden, har identifierats.

CONTENT

1. BACKGROUND, AIM AND SCOPE

A large number of Swedish and European bridges are in need for maintenance and upgrading. The upgrading activities for bridges usually involve strengthening and repair. At Chalmers, research group of Steel and timber structures developed a new method for applying pre-stressed fibre-reinforced-polymer (FRP) laminates to the structural member loaded in bending. The development of this method during the past 8 years focused on the pre-stressing and anchoring techniques which included fast execution and abolishment of the mechanical anchoring at the end of the laminate. A very high strength of carbon-fibre-reinforced polymer (CFRP) laminates makes them a suitable material to be used for pre-stressing purposes. CFRP laminates also display very small creep and relaxation which means that the loss in pre-stressing should be negligible. There are several advantages to pre-stress the CFRP-laminates compared to using un-pre-stressed laminates. Pre-stressing is primarily used in order to improve serviceability of strengthened structures, but there are several benefits with pre-stressing (El-Hacha et al., 2001; Kotynia et al., 2011) such as:

- Reduce crack widths and delay onset of cracking,
- Relieve stress in the internal reinforcement and delay yielding,
- Possible control of the crack distribution,
- Increase stiffness and reduce and/or limit deflections,
- Fatigue failure is resisted by induced compressive stress,
- Further increase the load bearing capacity of reinforced concrete beams,
- Higher utilization of both concrete and FRP,
- Replace lost pre-stress in internal reinforcement,
- Increase shear capacity by the compressive stresses induced in the beam.

Un-pre-stressed laminates have been widely used for strengthening with the only advantage over pre-stressed laminates that it is less labour-intensive.

The problem with pre-stressed CFRP laminates is the high stress concentrations at the ends of the laminate. The stresses developed in the adhesive layer due to pre-stressing force are so high that, already at low pre-stressing load levels the debonding of the laminate occurs. In order to prevent this debonding, mechanical anchors are normally used to clamp the pre-stressed laminates to the structural member. Using mechanical anchors is associated with several problems such as the need for further modification of the structure to fit in the anchor plates, durability of the anchorage system, time consuming installations, costly overall process and inspection problems. These problems have limited the application of pre-stressed FRP laminates even though their structural performance and benefits are clear in comparison to their un-pre-stressed counterparts.

An idea how to apply pre-stressing force without need of anchorage device was submitted for patent 2007 (Al-Emrani et al. 2007) and also became a possible project called TENROC for Encubator, Chalmers School of Entrepreneurship (CSE) 2008. Pre-stressing project focused at the beginning on glulam timber to minimise their cross-sections and was a joint project between Chalmers Encubator and the Department of Structural Engineering 2009-2012. As a result, TENROC Technologies became the owner of the pre-stressing technology. The technology of pre-stressed FRP laminates for strengthening and repair of structural members without the need for mechanical anchorage was further developed as part of EU project “PANTURA” (2011-2013) within Work Package 5, i.e. Toolbox for flexible refurbishment of existing bridges, (Haghani 2013). TENROC Technologies provides a patented method and a device for application of pre-stressed laminates. Within PANTURA, Chalmers group has taken this innovation one step further by adopting this device and modifying it for bridge applications. The new method combines the advantages of using pre-stressed laminates while eliminating the drawbacks of using mechanical anchorage systems. The pre-stressing method was shown in the lab on some concrete beams within PANTURA, but no demonstration on a real bridge on site was made, as this was not a goal within PANTURA from the beginning. At the end of the PANTURA project, the Swedish Transport Administration (TRV) received some extra funds to contribute a bridge as a demonstration project.

The aim of this project was to evaluate the innovative strengthening method (called here Chalmers/TENROC method) on the bridge over Nossan (Nossan at S. Härene church, bridge no. 15-376-1) with regard to practical production experience and sustainability, as well as, propose ideas for further development of the method.

The scope of this project was to present:
1) planning, logistics and assembly of pre-stressed laminate on the bridge,
2) environmental impact and LCC analysis.
3) material usage and adaptation of laminates for pre-stressing work
4) safety conditions for conducting on-site woks before and during pre-stressing of the laminates on a concrete bridge.

2. DEVELOPMENT OF THE CONCEPT AND A SPECIAL DEVICE FOR PRE-STRESSING CFRP LAMINATES

2.1. Principle and benefits of pre-stressing

Pre-stressing the laminates contributes to utilisation of a significantly larger capacity than un-pre-stressed laminates; it also increases the serviceability performance while the un-pre-stressed laminates lack to do so. By pre-stressing the laminates the failure mode often change from peeling failure or debonding to rupture of the FRP laminate itself, given that the capacity of the laminate is properly utilised.

The basic principle of an externally bonded pre-stressed laminate is shown in Fig.2.1. In the second step, the laminate is pre-stressed and applied to the beam and in the third step, the force is released and the upward cambering effect is obtained in the beam. When the laminates are pre-stressed with a force of approximately 5% of the laminate ultimate tensile strength, the laminate detaches at the end due to high shear stresses (El-Hacha et al., 2001). Shear stresses as high as 100 MPa at the very end of the laminate could built up, if a pre-stressing force of 20 tons is induced in the laminate. This is illustrated in Fig. 2.2.

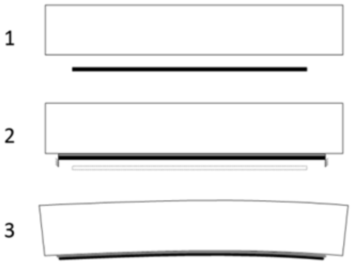	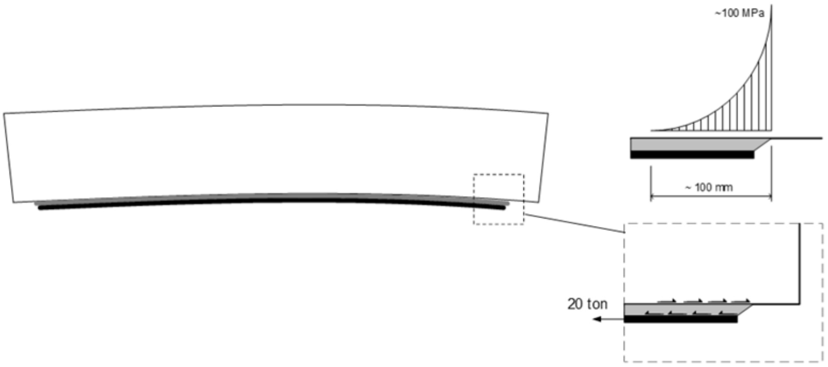
Fig. 2.1 The principle steps in pre-stressing.	Fig. 2.2. Illustration of the high shear stresses obtained at the end of pre-stressed laminates adhered to the substrate.

The typical shear strength of a structural adhesive is around 25 MPa and that of concrete around 3 MPa. Usually the failure initiates in the weaker of these two materials.

2.2. Concept of step-wise pre-stressing

It is a well-known fact that the shear stress in the adhesive layer between the CFRP and the substrate is proportional to the gradient of the pre-stressing force in the strengthening laminate. In other words, the slope of the pre-stressing force in the laminate determines the magnitude of the shear stress along the bond line. The steeper the slope, the higher the shear stress in the adhesive layer would be. One can assume that by manipulating the slope of the pre-stressing force in the laminate, it is possible to control the magnitude of the shear stress in the bond line. This concept is shown in Fig. 2.3.

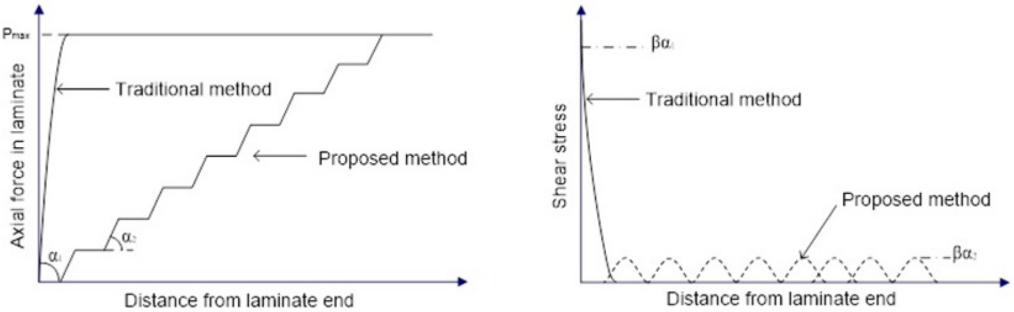

Fig. 2.3 The principle of the stepwise pre-stressing method (called here proposed method) compared to the traditional method.

TENROC Technologies developed a fairly simple device to apply pre-stressed laminates to the structures based on the principle of stepwise pre-stressing. In the TENROC's device, the pre-stressing force is built up along the laminate length until it reaches the maximum desired force. The concept of stepwise pre-stressing is based upon applying the pre-stressing force to the laminate at several locations to build up the force in steps as it is a direct relation between the slope of the axial force curve and the magnitude of the shear stress in the adhesive line. Distributing the full pre-stressing force over a long distance is translated to smaller slope of the axial force curve.

The pre-stressing system contains several different parts; a pre-stressing device, guiding bars, temporary supports, and a hydraulic jack. The temporary supports are used during the pre-stressing phase to anchor the pre-stressing force and the guiding bars are used to keep the device in place and will be removed after the pre-stressing is done. One device has to be mounted to each end of the laminate to achieve the stepwise effect at both ends, but the pre-stressing force is only applied at one end while the other end is passive and kept fixed using a temporary support of the same kind. The device is designed with a number of tabs which are connected to each other with steel rods acting as springs to serve as the dividing element of the pre-stressing force. When the system is mounted and the adhesive has been applied to the laminate as well as the substrate, the full pre-stressing force is applied to pre-stressing the device. The force is applied using a hydraulic jack that is connected to the pre-stressing device, which will distribute the force in several steps. The CFRP laminate is strengthened at both ends with GFRP strip (length about 1.2 m) which is tapered at one end to avoid the stress concentration. The reason to use GFRP strips is to transmit to force from pre-stressing device (see Fig. 2.4) which is connected via 10 small molded nuts which in turn are connected with screws to the GFRP strips. The GFRP strips include small molded nuts (where the screws will be connected on site) and these strips are glued to the CFRP in the workshop prior to the strengthening job on site. The pre-stressing device is connected on site to the GFRP via small screws connected to the molded nuts.

