BEHAVIOR OF CONCRETE BEAMS STRENGTHENED WITH CFRP AND LOADED IN FATIGUE DURING THE STRENGTHENING PROCESS

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Abstract

The need for structural rehabilitation of concrete structures all over the world is well known and a great amount of research is going on in this field. In recent years the use of CFRP (Carbon Fiber Reinforced Polymer) plate bonding has been shown to be a competitive method both regarding structural performance and economical aspects. This method implies that a thin carbon fiber laminate or sheet is bonded to the surface of the structure and acts as an outer reinforcement layer. However, most of the laboratory tests have been undertaken on beams without live load during the strengthening work.

Owners of structures want in many cases to continue with their activity or service when the strengthening system is applied. Full-scale applications have shown that this is possible, but there is lack of understanding as to how cyclic loads during strengthening, for example traffic loads, affects the final strengthening effect. This paper presents laboratory tests on concrete beams strengthened with CFRP. The beams are subjected to a cyclic load during setting of the adhesive. The beams are then loaded by deformation control up to failure. Tests have been performed on large-scale beams strengthened by traditional laminate plate bonding and the more recent NSMR (Near Surface Mounted Reinforcement) technique. For bonding, normal cold cured epoxy adhesives have been used as well as cementitious mixtures. The results show that strengthening with CFRP systems is possible even if loads are acting on the structure during strengthening.

Introduction

In the last decades it has become more and more important to repair and strengthen existing concrete structures. The reasons for this are numerous and vary often for each and every case. Many different methods can be suitable for repair and strengthening such as, shotcrete with steel fibers, additional reinforcement covered by concrete, and post-tension just to mention a few. One repair and strengthening method that has been growing rapidly for at least the last 10 years is plate bonding with fiber reinforced polymers, FRPs, Täljsten (1994) and Karbhari and Seible (1999). FRP, also referred to as composites, is a material with high stiffness and strength and it serves as reinforcement when bonded on to a structures surface. The material is lightweight, does not corrode and can come in almost any length and dimension. The reinforcement can be in the form of laminates that are bonded to plain surfaces. The composite can also be built up by hand lay-up with a thin fabric on the structure and is therefore also possible to use on curved surfaces. The method has been found to work both for shear and flexure strengthening and good theoretical models have been derived for strengthening in flexure. When strengthening for one failure mode, the others most also be investigated. For example, a flexure strengthening can lead to a shear failure instead of giving the desired bearing capacity, Sharif (1994). The advantages and drawbacks of the method can vary between the objects and must always be considered, Carolin (2001). It has been found that the reinforcement can be damaged from vehicle impacts and it can be necessary to protect the composite when used in applications if risks for impacts exist. The consequences from loss of strengthening effectiveness by fire, vandalism, collision etc must be considered, Chaallal et al. (1998).

One very important question from the owners of structures is whether it is possible to keep the structure in service during the strengthening process. The first answer would be that it is better if the structure can be completely unloaded including the self weight of the structure because this will enhance the utilization of the FRP's contribution before the structure reaches critical stages, yielding of reinforcement, concrete failure and so on. As presented by Meier et al. (1993) and Nordin et al. (2001), prestressing of FRP can be one way to get a more effective use of the fibers, however this is not further discussed here. Nevertheless, the result and some of the conclusions from this work will be applicable to prestressed FRP reinforcement as well. The answer to the owner also depends on what kind of structure needs to be strengthened and can of course be different for different structures. For structures with high dead loads from furniture and archives it is probable that the structure must not only be taken out of service, the fixtures must also be removed to unload the structure. For bridges it is not as easy to answer the question. Bridges do have a high amount of self-weight, especially railway bridges, but the frequent live service loads are in comparison quite low. The vehicles that give the highest loads are not so frequent compared to lighter vehicles.

This paper presents laboratory tests that investigate the effect of live loads during strengthening. Both laminate plate bonding and the use of NSMR have been investigated. NSMR, near surface mounted reinforcement is, when possible to use, a refined method of laminate plate bonding where the reinforcement is placed in cut grooves in the concrete cover. Further description of NSMR can be found in Täljsten and Carolin (2001), Carolin et al. (2001), Nanni (2001), and Rizkalla and Hassan (2001). A brief understanding of NSMR can be found by studying Figure 2.

