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EXPERIMENTAL AND NUMERICAL STUDIES ON THE SHARED ACTIVATION ANCHORING OF NSMR CFRP APPLIED TO RC BEAMS

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ABSTRACT
A shared activation anchoring method used for carbon fiber reinforced polymer (CFRP) near surface mounted reinforcement (NSMR) strengthening is hypothesized to provide a mean to exploit the full material capacity and to tailor desired responses. To investigate strengthening efficiency, failure control as well as ductility levels, the developed strengthening system were mounted on reinforced concrete T-beams with a length of 6400 mm. Initial activation stresses of 50% (1100 MPa) and 70% (1540 MPa) were applied to an 8 mm CFRP rod by the anchor system. Then, in some beams finite element simulations were carried out for better understanding the obtained results with regard to the overall structural behaviour. Good correlations between the FE-simulation and tested responses were observed, where a high utilization of the CFRP material (up to 3300MPa) was reached. Installation of the activated system worked well, without premature failure. Additionally it was possible to control the failure development, where intermediate crack de-bonding was achieved when testing the beams with an activation level of approximately 50%, while fibre rupture occurred at the level of 70% activation, thus providing a CFRP strain of approximately 0,02.

KEYWORDS
FRP, RC beams, strengthening, interfacial stresses, analytical solution.

INTRODUCTION
Modelling of near surface mounted reinforcement (NSMR) failure modes often shows that the strengthening effects can be well predicted (Michels et al. 2013), but also that failure is highly dependent on the concrete bond. Consequently, the main failure modes often relate to a brittle delamination of the concrete adherent, which additionally means a lack of CFRP material utilization. CFRP NSMR utilizing magnitudes are approximately 60-90%, where 70% is provided as a recommended threshold in ACI 440.2R-08 (ACI 2007), by the use of a dimensionless bond-dependent coefficient. It seems undesirable that the failure modes are brittle and full utilization is difficult to achieve, although a high strengthening effect is reached, when using NSMR systems. Thus, an essential part, which seem to be a shortcoming in such systems, is modifications, which provide improved failure control as well as increased stability when failure initiates. Anchoring of the NSMR could provide such behaviors to the system, but is often seen to be very challenging. This is due to the complex anisotropic properties of the CFRP material, where especially the transverse strength combined with the brittle nature of the CFRP material presents a challenge. Some of the most common failure modes seen from CFRP anchor testing are i) crushing of the CFRP, ii) soft slip, iii) power slip, iv) cutting of the fibers, v) bending of fibers, vi) frontal overload, and vii) fiber failure (Schmidt 2011). Power slip and fiber failure (birds nest) often provides the ultimate capacity threshold of the anchored CFRP systems. It was hypothesized that desired anchoring of the NSMR system can provide a more controlled response of NSMR strengthened structures, where a high capacity utilization, increased warning as well as failure mode reduction can be obtained.

This paper presents results from a part of ongoing research, which is conducted at the Technical University of Demark (DTU), where shared CFRP activation anchoring is used as a mean to investigate increased CFRP utilization as well as controlled failure mechanisms. Additionally, finite element simulations are used to predict the response when applying the shared activation method, and will be used as a future mean to research the failure mode change at different activation levels and material properties. Some of the research questions investigated in this paper are: i) Can higher utilization of the CFRP rod be obtained by combining anchor activation forces and de-bonding failure mode thresholds, ii) Can failure modes be controlled when using shared CFRP activation anchoring method (more related research is presented in (Schmidt et al. 2019)).

EXPERIMENTAL SETUP AND SYSTEM ACTIVATION

Figure 1a shows the mounting of a circular 8mm CFRP rod, anchored by an enclosure wedge (EW) anchor and inserted into an anchor block. The full CFRP NSMR strengthening system was applied to T-section RC beams and activated to the desired activation levels, (Figure 1a). The anchor blocks were pre-installed on the RC T-beam enabling the EW-anchored CFRP and tensioning tray to be installed as conventionally done when mounting NSMR systems. Figure 1b includes details about the T-section.

a) b)

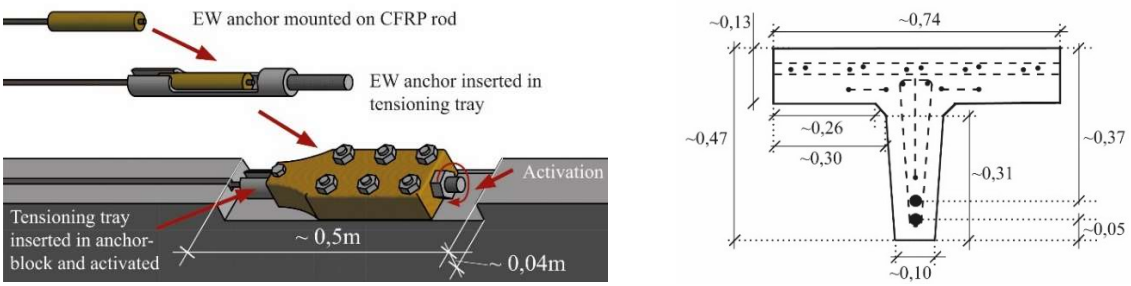

Figure 1. a) Anchored NSMR system mounted on bottom web surface, b) dimensions of the RC T-beam cross section in [m]