The full system, including the device, guiding bars, anchoring plate (box) and hydraulic jack, mounted to a concrete bridge is shown in Fig.2.4. The pre-stressing force is applied at the right-hand side in the figure where the hydraulic jack is located while the other side is passive. When the pre-stressing force is applied, the connection rod is locked in the anchoring plate with a nut and the hydraulic jack can be removed. When the adhesive is cured, the device, the guiding bars and the anchoring plates are removed from the structure leaving only the thin laminate together with GFRP strips left on the structure.

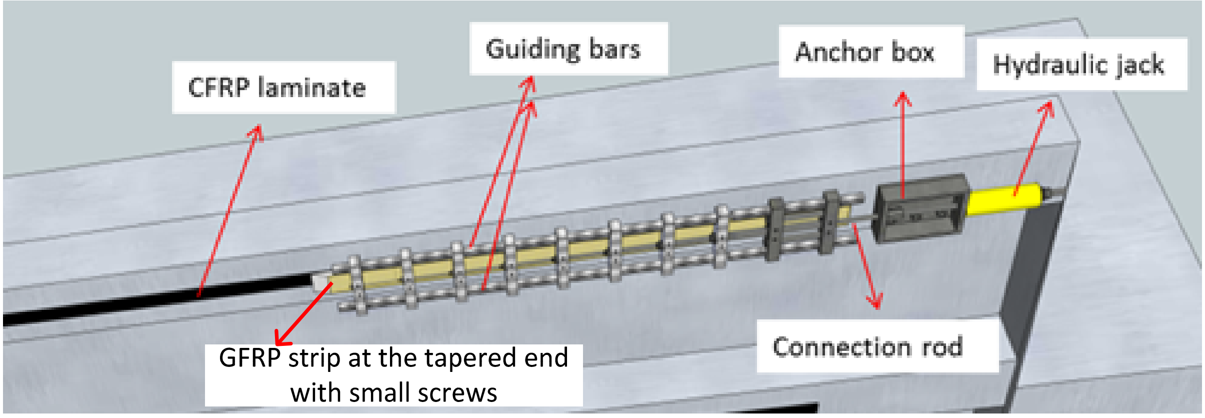

Fig. 2.4 Illustration of the system applied on a concrete bridge.

3. BRIDGE OVER THE RIVER NOSSAN

3.1. Bridge description

The bridge is located in western Sweden as illustrated in Fig. 3.1. The bridge is located on a secondary road connected to E20 and overpasses a small river. Nossan Bridge is a road bridge with two lanes and was built in 1938. The bridge is 20 m long and is 5.7 m wide and consists of a concrete frame system. The bridge was downgraded by TRV from class 4 to class 2 due to cracks at various locations including mid-span which were discovered during inspections. By pre-stressing TRV is hoping that the bridge could be upgraded again to its original class.

Fig. 3.1 Location of the Nossan Bridge.

A view of the bridge and the cross-section are shown in Figs 3.2 and 3.3. The structural system consists of two arch beams located on the sides and concrete slab on top of them.

Fig. 3.2 View of the bridge.

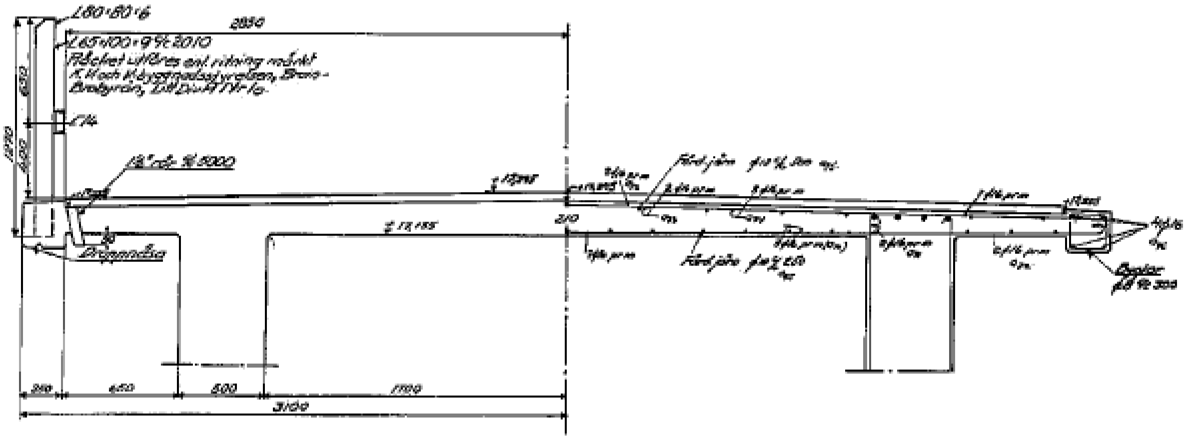

Fig. 3.3 Cross-section of the bridge.

3.2. Inspection of the bridge and checking the concrete condition

The contractor, Strong Solution, performed the first inspection of the bridge. This inspection revealed some cracks in the concrete at the crown of the arch as can be seen in Fig.3.4. The width of the cracks was in the range of 0.5 mm and it was concluded that the reason for cracking was constraint forces due to thermal changes. Due to rather large width of cracks, corrosion of the main reinforcement might also be expected in the bridge. However, no investigations were performed with regard to this issue. Due to specific geometry of the bridge, i.e. arch shape, it was not possible to mount the laminates underneath the beams. Therefore, the laminates had to be installed on the sides of the beams. Due to presence of a diaphragm beam at the mid span, it was not possible to apply laminate from the inner sides. As a result, the option was to either use one or two pre-stressed laminates on each beam from the external side.

Fig. 3.4 Cracks in the concrete beam at the mid span of the bridge.

Before the bridge was accepted as a suitable case for strengthening, four pull-off tests were performed at different locations on the bridge to control the tensile capacity of the concrete. In order to apply a FRP laminate with adhesives without pre-stressing, the requirement is that the concrete should have a tensile strength of at least 1 MPa. For pre-stressed laminate there is no such a requirement, but at least 2.5 MPa should be a minimum value. The results from the pull-off tests are presented in Table 3.1. These values were obtained from the outer side of both beams and in proximity of the position of the CFRP laminate.

Table 3.1 Test results from the pull-off test carried out on the bridge.

Test	**Strength [MPa]**
1	3.4
2	>3.5
3	3.2
4	>3.5

3.3. Assessment of the bridge and needed pre-stressing force

A numerical model was developed to investigate the current condition of the bridge as well as the effect of strengthening. The bridge was modeled using commercial FE program Abaqus. An axel load of 120 kN was applied on the bridge to model the traffic load. The modulus of elasticity of the concrete was assumed to be 33 GPa. A 3D solid model was developed in order to study the bridge. A pre-stressing force of 100 kN was applied on each girder according to the illustration shown in Fig. 3.5. The results from the numerical analysis revealed that a pre-stressing force of 100 kN would induce a compressive stress of 0.7 MPa in the midspan of the bridge and would contribute to 0.67 mm cambering at the middle section.

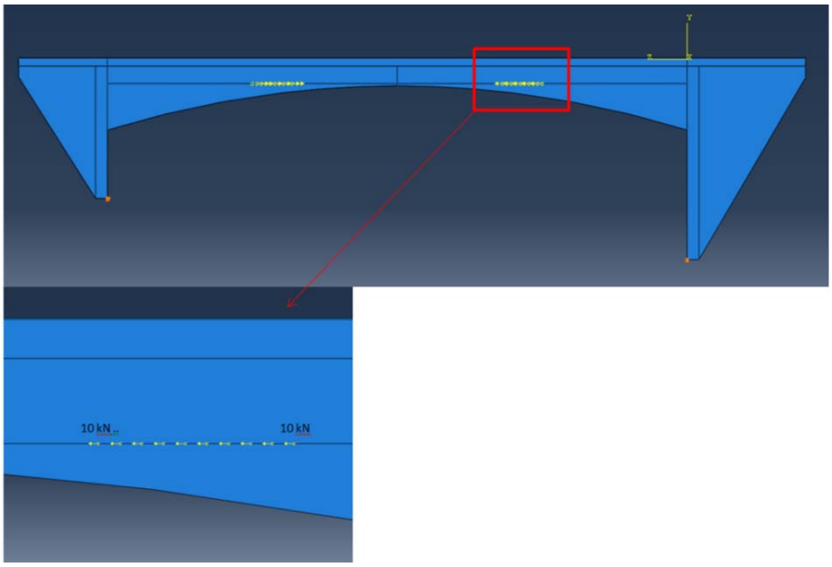

Fig. 3.5 Finite Element (FE) model of the bridge showing the application of the pre-stressing force, P=100 kN.

Also analytical rough calculations were made, Leppänen 2013 shown in Appendix A. Analytical calculations revealed crack width of 0.06 mm and mid deflection less than 1 mm. Tensile stresses in the reinforcement were quite small, i.e. 65 MPa and would decrease to about 60 MPa as a result of pre-stressing by 100 kN. Both estimations, i.e. FE and analytical modelled beams as fixed at both ends.

Further analyses revealed that if two laminates were to be installed, the second laminate would be closer to the neutral axis and will not be very effective. As a result, it was decided to use just one pre-stressed laminate with a force of 100 kN as close as possible to the edge of the beam as illustrated in Fig.3.6. The length of the laminates was 8m, extending 4m on each side from the center of the bridge.