Experimental Program

The tests have been undertaken on rectangular reinforced concrete beams presented in Figure 1. A total of 11 beams were tested, 6 beams were strengthened with NSMR and 4 beams with traditional plate bonding. Half of the strengthened beams were strengthened without loads during curing while the other half were subjected to live loads as described later. The beams are presented in Table 1. The beams were later tested together with a control beam.

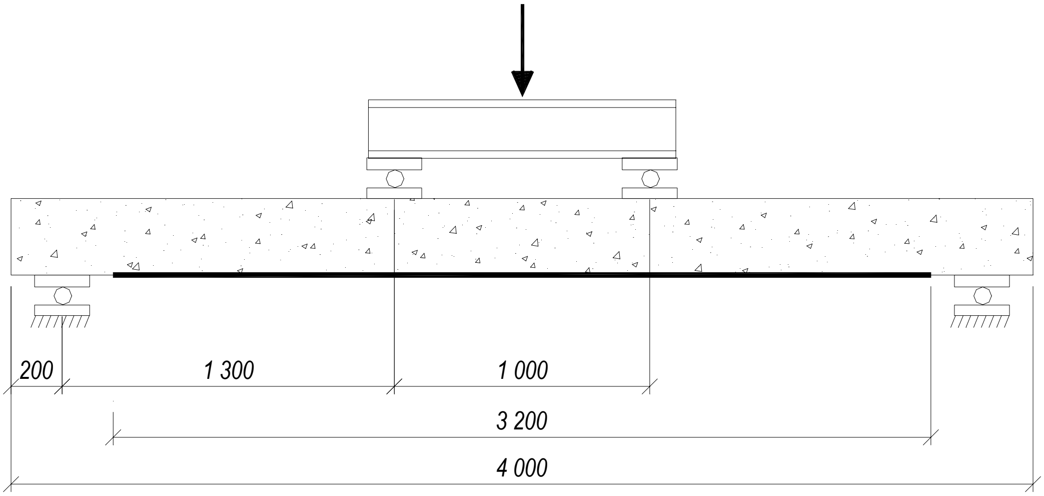


Figure 1. Test specimens

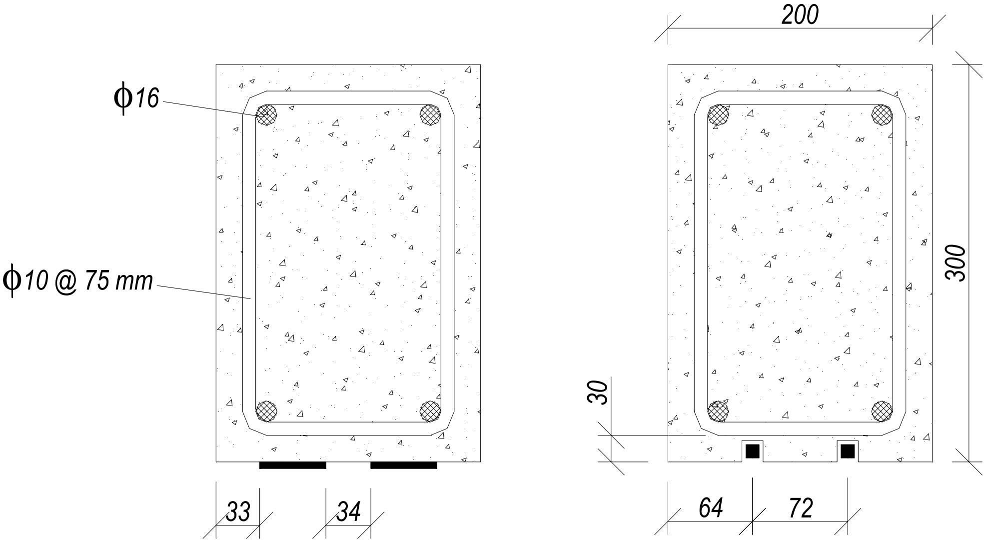


Figure 2. Cross-sections of test specimens

Previous tests have shown that it is possible to strengthen with NSMR and use a concrete mortar as bonding agent instead of epoxy, Carolin et al. (2001). Therefore, one beam was tested with cementitious bonding agent in combination with cyclic loads. The quadratic rods bonded with cement mortar were covered with a thin layer of quartz sand to improve the anchorage with the bonding agent (cement mortar). Before strengthening, the slots were saturated with water to get the best performance of the cement mortar. After strengthening the mortar was kept moist for 21 days.