The EW anchor is mounted to each end of the CFRP rod and inserted in the tensioning tray. The tensioning tray (with inserted anchor) is mounted into the anchor block. Anchor block design can vary depending on the application. The anchor block is mounted to the bottom surface of the RC T-section beam, where a cut out of 0,5 m × 0,04 m ensures that the CFRP rod can be glued into the longitudinally cut groove, see also Figure 2. The concrete compressive strength and E-modulus were experimentally assessed being equal to 62 MPa and 39 GPa, respectively. The internal steel reinforcement had a yielding strength of 565 MPa and an E-modulus of 200 GPa (values also obtained from testing). Y6 shear reinforcement stirrups were placed with a spacing of 100 mm within a distance of 1400 mm from each web end, whereas 200 mm spacing was used in the middle area. Bottom reinforcement consisted of Two Y25 reinforcement bars. An E-modulus of 165 MPa of the CFRP tendon was obtained from testing. The activation was done by applying a torque moment to the nut mounted on the threaded rod at the outer end of the anchor block.

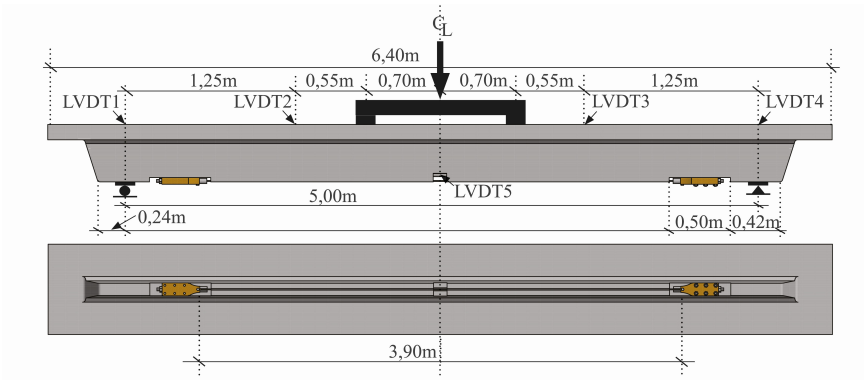

Figure 2. Strengthened RC T-section beam and location of LVDTs in the test setup.

This setup enabled activation to the desired stress levels which, for the present case were 50% (1100 MPa) and 70% (1540 MPa) of the recommended ultimate capacity of CFRP (2200 MPa, given

by the manufacturer). The activated NSMR strengthening anchor systems were applied to the ends of the bottom web-surface with an inner distance of approximately 3,9 m. The full test beam programme consisted of two un-strengthened reference (REF1 and 2) beams, two conventionally NSMR strengthened reference beams (NSMR-1 and 2), three beams with 50% NSMR activation (ANSMR50-1 to 3) and two beams with 70% NSMR activation (ANSMR70-1 and 2). Figure 2 depicts the four point bending test setup, in which the strengthened T-section RC beams were tested. All beams were tested using deformation controlled of 0,002 m/min. The beams with a length of 6,4 m were installed with the supports 5,0 m apart. The two point loads were applied 0,7 m from the centre line.

NUMERICAL SIMULATION

Finite element simulations were developed to provide a better understanding of the obtained results with regard to the overall structural behaviour. In the present work, results of the two reference beam types (un-strengthened and NSMR strengthened) are present only. These are deemed to provide the basis results related to the ongoing and future work. Diana Finite Element Analysis software was used (version 10.3) for the simulation. The beams were considered as a plane stress problem, where symmetry was utilized in the simulation of a half-span beam with related boundary conditions. The simulation of the different components were performed as follows and with described assumptions:

- Concrete component was modelled with two-dimensional quadrilateral, isoparametric plane stress elements (CQ16M), with appropriate constant thickness, namely, i) 740 mm for the flange, ii) 180 mm for the connection between the flange and the web and, iii) 125 mm for the web;
- Steel reinforcements were modelled as embedded reinforcement with truss elements (all the reinforcements included in the beam);
- CFRP rod was modelled with two-dimensional beam element (CL9BE);
- Perfect bond was assumed between concrete and reinforcements (steel and CFRP).