As the diaphragm beam prevented to add laminate on the inside of each beam, the effect from the pre-stressing was small. However two laminates pre-stressed to 100 kN, will help for the existing cracks not to propagate.

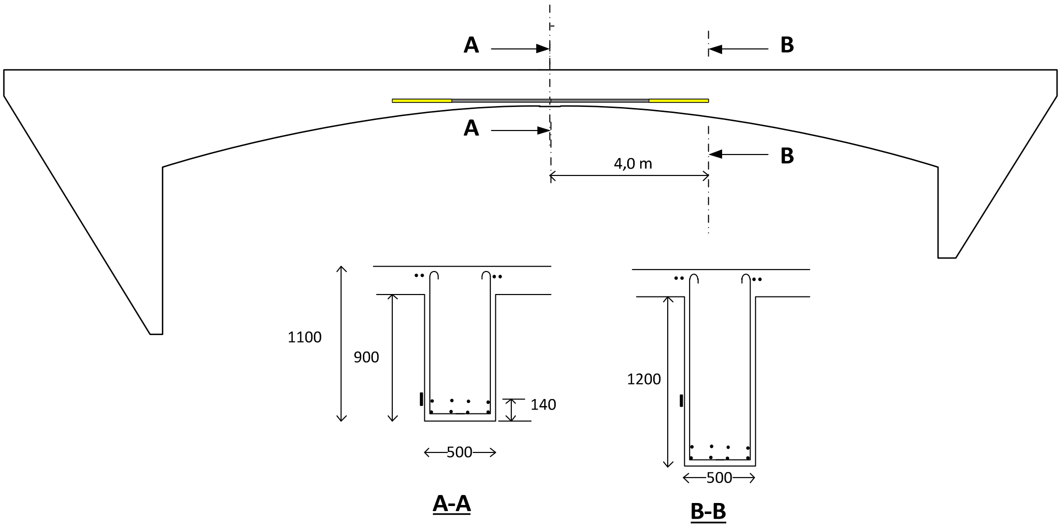

Fig. 3.6 Strengthening scheme with a CFRP laminate on the edge of the beams.

4. PREPARATION OF LAMINATES AND EQUIPMENT FOR PRE-STRESSING WORK

The pre-stressing device is connected to the CFRP laminate via glass-fibre (GFRP) strip glued at both ends of CFRP, cf. Fig 2.4. The preparation of strengthening CFRP laminate and pre-stressing device in the workshop includes the following steps:

- Getting GFRP strips of the same width as CFRP and about 1.2 m length with tapered one end of the strip.
- 20 small holes are drilled in GFRP following pre-defined template.
- Small molded nuts (2 screws/tab) are glued into the holes in GFRP
- GFRP with the molded nuts are glued at each end of the CFRP laminate, see Figs. 2.4 and 4.1 from the Nossan bridge
- Ten small tabs, which are part of the pre-stressing device, are connected to the GFRP strips via screws, cf. 2.2 and Fig. 4.2.

Fig. 4.1 Glass fibre (GFRP) strip with small molded nuts where the screws will be connected.

Fig. 4.2 Mounted pre-stressing device to the CFRP ready to be used on site.

The critical place on the final CFRP laminate with mounted pre-stressing device is where stiff part of GFRP ends (tapered part of GFRP) and CFRP laminate begins. In this place some short pieces of wood were added on both sides and taped with building tape prior to transportation to the bridge site. One extra laminate was made in case of some unexpected events.

Four anchoring plates (box, cf. Fig. 2.4) and Hilti® concrete screws together with Hilti drills and equipment such as spanners were also taken to the bridge site.

5. STRENGTHENING WORK AND MEASURED TIME TO PERFORM EACH STEP

5.1. On-site establishment

TRV was responsible for the establishment on site. It was decided during the planning phase that it was not necessary to stop the traffic on the bridge. Usually, only during the pre-stressing phase (about an hour) the heavy traffic should be limited. However, after the performed calculations it was decided that on this bridge we would not have any traffic restrictions not even during pre-stressing work. In the preparation phase, to provide access to the bridge, scaffolding was installed under the bridge, see Fig. 5.1. Safety road measures were also taken with signs to limit the speed as standard procedures when working is on-going around the bridge.

Fig.5.1 Traffic safety measures on the bridge and scaffolding with protection.

The scaffolding was rented for 3 weeks and it took approximately three days to build it and less than two days to dismantle it. The total cost for the establishment, safety, rent of personnel cabin (changing and shower room) and scaffolding, transportation and so on was around 140 thousands Swedish crowns.

5.2. Strengthening procedure

Each step of the procedure is described separately.

Marking the approximate location for the laminates on bridge beams

This was done to specify the line along which the surface preparation must be made.

Surface preparation

In this step, the surface of the concrete was grounded over the area on which the laminate will be bonded. The aim of grounding the concrete was to take off a thin layer of weathered concrete with low strength and quality. This operation is illustrated in Fig.5.2. The noise from the surface preparation operation was measured during the strengthening. After grinding the surface, the remaining dust was taken by means of vacuum cleaner as shown in Fig. 5.2. The time needed for grinding two lines, including 16 m of preparation, took about 20 minutes. The cleaning of the surface with vacuum cleaner took about 15 minutes for the whole length. This work was performed by Strong Solution AB.

Fig. 5.2 Preparation of the concrete surface by grinding (left) and removing the dust from the ground surface (right).

Specifying the exact location of the laminate and holes for the temporary anchoring system

In this step, the exact location of the laminates and temporary bolts were specified and marked. Prior to drilling the holes of 22 mm diameter to install Hilti® bolts to fasten temporary steel anchors, reinforcement detection was conducted in order to avoid drilling into the reinforcement. This was simple procedure and it was easy to find a place on a concrete beam where four holes/ anchor could be drilled without drilling into reinforcement. The number of the holes to be drilled for each laminate and the time consumed for drilling is listed in Table 5.1. Marking the location for the laminate and drilling the holes for the installation of the temporary anchors is shown in Fig. 5.3.

Fig. 5.3 Marking the location of the laminate on the beam (left) and drilling the holes to install Hilti® bolts to fasten temporary steel anchors (right).

Table 5.1 List of holes and time needed for drilling holes on the bridge

Hole	**No. ***	**Time per hole [min]**	**Total time [min]**
M22 x 125	2 x 4	6	48
M12 x 60	2 x 2	3	12
Total amount of time spent for 2 laminates			120

* There are two ends of each laminate and four bolts at each end

Application of primer on the surface

In order to enhance the bond between the laminate and the concrete, according to the manufacturer's recommendation, a primer was applied to the surface of the concrete. The primer needed 24 hours for curing. The time needed for application of primer was about 5 minutes for two lines with total length of 16 m.

Installation of anchor plates and guiding bars

The temporary anchor plates and the guiding bars were then installed, see Fig. 5.4. The time needed for installation of anchors and bars at both ends was 15 minutes. Two persons were working on each end of the laminates at the same time and therefore, the installation took 15 minutes per laminate and totally 30 minutes for two laminates. However, one of the anchor plates was difficult to install as a result of skew Hilti bolts due to skew drilled holes.

It is important to have larger holes in the anchor plates to be prepared for some deviations from straight bolts.

Fig. 5.4 Installation of temporary anchors, guiding bars and pre-stressing jack (red).

Fig. 5.5 Application of adhesive on the concrete surface.

Application of the adhesive on the concrete surface on top of the primer

After the installation of temporary anchors and guiding bars, the adhesive was applied on the concrete surface as shown in Fig. 5.5. The application of the adhesive on the concrete surface took 10 minutes for two persons for a line of 8 m.

Pre-stressing of the laminates, locking the system and demounting the hydraulic jacks

The laminate and the pre-stressing device were then mounted on the guiding bars and the device was connected to the hydraulic jacks on the active end and to the anchor plate on the passive end. The force in the laminate was controlled during pre-stressing by means of a strain gauge mounted on the laminate at mid-length. After the full force was applied to the laminate the nuts were tightened to the temporary anchor plates and the jack was removed. See Fig. 5.6 of the CFRP laminate directly after the pre-stressing job. The entire pre-stressing operation including the installation of device on the bars and pre-stressing took 10 minutes per laminate. In the future, it is important to have even better control over the applied pre-stressing force. This could be done using digital load cell to read the force more easily than using strain gauges and perhaps with better accuracy.

The concrete surface was a bit wavy where the laminate was attached, and as a result, some adhesive was missing between the laminate and the concrete. This could be noticed after the force was applied to the laminate, as the laminate get stretched and straight between the anchoring points. Some adhesive was added between the concrete and stretched CFRP using a putty knife. It added perhaps 15 minutes after the pre-stressing work was finished.

Curing, releasing of the device and demounting of the anchoring plates

The epoxy adhesive that was used in this project needed 7 days for full curing. As a result, the release of the anchoring system, see Fig. 5.7, was made 7 days after pre-stressing operation in order to obtain the full adhesive strength according to the manufacturer's recommendation. All the bolts which were used for installation of temporary anchors were demounted, see Fig. 5.7. The holes were repaired using premixed concrete. Total time needed for releasing and demounting each anchoring system was about 7 á 8 minutes for two persons.

Fig. 5.6 Directly after the pre-stressing job.

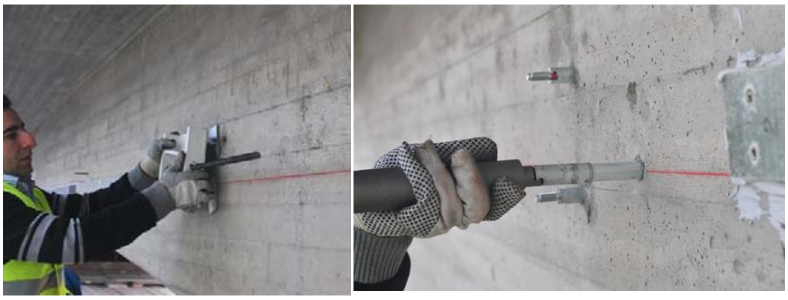

Fig. 5.7 Release of the anchoring steel plate and demounting of the temporary anchor Hilti® bolts .