Table 1. Test specimens

	Condition	*Concrete strength [MPa]*	*Slot size [mmxmm]*	*Strengthening Reinforcement*	*Adhesive*
Reference beam	-	61	-		-
Plate bonding				Area 1.4x50 mm^2	
LMstat	static	57	-	BPE® Laminate 145 M	BPE® 567 epoxy
LMdyn	dynamic	64	-	BPE® Laminate 145 M	BPE® 567 epoxy
LSstat	static	57	-	BPE® Laminate 145 S	BPE® 567 epoxy
LSdyn	dynamic	64	-	BPE® Laminate 145 S	BPE® 567 epoxy
NSMR				Area 10x10 mm^2	
BMstat	static	68	16x16	BPE® NSMR 101 M	BPE® 465 epoxy
BMdyn	dynamic	67	16x16	BPE® NSMR 101 M	BPE® 465 epoxy
BSstat	static	61	16x16	BPE® NSMR 101 S	BPE® 465 epoxy
BSdyn	dynamic	68	16x16	BPE® NSMR 101 S	BPE® 567 epoxy
BScem-stat	static	58	20x20	BPE® NSMR 101 QS	BPE® cement
BScem-dyn	dynamic	66	20x20	BPE® NSMR 101 QS	BPE® cement

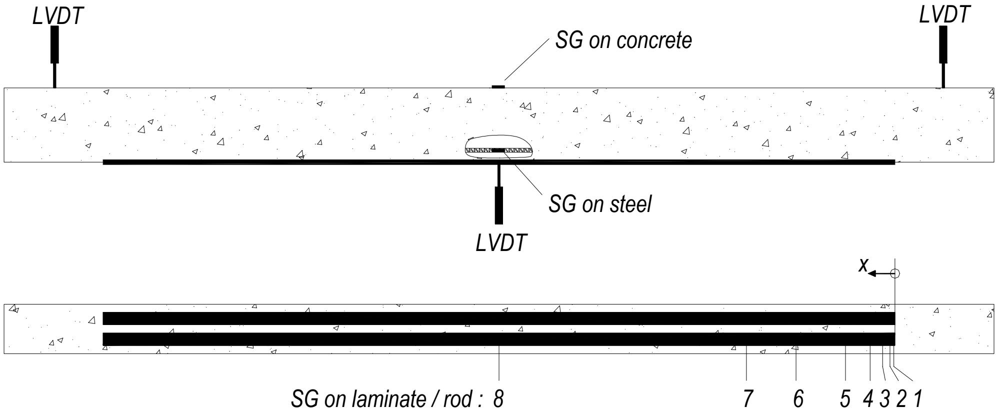
Properties of the used materials can be found in Table 2. The properties of the composites and the adhesive are given by the supplier and are not tested. The composites are made up of carbon fibers and vinyl ester matrix. The concrete quality is tested on 150 mm cubes. Empirical relation to the tested split strength obtains the tensile strength of the concrete.