Regarding the material constitutive relationships, the following main options were considered:

- Concrete: total strain based crack model (tensile behavior – Hordjk; compressive behavior – parabolic; i) rotating and ii) fixed crack orientation). Shrinkage was also considered, based on the model proposed by MC2010;
- Steel: uniaxial stress-strain relationship based on the material testing results, assuming a linear kinematic hardening model;
- CFRP rod: linear elastic behaviour until the failure based on material testing results.

Phased analysis was adopted in the present simulations, with the following sequence: Phase 1: Effect of shrinkage until 90 days of age of the beams; Phase 2: Application of the NSMR CFRP rod (when applicable); Phase 3: Application of the self-weight; Phase 4: Application of additional support condition at the top in order to impose prescribed displacement at the point location.

The maximum number of iterations per increment was the stopping criterion adopted in the present analyses, based on the predefined convergence criteria (force and displacement).

RESULT DISCUSSION

Figure 3a shows the load-deformation curves related to all the tested beams, where a higher cracking level is reached for all the NSMR strengthened beams. As expected, the cracking initiation load level is higher when applying activation to the NSMR system. When testing the un-strengthened reference beams, significant yielding plateau is obtained. The yielding continues until the occurrence of compressive concrete failure. The NSMR strengthened reference beams provide a higher load carrying capacity, which fail with occurrence of intermediate crack (IC) de-bonding at a stress level of approximately 2240 MPa. An even higher strengthening effect was reached when 50% activation was applied to the NSMR. The activation of these beams was approximately 950 MPa where a CFRP stress of 3101 MPa was reached at the failure (IC-debonding). Fiber rupture was obtained for the two beams with an activation stress of 70% (1450 MPa). The CFRP stress measured was approximately equal to 3300 MPa, although the beam capacity was comparable to that of 50% activation. The ultimate stress is hereby approximately 150% of the manufacturers values and this was only reached due to application

of the shared activation system. In addition, a high consistency in the test results from all configurations was observed. It should also be noted that ductility levels were reduced when applying activation.

Figure 3b, shows the results obtained in the numerical simulations. In general, the numerical simulations satisfactorily predicted the cracked pre- and post-yield stages of the experimental results. The rotating crack orientation option predicted the post-yield stage well, while fixed crack orientation option predicted the cracked pre-yield stage well. With regard to the cracking load, the models have shown higher values, compared to the ones obtained experimentally. A reason for this may be related to the fact that beams during the transport and preparation of the tests may be slightly loaded, resulting in premature cracks.

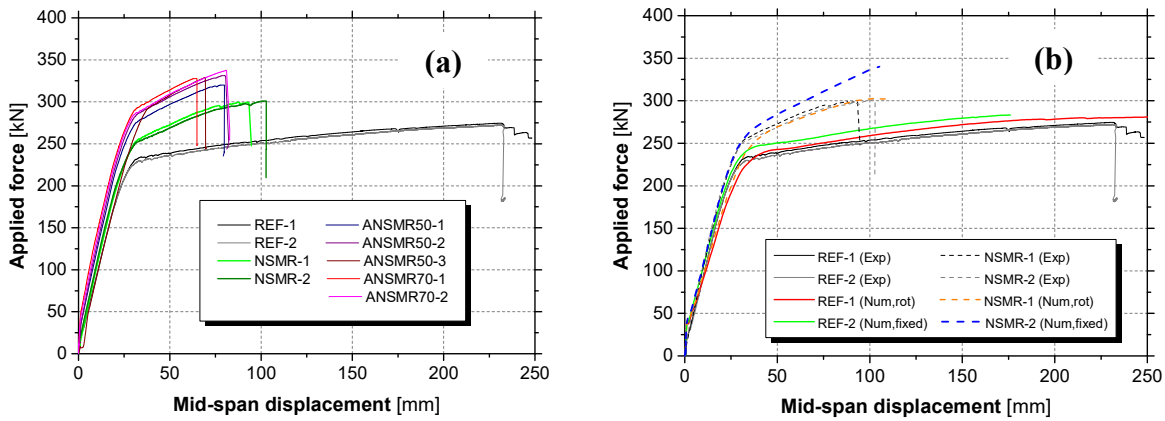

Figure 3. Comparison between experimental (a) and numerical predictions (b)

CONCLUSIONS AND FUTURE RESEARCH

It was seen from testing that full CFRP utilization (3300 MPa, strain 0,02) of the CFRP NSMR was possible when combining anchor activation forces and de-bonding failure mode thresholds. In addition, a high consistency was reached in the results, where a change of failure mode from IC-de-bonding into fibre failure could be controlled by the activation of the NSMR system. A high strengthening level was experienced but on the expense of a reduced ductility level. A good correlation was found when comparing test results and finite element simulation results. Further research is presently ongoing which includes more ductile NSMR systems. The outcome of these results will compared to a further developed finite elements, which additionally will include a sensitivity analysis.

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