As it can be seen in Fig. 5.7 (right corner), the strip of GFRP glued to the CFRP laminate was left on the site after the whole job was completed.

Waste management

During the entire job, there was a large plastic bag on the scaffolding. All waste such as packaging, tapes from transportation of the laminate, waste from extra epoxy adhesives, metal containers from primer and epoxy and repair premixed concrete waste was all collected in the plastic bag. At the end, even the long strip of paper which protected the scaffolding from primer and epoxy was also collected in the bag. On the way back, the bag was deposited at the recycling place.

6. Evaluation of the method based KPI and Comparison with other pre-stressed method

6.1. Commercially available pre-stressing systems with permanent anchors

There are a number of different commercially available pre-stressing systems on the market. What they all have in common is the pre-stressing method, in which the pre-stressing is carried out by tensioning against the strengthened beam, and that they use some kind of mechanical anchors. The laminate is anchored to the pre-stressing device at both ends and separate permanent anchors are mounted to the strengthened beam. The laminate is then pre-stressed by pulling the anchors attached to the laminate reacting to the anchors that are fixed permanent on the strengthened beam. The most common systems are: Sika LEOBA, Sika StressHead system, S&P pre-stressing system and Neoxe pre-stressing system. The minor differences between these systems are the way temporary and permanent anchors are used and when and how the permanent anchors are fixed and connected. For simplicity only Sika and S&P systems are shortly described in this report.

The Sika LEOBA pre-stressing system is based on using temporary as well as permanent mechanical anchors (www.sika.com). These anchors are attached to an anchor plate which is located in a cavity in the concrete, see Fig. 6.1. This cavity has to be cut out of the concrete. The anchor plate is used as a base plate to transfer the force from the anchor to the concrete. The CFRP laminates are pre-stressed using a hydraulic jack and the temporary anchorage (in blue, Fig. 6.1) is blocked with locking screws. Permanent anchors (in white, Fig. 6.1) are then installed with both bolts and adhesive and when the adhesive has fully cured it is possible to remove the temporary anchors and solely rely on the permanent anchors.

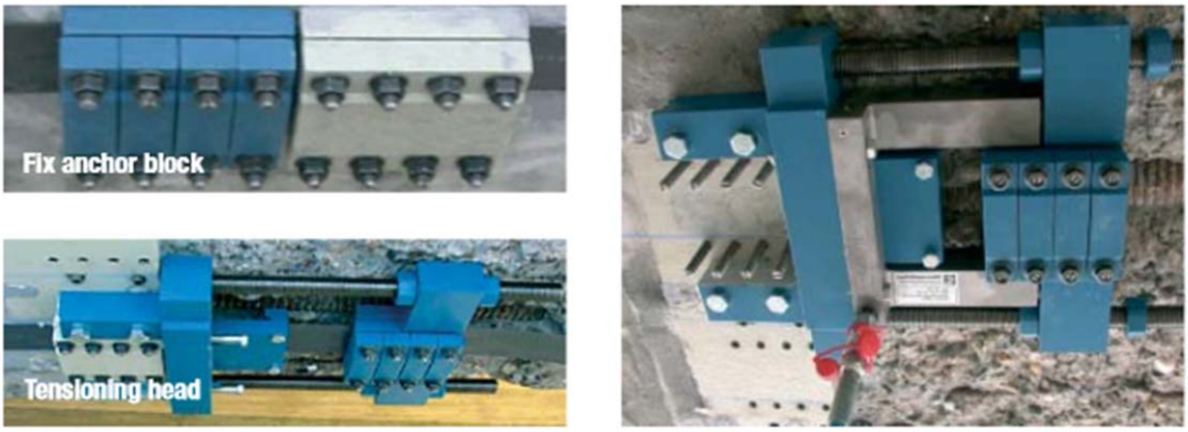

Fig. 6.1 Tension head with temporary anchors and permanent anchor block from the Sika LEOBA system (www.sika.com).

S&P is another company that provides a pre-stressing system for CFRP laminates (www.reinforcement.ch). This system is, like the Sika systems, based on using mechanical anchorage. The CFRP laminates are prepared with a special anchorage element consisting of two steel plates and one cylindrical element that are fixed to the laminates. The laminates are then pre-stressed using a hydraulic jack and when the adhesive has cured the jack can be removed and the anchorage is secured.

6.2. Advantage of Chalmers/Tenroc's method based on KPI and environmental impact

The evaluation of Chalmers/TENROC innovative method is based on some Key Performance Indicators (KPI). The key performance indicators (KPI) were defined for this project and they were: safety, reliability of the system, design life, maintenance of the pre-stressed material, measured time to perform each part of the work, noise and dust emissions, and minimum traffic disruption during preparatory and strengthening work on site. Some of these KPIs are also use to define to describe the environmental impact of the pre-stressing system, where minimising the use of materials, sustainability and durability of the system and minimum traffic disruption during the strengthening work are the most important parameters.

The Chalmers/TENROC pre-stressed FRP system is compared in terms of KPI and other various criteria with traditional pre-stressed FRP systems with mechanical anchors see Table 6.1.

Table 6.1 Advantages of the Chalmers/TENROC pre-stressing (new) system compared to pre-stressing systems with mechanical anchors. The sign "+" means that the new system has some advantage/s compared to the existing systems. Numbers (1) to (12) refer to explanations following this Table.

Criterion and requirements	**Advantages of proposed pre-stressing system-comments**
Safe	+(1)
Reliable	+(2)
Design life	+(3)
Minimize traffic disturbance	+(4)
Robust	Comparable
Designable	Comparable
Verifiable design	Comparable
Validated	Comparable
Quality assurance during construction	+(5)
Low maintenance	+(6)
Biddable	Comparable
Affordable	+(7)
Sustainable	+(8)
Reuse of material	+(9)
Inspectable	+(10)
Durable	+(11)
Added technical value	See advantages (2) to (12)
Aesthetic	+(12)
Usable with different contract forms	n/a

(1) The safety of the proposed system and the device was tested in the lab experiments beforehand. The pre-stressing system was supposed to take up a load of 100 kN. A test was set up in the lab condition to make sure that the system can safely withstand this load. The pre-stressing device was loaded up to 160 kN without any signs of failure in any parts of the device. This safety margin was acceptable for TRV. The system was designed with safety factor between 1.6 and 3.0. A safety factor of 3.0 is used with respect to the interfacial stresses resulting in the concrete substrate due to force transfer between the pre-stressed laminate and concrete (shear stress of about 1.0 MPa with respect to shear strength of 3 MPa).

Using this pre-stressing system, two possible failure scenarios may occur during the pre-stressing and releasing operations:

1. Failure of the bonded glass fibre plate. A safety factor of 2.0 is applied. Such failure will result in a sudden release of the pre-stressing force. No damage is expected to take place to the bridge structure, but the safety of the workers needs to be secured. Each system have some weaknesses and during the pre-stressing, before the adhesive harden, it is important not to be close to the CFRP between two anchors in case of brittle tensile failure occurs. This can happened due to manufacturing errors of CFRP and this risk applies to all pre-stressing systems. Some safety procedures for workers must be established and clarified in the future.

2. Failure of the concrete surface (cover separation) directly after the release operation. The design is made with a safety factor of 3.0 with respect to this mode. However, if the failure takes place in this mode, only a thin layer of concrete, i.e. concrete cover, would fall off which imposes no risk for the workers on site. Such damage is easily repaired afterwards.

The creep deformation of the adhesive is negligible from pre-stressing (ca 1 MPa). No relaxation is expected in the laminate.

Creep of the concrete will depend on the pre-stressing level, but is judged to be negligible (also based on observations and measurements made during large scale testing).

Visual inspection is performed after the pre-stressing operation and before release. Local adhesive repairs are made, if necessary, to insure good bond line and bond strength.

(2) One of the drawbacks of the existing pre-stressed FRP systems with mechanical anchorage is the concentration of a large force in a localized area, i.e. anchors in the structure. Usually, concentration of stress is not a desirable phenomenon in structures and should be avoided. In case of failure, in one of the anchors, the pre-stressed laminate would be detached from the structure in an abrupt manner. Away from potential damage that release of such a huge force can cause, the structure would be situated in an imbalance condition since there are usually more than one laminate used for the strengthening and repair of the structure. This might jeopardize the safety of the structure. The new proposed system, would avoid such force concentration by distributing the pre-stressing system over a rather long length. In a test which was made in the lab, a vandalism act was simulated by peeling the pre-stressed laminate from the concrete beam. It was observe that the system had rather good strength against delamination, and displayed a progressive damage mechanism as the laminate

detached from the concrete substrate. Therefore, it could be concluded that the reliability of the proposed system against unpredicted action such as vandalism and impacts, would be more compared to anchored pre-stressed laminates.

(3) Since the new system does not need the mechanical anchorage, from durability view point the new system has advantage over the existing systems with mechanical anchorage. This means that the risk of corrosion or malfunction of the anchorage system is eliminated in the new system.

(4) One of the advantages of the proposed system compared to traditional systems is that it does not need mechanical anchorage. The installation of mechanical anchorages, involves extra modification of the structure to fit the steel plates, in terms of cutting the concrete and drilling holes, which takes time and cost money. Since the proposed system does not need any mechanical parts to be installed, it is faster to install with that respect which means shorter installation time and thus less traffic disruption.

(5) Quality assurance of the proposed system is easier compared to the system with mechanical anchors since all the parts are visible. For example, just in case of lack of adhesive in the bond line, extra adhesive could be injected while in the other system, there are hidden parts which could not be controlled with regard to manufacturing.