Table 2. Material properties

	Compressive strentgth [MPa]	*Tensile strength [MPa]*	*Young's module [GPa]*
Concrete	$63^{1)}$	$3.8^{1)}$	42
Steel	$515^{2)}$	$515^{2)}$	210
Adhesive$^{3)}$			
BPE® 567 epoxy	$93^{3)}$	$46^{3)}$	$7^{3)}$
BPE® 465 epoxy	$103^{3)}$	$31^{3)}$	$7^{3)}$
BPE® cement	$45^{3)}$	$9^{3)}$	$26.5^{3)}$
Composite$^{3)}$			
BPE® Quality M		$2000^{3)}$	$250^{3)}$
BPE® Quality S		$2800^{3)}$	$160^{3)}$

1) Average
2) Yielding
3) Suppliers data

All beams had an age of approximately 180 days and considered to be "fully" cured without any significant changes of the properties, compressive strength for instance, during the test period. The beams were equipped with strain gauges on the concrete, the internal steel bars and on the fibers. The beams were subjected to four-point bending both during the strengthening period and when they were taken into failure. In addition to the strain gauges, SG, were midpoint deflection and support settlement registered with LVDTs, as shown in Figure 3.



Gauge	*Location, x [mm]*
1	5
2	20
3	50
4	100
5	200
6	400
7	600
8	1600

Figure 3. Monitoring of the specimens

Strengthening

Five beams were strengthened while unloaded. The beams strengthened with laminate plate bonding were ground on the surface to expose the aggregates. The surface was then subjected to compressed air to get a clean surface with neither dust nor debris. The laminates were then bonded to the surface and the adhesive were allowed to cure unloaded in 20 ºC. The beams strengthened with NSMR had their grooves cut, cleaned and half filled with adhesive before the rods were placed, so that the groove were completely filled and the rod had adhesive on three sides. The other five beams were strengthened in the same manner but with live loads acting during curing of the adhesive. Due to the size of the beams they were mounted in the load set-up prior to strengthening. The beams were strengthened upside down to facilitate the monitoring and visual inspection, see Figure 4.

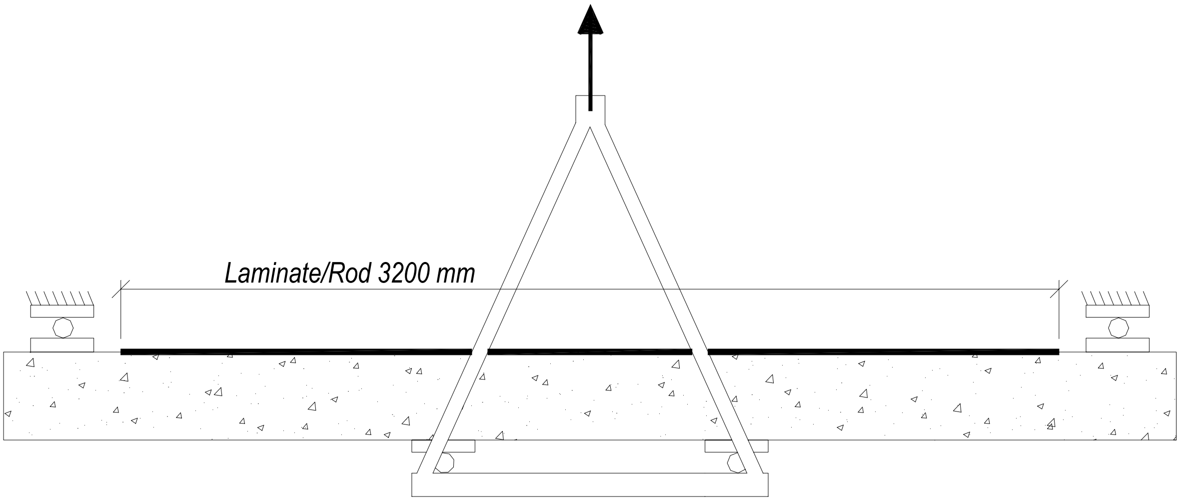


Figure 4. Test set-up for curing under cyclic load

The length of the laminates and rods, 3200 mm, was chosen to be critical for anchorage since it is believed that the cyclic loads can affect the anchorage. This length gives laminates and rods that end between the supports and will therefore not be significantly affected by the bearings. In order to keep the test set-up steady a load of 5 kN was chosen as the lower limit. The load program for the live loads started 20 minutes after the mixing of the two adhesive compounds had commenced. This time allowed the strengthening system to be mounted in the same way for all the beams.

Every 108 seconds one “sinus shaped” load cycle with a maximum of 40 kN was applied and then the beam was unloaded to 5 kN. The load level was chosen as 60 % of the load for yielding of internal steel bars for the control beam. This load gave mid-point deflections of about 8 mm at the start of the test and about 6 mm when the epoxy had set. The crack load for the control beam is about 10 kN, which means that the strengthened beams were in stadium 2 during curing. The frequency was chosen together with Swedish Road Authorities to simulate real conditions for heavier vehicle overpasses on a fairly frequented bridge. The value comes from a real bridge that has 800 overpasses of heavier vehicles each day. This is a frequency of 0.0093 Hz or one overpass every 108 seconds. It is only of interest to simulate trucks since the load and deformation from private cars can be neglected. The “sinus shape” of the load-time curve is to simulate the global behavior of a bridge rather than isolating each axel on the vehicle. The beams were subjected to the live load for 72 hours and then unloaded and stored until they were tested to failure. The beams strengthened with epoxy adhesive showed no signs of damage immediately after live loading. The beam strengthened with cementitious adhesive had cracks in the adhesive all along the length of the rods. All strengthened beams except the beam with cementitious adhesive were allowed to cure one week after the strengthening commenced until tested to failure. The cementitious bonding agent was allowed to cure for 28 days.

Results and evaluation

Strengthening

The effect of the strengthening system during curing of the adhesive is shown in Figure 5. The figure shows on the left vertical axis the strains over the cross-section versus time plotted for the peak load for every load cycle, beam *BS-dyn*. The mid-point deflection as function of time is also plotted in the same figure with numbers on the right vertical axis.

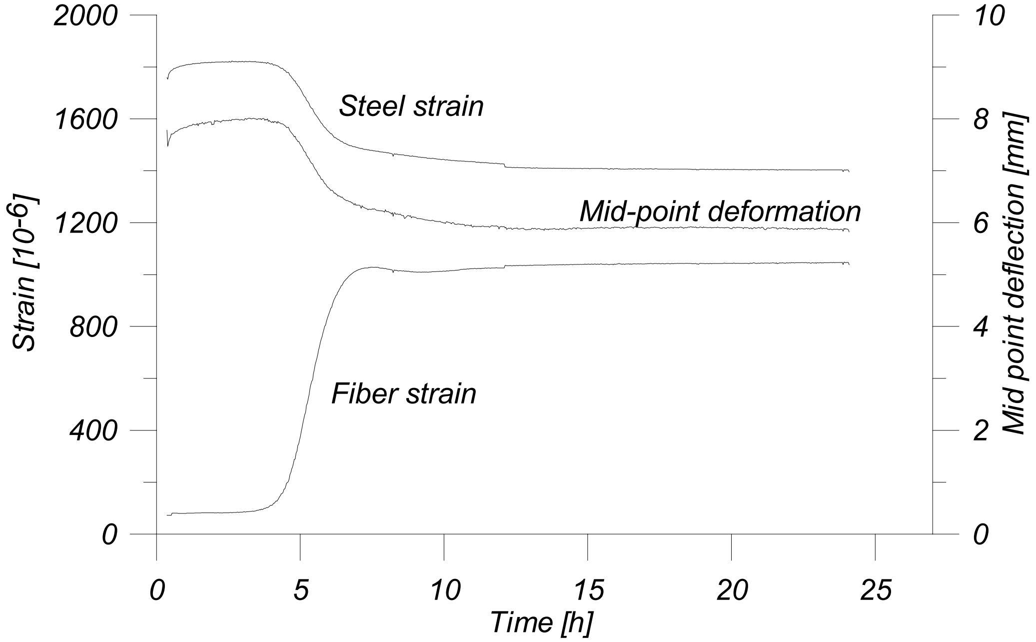


Figure 5. Typical cross-section strains at peak load and mid-point deformations for every load cycle versus time from mixing of epoxy.

It can be found from Figure 5 that initially the strains are slightly increasing due to crack distribution in the concrete. The strains are then quite stable until initiation of polymer setting, which seems to occur approximately at 4 hours. As the epoxy cures the composite rods start to be stressed. Meanwhile the steel bars are unloaded to an equivalent degree. After setting of the polymer, another 4 hours, the beam has reached its strengthened capacity and the peak strains are unaffected during the remaining load cycles. The mid-point deflection shows the same behavior and a decrease from 8 mm to 6 mm could be noticed. The decrease of mid-point deflection and steel strains for all beams during hardening of the adhesive can be found in Table 3.