(6) One of the advantages of the proposed system is the lower need for maintenance. The pre-stressed systems with mechanical anchors involve more parts and thus greater possibilities of failure. The fact that the resistance of the system comes from the friction mechanism in the clam and it is very sensitive to degradation of the friction agent, i.e. adhesive in the anchorage area, need more maintenance. Regular inspections should be set up to assure that there is no sign of degradation or corrosion in the anchors. Another shortcoming is that the inspection of the anchors, since they cannot be opened, is hard. However, the new system does not involve these shortcomings.

(7) The cost comparison for the proposed system and the pre-stressed system with mechanical anchors was not carried out. However, since the need for drilling holes is less and modification of the structure does not exist in the proposed system, it could be anticipated that the proposed method would be cheaper.

(8, 9) Less traffic disruption, no need for mechanical anchorage, less maintenance and less number of holes needed for installation which cause less noise and dust, all contribute in making the proposed solution more sustainable. The anchoring plates and pre-stressing device can be reuse many times. The maintenance of the pre-stressing device can be done in the workshop. Apart of the CFRP, the new method needs a strengthening material (in this case GFRP strips) which is left on the bridge. However, using and leaving GFRP strips together with CFRP laminate on the bridge is considered to create substantially less problems in the future with these strips compared to the permanent mechanical anchors.

(10) Since there are no hidden parts in the proposed system, it is easier to inspect it compared to pre-stressed systems with mechanical anchors.

(11) The proposed system is more durable due to the fact that it does not involve mechanical parts.

(12) From an aesthetic point of view, since there is no need for extra parts to be attached to the structure, the proposed system has an advantage compared to the system with mechanical anchors.

The advantages of the new strengthening system in comparison with the established systems with the permanent use of heavy anchors were shown to be very clear.

6.3. Evaluation of Chalmers/TENROC system in terms of different implemented operation

The proposed method for application of pre-stressed CFRP laminates proposed on the Nossan Bridge was found to be straight forward and easy to apply. Based on the interview with all people involved who carried out the work, the steps were well defined and easy to perform. The work was not complicated and was performed rather quickly. The level of noise was also documented for all operations. The time needed for performing different steps for each laminate and maximum noise measured on bridge is shown in Table 6.2.

Table 6.2. Application time for different stages of the work for each laminate and maximum noise measured on bridge.

Operation	**Time [min]**	**Persons involved**	**Noise level [dB]**
Surface preparation - Grinding	10 [≈1. 5 min/m]	1	70
Surface preparation - Cleaning	7.5 [≈1 min/m]	1	-
Drilling holes	60	1	81
Application of primer	2.5 [≈0.5 min/m]	1	-
Installation of temporary anchors	15	2	-
Adhesive application	10 [≈1.5 min/m]	2	-
Demounting	15	2	-
Total time	**120**		

During the pre-stressing, only two operations contribute to high noise level. They are grinding and drilling the holes in concrete to install Hilti® bolts to fasten temporary steel anchors.

During the surface preparation and grinding of the concrete, the noise was measured in three different locations, under the bridge, on the bridge and 25 m away from the bridge. The noise level under the bridge was measured as 95 dB, on the bridge 70 dB and 25 m away from the bride 52 dB.

The noise from drilling the holes was also measured during the operation at three locations to assess the noise disturbance. The measured noise under the bridge was 102 dB, on the bridge 81 dB and at 25 m away from the bridge it was 60 dB.

6.4. Evaluation of the new method in terms the remaining uncertainties and possible difficulties with the method

The evaluation of the new method showed very clearly that the system worked very well in practice despite the fact that it was done for the first time. All steps were well managed. The entire installation of two laminates, 8 metre long, on site was performed in less than 2 hours by 2 persons. However, some insufficiencies could be improved and, perhaps, half an hour could be saved in the future (based on only two laminates). These were: too small tolerances for holes diameters in the anchor plates in order to account for some deviations from straight bolts mounted in the concrete and lack of straight surface of the concrete where CFRP was glued. As long as both ends of the stretched laminate (about 1.5 metre) are well in contact with concrete surface and no adhesive is missing, then there is no danger for the whole system. After the pre-stressing job, it is easy to add some missing adhesive between CFRP and the concave surface of the concrete, but it will add some extra time. In the case of this pre-stressing at the Nossan Bridge, only one beam was concave and there was some air between the stretched laminate and the surface. Adhesive was added directly after the pre-stressing job to fill the gap.

We believe that there will not be other possible difficulties with this method for other applications such as other type of bridges or industrial applications. However, it is important to remember that this new method is most suitable for bridges which have straight beams made of any materials and which are in need to improve bending performance, especially in SLS. The method is also well suited to industrial beams and slabs. If the pre-stressed laminate is easily accessible by the public, it is important that it is prevented from vandalism as it would be dangerous to try to break it from the concrete surface. The solution in such a case is to cover the entire laminate including the GFRP and both ends with a thin layer of concrete.

7. COMPARISON BETWEEN THE NEW METHOD AND ONE ESTABLISHED METHOD IN TERMS OF LCC ANALYSIS

The purpose is to compare the total life-cycle costs of strengthening alternatives for the bridge in order to reveal the most cost-effective solution.

Two alternatives of strengthening are assumed for applying in the bridge:

i. Strengthening with pre-stressed CFRP plates without the need of mechanical anchors developed by Chalmers and TENROC.
ii. Strengthening with pre-stressed CFRP plates with permanent mechanical anchors developed by Sika LEOBA

Both alternatives fulfill the performance-based requirements.

Identification, classification and estimation of costs and project parameters that occur over the service life of the strengthened bridge

Project life-cycle cost includes two main categories: agency costs and social costs as shown in the Fig.7.1.

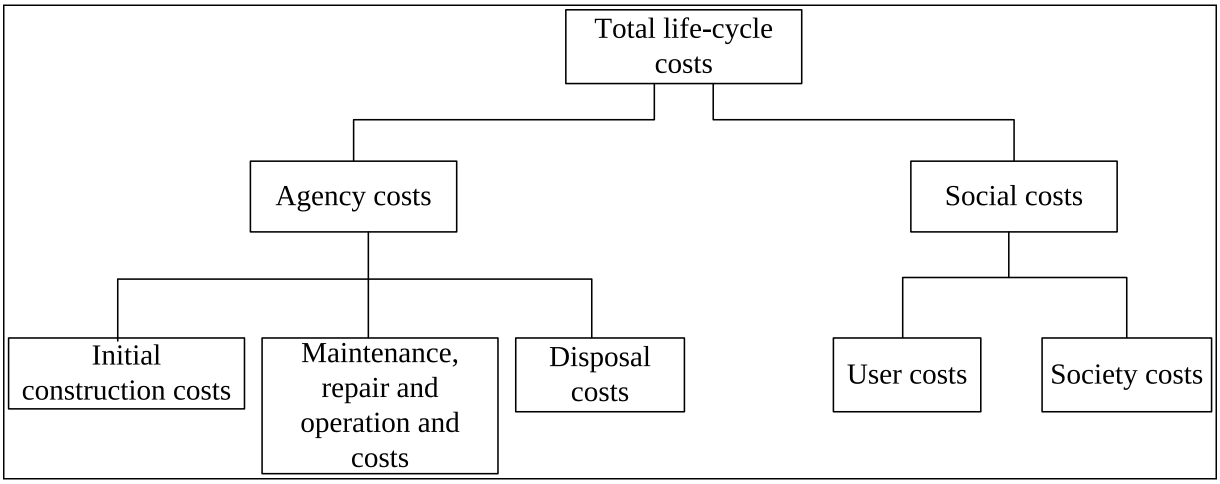

Fig. 7.1 The life-cycle cost model.

In this analysis, the costs that are the same for both alternatives are disregarded such as inspection costs during the service life of the bridge, disposal costs and society costs. The costs considered in the analyses for each category are described in the following.

Agency Costs

Initial construction costs:

Firstly, the inventory of each strengthening process is defined together with the traffic restrictions in order to account for the user costs, cf. Table 7.1.

Table 7.1 Traffic restrictions and disturbance for Alternative 1 (Chalmers/TENROC) and Alternative 2 (source S&P reinforcement, Germany).

Day	1	2	3	4	5	6	7	Traffic disturbance
Alternative 1								
Construction of scaffolding	🟩							The traffic speed is reduced from 70 km/h to 50 km/h during the works for two hours. In addition, the heavy traffic is restricted for 1 hour during prestressing activities.
Application of the strengthening		🟦						
Demounting the pre-stress device							🟨	
Alternative 2								
Construction of scaffolding	🟩							The traffic is restricted for two hours.
Preparation and gluing of the laminates		🟦						
De-installation of pre-stress device			🟨					

The traffic restrictions for the first alternative are based on the procedure followed for the installation of the pre-stressed laminates, which is described in detail in Chapter 5.1. We assumed that in normal situation we will have restriction for a heavy traffic, but this restriction did not apply to Nossan's Bridge.

During the installation of the laminates for the second alternative, there should not be any vibration in the elements. Therefore, the traffic is restricted for two hours which is the required time to install the laminates.

In Table 7.2 the breakdown of the installation costs are defined.

Table 7.2 Input data for costs of Alternative 1 (Chalmers/TENROC) and Alternative 2 (source S&P reinforcement, Germany).

	Alternative 1	**Alternative 2**[**]
Material costs		
Finished CFRP laminates[*]	29,200 SEK	14,400 SEK
Equipment + installation costs		
Pre-stress device + anchor plates	16,600 SEK	36,000 SEK
Total	**45,800 SEK**	**50,600 SEK**

[*] and GFRP in case of Alternative 1

[**] Rate for 1Euro is based on 9 SEK.

Maintenance, repair and operation costs

It is anticipated that no maintenance is needed for the first or second alternative. Usually, there is no specific inspection needed for the strengthening system. The requirement is to inspect a specific bridge type after a specific period of time and at the same time the pre-stressing may also be inspected. This would apply to both alternatives.

Social costs

Only the user costs (driver delay costs and the vehicle operating costs) are included in the calculation of the social costs for this analysis.

The social costs are calculated during initial strengthening since the traffic is restricted during operation time.

Table 7.3 Input data for social costs.

Item	**Alternative 1**	**Alternative 2**
Average daily traffic (ADT) [vehicles/day]	5000	
Percentage of trucks on the bridge (%)	10	
Hours of closure of the bridge	11	22
Hourly user costs cars	180 SEK/h	180 SEK/h
Hourly user costs trucks*	360 SEK/h	360 SEK/h
Normal traffic speed	70 km/h	
Traffic speed during strengthening	50 km/h	-
Length of the affected roadway	50 m	

1 Only the heavy traffic (lorries and agricultural machines) is restricted
2 All the traffic is restricted
* Ref. Mohammed Abed El-Fattah Safi, *LCC Applications for Bridges and Integration with BMS*, Licentiate thesis, 2012.

Computation of life-cycle cost analyses of each alternative

Table 7.4 The total costs are computed based on data presented in Tables 7.2 and 7.3.

	Alternative 1	**Alternative 2**
Agency costs (SEK)	45,800	50,400
Social costs (SEK)	2,921	5,834
Total (SEK)	**48,721**	**56,234**

It is observed that the first alternative (Chalmers/TENROC) yields lower costs than the second one due to fewer investment and social costs. Hence, the cost-effective alternative is the first alternative as it meets the performance requirements of the overall bridge and has the lowest life-cycle cost. In addition, there are other advantages of the first alternative which cannot be quantified and are not reflected by this life-cycle cost analysis, cf. Table 6.1. For a larger bridge with much higher traffic intensity the social costs will become much more important and, as a result, it will be much more beneficial for the Chalmers/TENROCs method. Another obvious advantage of the Chalmers/TENROCs method in comparison with the alternative 2 is the aesthetic and durability issues. The large visible anchorage system, cf. Fig. 6.1, is the main disadvantage of the alternative 2. Is also unclear, what is the real maintenance cost of the anchorage system? It is also a well-known fact that if the insulation between anchor plate and concrete beam is not perfect during the service life of a bridge then there is a risk for galvanic corrosion to develop.

8. FUTURE IMPROVEMENTS OF THE NEW PRE-STRESSING METHOD

The main aim for the future improvements are related to minimising the costs of finished laminate, see material costs in Table 7.2. Costs of GFRP and its preparation today are too expensive; cf. the results from LCC analysis. In the future, new strips will be investigated to replace GFRP to a cheaper and more sustainable material. There are many different hard plastics or other materials on which the small molded nuts can be mounted where screws can be put in and the force from the pre-stressing device to the CFRP laminate can be transferred.

Another alternative is to develop FRP strip with small molded nuts already placed during the infusion process. In the infusion method, dry components (fibres, core materials and small cylinders, for example) are placed in a mould. The shape of the mould allows for flexible arrangement of layers of the materials and direction of the fibres. This development can be made by TENROC or by other company in collaboration with TENROC.

Other improvements can be related to anchor plates, i.e. better holes tolerances, easy and reliable way to measure the pre-stressing force on the site and easier ways to dismantle the anchorage system after hardening of the adhesive. In the future, it is possible that at least two laminates may be pre-stressed at the same time, and as a result, an anchor plate for two laminate and still perhaps only four Hilti bolts may be enough.

Quality assurance and self-control of the performed pre-stressing work with simple instruction procedures are also needed to warranty the same quality at the end of the performed strengthening job.

After some discussion we arrive at the conclusion that we should implement this technique on some other projects for the technology to mature and only then should we evaluate and improve it.

9. CONCLUSIONS

The innovative strengthening method (called here Chalmers/TENROC method) on the bridge over Nossan river has been performed with regard to practical production experience and sustainability criteria. The whole process of planning, logistics and assembly of pre-stressed laminates on the bridge has been reported. This was the first pre-stressing work of this kind performed on the bridge in the field in Sweden. The bridge itself was not a perfect type of bridge for this kind of pre-stressing work, as the bridge consists of two arch beams located on the sides and concrete slab on top of them. Due this specific geometry of the bridge, it was not possible to mount the laminates underneath the beams. Therefore, the laminates had to be installed on the sides of the beams and only on one side. Due to presence of a diaphragm beam at the mid span, it was not possible to apply laminate from the inner sides. As a result, only two laminates, 8 meter long, were used, one on each beam.

The entire pre-stressing job was very successful from the production and practical viewpoints. The key performance indicators (KPI) were defined for this project and they were: safety, reliability, design life, maintenance of the pre-stressed material, measured time to perform each part of the work, noise and dust emissions, and minimum traffic disruption during preparatory and strengthening work on site. Some of these KPIs are also used to define the environmental impact of the pre-stressing system where minimising the use of materials, sustainability and durability of the system and minimum traffic disruption during the strengthening work are the most important parameters. The advantages of the new strengthening system in comparison with the established systems with the permanent use of heavy anchors were shown to be very clear. Also the estimated Life-Cycle Costs (LCC) showed clear advantage for the new system. The specific cost that needs to be reduced to improve the LCC has been identified.

The comparison with other commercially existing method in terms of material and installation costs and in terms of social costs which take into account traffic disruptions and other important indicators showed large potential and some major advantages of the proposed innovative new method. The main advantages were low environmental impact and lower life cycle costs than other existing commercial systems, fast and easy assembly and very positive aesthetic aspects by avoiding the anchoring systems and its maintenance.

The need for future improvement of the system has been also recognised.

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APPENDIX: ÖVERSLAGSBERÄKNING I MITTSNITT AV BRO ÖVER NOSSAN

Överslagsberäkning i mittsnitt av bro över Nossan vid s.Härene kyrka

Nedan görs en grov uppskattning av vad en förstärkning med laminat kan tillföra bron med dess problem med sprickor i mittsnitt.

Egenvikt hämtas från beräkning som redovisas i BaTMan

En förenklad beräkningsmodell nyttjas för att ta fram snittkrafter av trafiklast. Denna beräkningsmodell är en fast inspänd vid båda stöden, där inspänningssnittet ligger 200mm in i stödet. Spännvidden blir där med fri öppning på 9800mm + 400 mm = 10.2m.

I beräkning beaktas långtidseffekter enligt dagens norm.

Hänvisningar. Broritningar i BaTMan (2 st), beräkning i BaTMan, där egenvikt hämtas.

En uppskattning görs av sprickvidder baserat på last från temp.- och andra längdändringar enligt ursprunglig beräkning.

Vidare görs en grov uppskattning av nedböjning av last.

Slutsats: Beräknad sprickbredd är 0.06mm! Nedböjning är < 1mm.

Uppstodda sprickor kan beror på tvång orsakad av temperaturrörelser,
då bron kan ses som fast inspänd.

Dimensionerande materialegenskaper

Betong kubhållfasthet 300

$f_{ck} := 30 \cdot MPa$ $f_{cm} := 38 \cdot MPa$ $E_{cm} := 33 \cdot GPa$ $E_{cd} := 33GPa$

$f_{ctm} := 2.9MPa$

Armering St44

$f_{yk} := 260 \cdot MPa$ $E_s := 200 \cdot GPa$

$$f_{yd} := \frac{f_{yk}}{1.15} = 226.1\ MPa$$

Geometri

$L := 10.2m$ spännvidd fast inspänd

$b_w := 500mm$ $b_{eff} := 1.8m$

$h := 905mm$ $h_f := 170mm$

$h_w := h - h_f = 735 \cdot mm$

$\phi := 35mm$ armerings diameter

$TB := 30mm$ antaget värde

$c_{bygel} := 8mm$

$c := TB + c_{bygel} + \frac{\phi}{2} = 55.5 \cdot mm$

$c_{fri} := 40mm$ antaget värde

$d_1 := h - c = 849.5 \cdot mm$

$d_2 := h - c - c_{fri} = 809.5 \cdot mm$

$d' := c = 55.5 \cdot mm$ antaget värde

$A_{si} := \frac{\pi \cdot \phi^2}{4} = 962.1 \cdot mm^2$

$A_{s1} := 4 \cdot A_{si}$

$A_{s2} := 4 \cdot A_{si}$

$A'_s := 4 \cdot A_{si}$

Laster

$M_{G.platta} := 98kNm$ från beräkning i BaTMan

$M_{G.balk} := 141kNm$ från beräkning i BaTMan

$M_G := M_{G.platta} + M_{G.balk} = 239\,kNm$ moment av egenvikt

α

$B := 160kN$

$M_{trafik} := \frac{B \cdot L}{8} = 204\,kNm$ bron är dimensionerad för 183 kNm

$M_{def} := 449 \cdot kNm$ temperatur och andra längdändringar, från beräkning i BaTMan

Brottgränstillstånd

snabbt överslag, räknar med faktor 1.35 för egenvikt, 1.5 för trafik, 0.7 för övriga laster

$$M_{Rd} := f_{yd} \cdot \left(A_{s1} + A_{s2}\right) \cdot 0.9 \cdot \frac{\left(d_1 + d_2\right)}{2} = 1.299 \times 10^3 \, kNm$$

$$M_{Ed} := 1.35 \cdot M_G + 1.5 \cdot M_{trafik} + 0.7 \cdot M_{def} = 942.95 \, kNm$$

bron är dimensionerad för 897kNm

Tvärsnittskonstanter böjsprucket stödtvärsnitt

$$\alpha := \frac{E_s}{E_{cm}} = 6.061$$

korttidsrespons

Långtidseffekter

Krypning (**Komp. avsnitt** B.2.1.6**)**

$f_{cm} := 38MPa$

Slutligt kryptal:

$$\varphi(\infty, t_0) = \varphi_{RH} \cdot \beta(f_{cm}) \cdot \beta(t_0)$$

$$\varphi_{RH} = 1 + \frac{1 - RH/100}{0.1 \cdot \sqrt[3]{h_0}}$$

För $f_{cm} \le 35MPa$

$RH := 50$

(Inomhuskonstruktion, antag 50% luftfuktighet)

$$h_0 = \frac{2 \cdot A_c}{u}$$

u är omkretsen av den del av tvärsnittet som utsätts för uttorkning

$u := 2 \cdot \left(b_{eff} + h\right)$ $u = 5.41 \, m$

$$A_c := \left(b_{eff} - b_w\right) \cdot h_f + h \cdot b_w = 0.673 \, m^2$$

$$h_0 := 2 \cdot \frac{A_c}{u} = 0.249 \, m$$

$\beta_{fcm} := 2.93$

$\beta_{t0} := 0.48$

h_0 måste vara uttryckt i mm i nedanstående ekvation:

$$fi_{RH} := \left[1 + \frac{1 - \frac{RH}{100}}{0.1 \cdot \sqrt[3]{\frac{h_0}{mm}}} \cdot \left(\frac{35MPa}{f_{cm}}\right)^{0.7}\right] \cdot \left(\frac{35MPa}{f_{cm}}\right)^{0.2} \qquad fi_{RH} = 1.722$$

Slutligt kryptal:

$$\varphi := fi_{RH} \cdot \beta_{fcm} \cdot \beta_{t0} \qquad \varphi = 2.421$$

$$\alpha_{ef} := (1 + \varphi) \cdot \frac{E_s}{E_{cm}} \qquad \alpha_{ef} = 20.736$$

Krympning

Slutlig krympning:

$$\varepsilon_{cs}(\infty) = \varepsilon_{cd}(\infty) + \varepsilon_{ca}(\infty)$$

Uttorkningskrympning:

$$\varepsilon_{cd}(\infty) = k_h \cdot \beta_{RH} \cdot \varepsilon_{cdi}$$

$\varepsilon_{cdi} := 0.378$ **(Komp.Tabell B2.5)**

$\beta_{RH} := 1.36$ **(Tabell B2.6**)

$k_h := 0.868$ **(Tabell B2.7, h_0=188mm)**

$$\varepsilon_{cd} := k_h \cdot \beta_{RH} \cdot \varepsilon_{cdi} \qquad \varepsilon_{cd} = 0.446$$

Autogen krympning:

$\varepsilon_{ca} := 0.0375$ **(Tabell B2.8)**

Slutlig krympning:

$$\varepsilon_{cs} := \left(\varepsilon_{cd} + \varepsilon_{ca}\right) \cdot 10^{-3} \qquad \varepsilon_{cs} = 4.837 \times 10^{-4}$$

Krympkraft:

$$F_{cs1} := E_s \cdot \varepsilon_{cs} \cdot A_{s1} = 372.316\,\mathrm{kN}$$

$$F_{cs2} := E_s \cdot \varepsilon_{cs} \cdot A_{s2} = 372.316\,\mathrm{kN}$$

$$F_{cs'} := E_s \cdot \varepsilon_{cs} \cdot A'_s = 372.316\,\mathrm{kN}$$

<u>Påkänningsberäkning i Stadium II</u>, (uppsprucket)

$$\sigma_c := \frac{F_{cs1} + F_{cs2} + F_{cs'}}{A_{II.eff}} + \frac{\left(F_{cs1} \cdot e_{s1} + F_{cs2} \cdot e_{s2} + F_{cs'} \cdot e_{s'} + M_L\right) \cdot z}{I_{II.ef}}$$

Tyngdpunktsekvation:

Den övre tryckta betongen måste balansera den dragna armeringen

$$\left(b_{eff} - b_w\right) \cdot h_f \cdot \left(x - \frac{h_f}{2}\right) + b_w \cdot x \cdot \frac{x}{2} + \alpha_{ef} \cdot A'_s \cdot (x - d') = \alpha_{ef} \cdot A_{s1} \cdot \left(d_1 - x\right) + \alpha_{ef} \cdot A_{s2} \cdot \left(d_2 - x\right)$$

Lös ut x:

$x := 0.150 \cdot \mathrm{m}$ (startgissning) antag x>hf

$$x := \mathrm{root}\left[\left[\left(b_{eff} - b_w\right) \cdot h_f \cdot \left(x - \frac{h_f}{2}\right) + b_w \cdot x \cdot \frac{x}{2} + \alpha_{ef} \cdot A'_s \cdot (x - d')\right] \ldots, x \atop + -\left[\alpha_{ef} \cdot A_{s1} \cdot \left(d_1 - x\right) + \alpha_{ef} \cdot A_{s2} \cdot \left(d_2 - x\right)\right]\right]$$

$$x = 0.292\,\mathrm{m}$$

$h_f = 0.17\,\mathrm{m}$ OK!

$$A_{II.eff} := \left(b_{eff} - b_w\right) \cdot h_f + b_w \cdot x + \left(\alpha_{ef} - 1\right) \cdot A'_s + \alpha_{ef} \cdot \left(A_{s1} + A_{s2}\right) = 0.602\,\mathrm{m}^2$$

$$I_{II.eff} := \left[\frac{b_{eff} \cdot x^3}{3} - \frac{\left(b_{eff} - b_w\right)\left(x - h_f\right)^3}{3} + \left(\alpha_{ef} - 1\right) \cdot A'_s \cdot (x - d')^2 \ldots \atop + \alpha_{ef} \cdot A_{s1} \cdot \left(d_1 - x\right)^2 + \alpha_{ef} \cdot A_{s2} \cdot \left(d_2 - x\right)^2\right]$$

$$I_{II.eff} = 0.065\,\mathrm{m}^4$$

$x_{tp} := x = 0.292\,\text{m}$ ren böjning

$e_{s1} := d_1 - x = 0.558\,\text{m}$

$e_{s2} := d_2 - x = 0.518\,\text{m}$

$e_{s'} := -(x - d') = -0.236\,\text{m}$

Kontroll av långtidsmoment

Betongpåkänningar egenvikt + 0.3 Mdef

$M_L := M_G + 0.3 \cdot M_{def} = 373.7\,\text{kNm}$

$M_G = 239\,\text{kNm}$ $0.3 \cdot M_{def} = 134.7\,\text{kNm}$

$$\sigma_c(z) := \frac{F_{cs1} + F_{cs2} + F_{cs'}}{A_{II.eff}} + \frac{\left(F_{cs1} \cdot e_{s1} + F_{cs2} \cdot e_{s2} + F_{cs''} \cdot e_{s'} + M_L\right)}{I_{II.eff}} \cdot z$$

betongspänning i överkant:

$\sigma_c\left(-x_{tp}\right) = -1.246\,\text{MPa}$

armeringspåkänning

$\sigma_c\left(d_1 - x_{tp}\right) = 7.781\,\text{MPa}$

$$\sigma_{s1} := -\frac{F_{cs1}}{A_{s1}} + \alpha_{ef} \cdot \sigma_c\left(d_1 - x_{tp}\right) = 64.6\,\text{MPa}$$

Sprickbredd (B9-18)

(sprickbredden beräknas i understa lagret, där den är störst)

$$w_k = s_{r.max} \cdot (\varepsilon_{sm} - \varepsilon_{cm})$$

$$s_{r.max} = k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \frac{\phi}{\rho_{p.eff}}$$ Maximalt sprickavstånd

$k_1 := 0.8$ kamstänger

$k_2 := 0.5$ töjningsfördelning; ren böjning (approximativt $x=x_{tp}$)

$k_3 := 3.4$ rekommenderat värde

$k_4 := 0.425$ rekommenderat värde

$$\rho_{p.eff} = \frac{8 \cdot A_{si}}{A_{c.eff}} \qquad d_m := \frac{4d_1 + 4 \cdot d_2}{8} \qquad d_m = 829.5 \cdot mm$$

$$h_{c.eff} := \min\left[2.5 \cdot (h - d_m), \frac{h - x}{3}, \frac{h}{2}\right] \qquad h_{c.eff} = 0.189\,m$$

$$A_{c.eff} := h_{c.eff} \cdot b_w \qquad A_{c.eff} = 0.094\,m^2$$

$$\rho_{p.eff} := \frac{6 \cdot A_{si}}{A_{c.eff}} \qquad \rho_{p.eff} = 0.061$$

$$s_{r.max} := k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \frac{\phi}{\rho_{p.eff}} \qquad s_{r.max} = 0.286\,m$$

$$\Delta\varepsilon_m = \varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - \frac{k_t \cdot f_{ctm}}{\rho_{p.eff}} \cdot (1 + \alpha_e \cdot \rho_{p.eff})}{E_s}$$ Ekv B9-19

$k_t := 0.4$ Långtidslast

$$\alpha_e := \frac{E_s}{E_{cd}} \qquad \alpha_e = 6.061$$

$$\Delta\varepsilon_m := \frac{\sigma_{s1} - \frac{k_t \cdot f_{ctm}}{\rho_{p.eff}} \cdot \left(1 + \alpha_e \cdot \rho_{p.eff}\right)}{E_s} \qquad \Delta\varepsilon_m = 1.93 \times 10^{-4}$$

stålspänning utifrån egenvikt

$\sigma_{s1} = 64.6 \cdot \text{MPa} \quad k_t = 0.4 \quad f_{ctm} = 2.9 \cdot \text{MPa} \quad \rho_{p.eff} = 0.061 \quad E_s = 200 \cdot \text{GPa}$

ger

$$\Delta\varepsilon_m = 1.93 \times 10^{-4} \quad > \quad 0.6 \cdot \frac{\sigma_{s1}}{E_s} = 1.938 \times 10^{-4} \quad \text{OK!}$$

$$w_k = s_{r.max} \cdot \left(\varepsilon_{sm} - \varepsilon_{cm}\right)$$

$s_{r.max} = 0.286\,\text{m} \quad \Delta\varepsilon_m = 1.93 \times 10^{-4}$

$w_k := s_{r.max} \cdot \Delta\varepsilon_m \qquad w_k = 0.06 \cdot \text{mm}$

sprickbredden OK!
Uppstodda sprickor beror troligen på tvång orsakad av temperaturrörelser, då bron kan ses som fast inspänd

Med tryckande normalkraft på 200kN

$N := -200\text{kN}$

excentricitet från tyngdpunkt

$h_{lam} := 80\text{mm}$ höjden för laminat

avstånd från xtp

$$e_{lam} := h - x - \left(c + c_{fri} + \frac{h_{lam}}{2}\right) = 0.478\,\text{m}$$

Påkänningsberäkning i Stadium II, (uppsprucket)

$$\sigma_c := \frac{F_{cs1} + F_{cs2} + F_{cs'} + N}{A_{II.eff}} + \frac{\left(F_{cs1} \cdot e_{s1} + F_{cs2} \cdot e_{s2} + F_{cs'} \cdot e_{s'} + M_L + N \cdot e_{lam}\right) \cdot z}{I_{II.ef}}$$

Tryckande normalkraft x skillt från xtp, antag x hamnar i flänsen

iterera x så att spänningen blir noll i neutrala lagret

$x := 0.165\text{m}$

Tvärsnittskonstanter för ekvivalent tvärsnitt i stadium II:

$$A_{II.eff} := \left(b_{eff} - b_w\right) \cdot x + \left(\alpha_{ef} - 1\right) \cdot A'_s + \alpha_{ef} \cdot \left(A_{s1} + A_{s2}\right) = 0.45\,\text{m}^2$$

Tyngdpunktsekvation för det ekvivalenta tvärsnittet:

$$x_{tp} := \frac{b_{eff} \cdot x \cdot \frac{x}{2} + \left(\alpha_{ef} - 1\right) \cdot A'_s \cdot d' + \alpha_{ef} \cdot A_{s1} \cdot d_1 + \alpha_{ef} \cdot A_{s1} \cdot d_2}{A_{II.eff}}$$

$x_{tp} = 0.358\,\text{m}$

$$I_{II.eff} := \frac{b_{eff} \cdot x^3}{3} + b_w \cdot x \cdot \left(x_{tp} - \frac{x}{2}\right)^2 \ldots$$
$$+ \left(\alpha_{ef} - 1\right) \cdot A'_s \cdot \left(x_{tp} - d'\right)^2 + \alpha_{ef} \cdot A_{s1} \cdot \left(d_1 - x_{tp}\right)^2 + \alpha_{ef} \cdot A_{s2} \cdot \left(d_2 - x_{tp}\right)^2$$

$$I_{II.eff} = 0.051\,m^4$$

Påkänning i neutrala lagret, Naviers formel:

Teckenregler

Normalkraft - positiv vid drag
Moment - positiv vid dragen underkant
Koordinaten *z* mäts från det ekvivalenta betongtvärsnittets tyngdpunkt - positiv nedåt
Normalkraftens excentricitet mäts från det ekvivalenta betongtvärsnittets tyngdpunkt - positiv nedåt
Beräknad spänning - positiv vid drag

Nya excentriciteter, räknar från xtp

$$e_{s1} := d_1 - x_{tp} = 0.492\,m$$

$$e_{s2} := d_2 - x_{tp} = 0.452\,m$$

$$e_{s'} := -\left(x_{tp} - d'\right) = -0.302\,m$$

$$e_{lam} := h - x_{tp} - \left(c + c_{fri} + \frac{h_{lam}}{2}\right) = 0.412\,m$$

Påkänning i neutrala lagret z = x-xtp

$$x = 0.165\,m \quad x_{tp} = 0.358\,m$$

$$\sigma_c := \frac{F_{cs1} + F_{cs2} + F_{cs'} + N}{A_{II.eff}} + \frac{\left(F_{cs1} \cdot e_{s1} + F_{cs2} \cdot e_{s2} + F_{cs'} \cdot e_{s'} + M_L + N \cdot e_{lam}\right)}{I_{II.eff}} \left(x - x_{tp}\right)$$

$$\sigma_c = 0.05 \cdot MPa$$

OK, nära noll!

$F_{cs1} = 372.316\ \mathrm{kN}$ $e_{s1} = 0.492\ \mathrm{m}$ $A_{II.eff} = 0.45\ \mathrm{m}^2$

$F_{cs2} = 372.316\ \mathrm{kN}$ $e_{s2} = 0.452\ \mathrm{m}$ $I_{II.eff} = 0.051\ \mathrm{m}^4$

$F_{cs'} = 372.316\ \mathrm{kN}$ $e_{s'} = -0.302\ \mathrm{m}$

$N = -200\ \mathrm{kN}$ $e_{lam} = 0.412\ \mathrm{m}$

$M_L = 373.7\ \mathrm{kNm}$

Betongspänng uttrycks som:

$$\sigma_c(z) := \frac{F_{cs1} + F_{cs2} + F_{cs'}}{A_{II.eff}} + \frac{\left(F_{cs1}\cdot e_{s1} + F_{cs2}\cdot e_{s2} + F_{cs'}\cdot e_{s'} + M_L + N\cdot e_{lam}\right)}{I_{II.eff}} z$$

Fiktiv påkänning i betongen invid dragarmering, z = d-xtp

$e_{s1} := d_1 - x_{tp} = 0.492\ \mathrm{m}$

$F_{cs1} = 372.316\ \mathrm{kN}$ $e_{s1} = 0.492\ \mathrm{m}$

$F_{cs2} = 372.316\ \mathrm{kN}$ $e_{s2} = 0.452\ \mathrm{m}$

$F_{cs'} = 372.316\ \mathrm{kN}$ $e_{s'} = -0.302\ \mathrm{m}$

$N = -200\ \mathrm{kN}$ $e_{lam} = 0.412\ \mathrm{m}$

Påkänning i dragarmeringen

$\sigma_c\left(e_{s1}\right) = 7.544\ \mathrm{MPa}$

$\sigma_{s1} := -\frac{F_{cs1}}{A_{s1}} + \alpha_{ef}\cdot\sigma_c\left(e_{s1}\right) = 59.7\ \mathrm{MPa}$

väldigt liten inverkan på dragspänningen i armeringen, tidigare 65MPa

Sprickbredd (B9-18)

(sprickbredden beräknas i understa lagret, där den är störst)

$$w_k = s_{r.max} \cdot (\varepsilon_{sm} - \varepsilon_{cm})$$

$$s_{r.max} = k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \frac{\phi}{\rho_{p.eff}}$$ Maximalt sprickavstånd

$k_1 := 0.8$ kamstänger

$k_2 := 0.5$ töjningsfördelning; ren böjning (approximativt x=x_{tp})

$k_3 := 3.4$ rekommenderat värde

$k_4 := 0.425$ rekommenderat värde

$$\rho_{p.eff} = \frac{8 \cdot A_{si}}{A_{c.eff}} \qquad d_m := \frac{4d_1 + 4 \cdot d_2}{8} \qquad d_m = 829.5 \cdot mm$$

$$h_{c.eff} := \min\left[2.5 \cdot (h - d_m), \frac{h - x}{3}, \frac{h}{2}\right] \qquad h_{c.eff} = 0.189\,m$$

$$A_{c.eff} := h_{c.eff} \cdot b_w \qquad A_{c.eff} = 0.094\,m^2$$

$$\rho_{p.eff} := \frac{6 \cdot A_{si}}{A_{c.eff}} \qquad \rho_{p.eff} = 0.061$$

$$s_{r.max} := k_3 \cdot c + k_1 \cdot k_2 \cdot k_4 \cdot \frac{\phi}{\rho_{p.eff}} \qquad s_{r.max} = 0.286\,m$$

$$\Delta\varepsilon_m = \varepsilon_{sm} - \varepsilon_{cm} = \frac{\sigma_s - \frac{k_t \cdot f_{ctm}}{\rho_{p.eff}} \cdot (1 + \alpha_e \cdot \rho_{p.eff})}{E_s}$$ Ekv B9-19

$k_t := 0.4$ Långtidslast

$$\alpha_e := \frac{E_s}{E_{cd}} \qquad \alpha_e = 6.061$$

$$\Delta\varepsilon_m := \frac{\sigma_{s1} - \frac{k_t \cdot f_{ctm}}{\rho_{p.eff}} \cdot \left(1 + \alpha_e \cdot \rho_{p.eff}\right)}{E_s} \qquad \Delta\varepsilon_m = 1.684 \times 10^{-4}$$

stålspänning utifrån egenvikt

$\sigma_{s1} = 59.7 \cdot \text{MPa}$ $k_t = 0.4$ $f_{ctm} = 2.9 \cdot \text{MPa}$ $\rho_{p.eff} = 0.061$ $E_s = 200 \cdot \text{GPa}$

ger

$$\Delta\varepsilon_m = 1.684 \times 10^{-4} > 0.6 \cdot \frac{\sigma_{s1}}{E_s} = 1.79 \times 10^{-4}$$ OK!

$$w_k = s_{r.max} \cdot \left(\varepsilon_{sm} - \varepsilon_{cm}\right)$$

$x_{tp} = 0.358\,\text{m}$

$s_{r.max} = 0.286\,\text{m}$ $\Delta\varepsilon_m = 1.684 \times 10^{-4}$

$w_k := s_{r.max} \cdot \Delta\varepsilon_m$ $w_k = 0.05 \cdot \text{mm}$

Nedböjning

Kontrolleras för trafiklast

$M_{trafik} = 204\,\text{kNm}$

Elementarfall:

$B = 160\,\text{kN}$ $L = 10.2\,\text{m}$ $E_{cm} = 33\,\text{GPa}$ $I_{II.eff} = 0.051\,\text{m}^4$

$$w_{mitt} := \frac{B \cdot L^3}{192 \cdot E_{cm} \cdot I_{II.eff}} = 0.521\,\text{mm}$$