From Table 3 it is obvious that the beams, except for *BScem-dyn*, had gained stiffness from the applied FRP. The mid-point deflections had decreased which is the best indicator of the strengthening effect. Measured values of the strains in the steel are affected by the distances to the closest crack on each side of the gauge, which will be different for all beams. Nevertheless, the steel has been unloaded by the composite but it is important to keep in mind that the strains from the lower cyclic load limit, 5 kN, will never be unloaded without prestressing.

Table 3. Level of mid-point deflections and steel strains for all beams during hardening of adhesive

	Mid-point deflection			*Steel strain*		
	Before hardening [mm]	*After hardening [mm]*	*Decrease [%]*	*Before hardening [10^{-6}]*	*After hardening [10^{-6}]*	*Decrease [%]*
Plate bonding						
LMdyn	7.6	5.3	30	1870	1440	23
LSdyn	8.4	6.4	24	1220	850	30
NSMR						
BMdyn	8.4	5.2	38	1820	1270	30
BSdyn	8	5.9	26	1820	1400	23
BScem-dyn	8.7	8.7	0	1880	1880	0

Failure tests

The load deflection plots for the beams strengthened by laminates are shown in Figure 6.

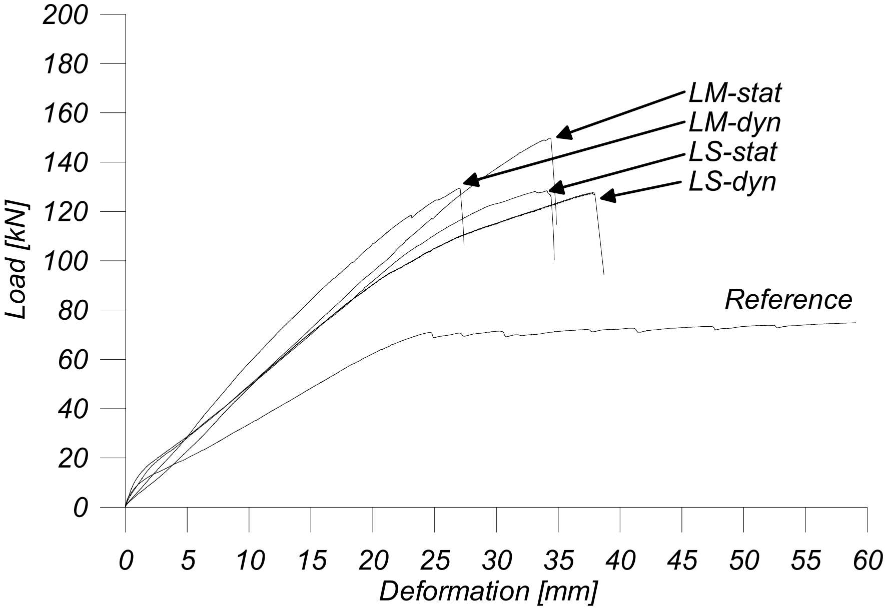


Figure 6. Load-deflection plots for the plate bonded beams

Figure 6 shows in general that strengthening with bonded carbon fibre laminates is an effective strengthening method both regarding ultimate load and load when internal steel yields. What is even more interesting is that the dynamic loads during curing do not affect the strengthening effect from high strain laminates. For laminates of High Modulus quality a decrease in ultimate load can be noticed. The strengthening effect regarding initiating of yield in internal steel is the same and not dependent on the curing condition. The beams strengthened with laminates failed by anchorage failure in the concrete for both laminates, see Figure 7, except for beam *LM-stat* that failed by rupture of one of the laminates and anchorage failure in the other.

Figure 7. Anchorage failure in the concrete for beam *LS-stat*.

The load deflection plots for the beams strengthened by NSMR and epoxy are shown in Figure 8.

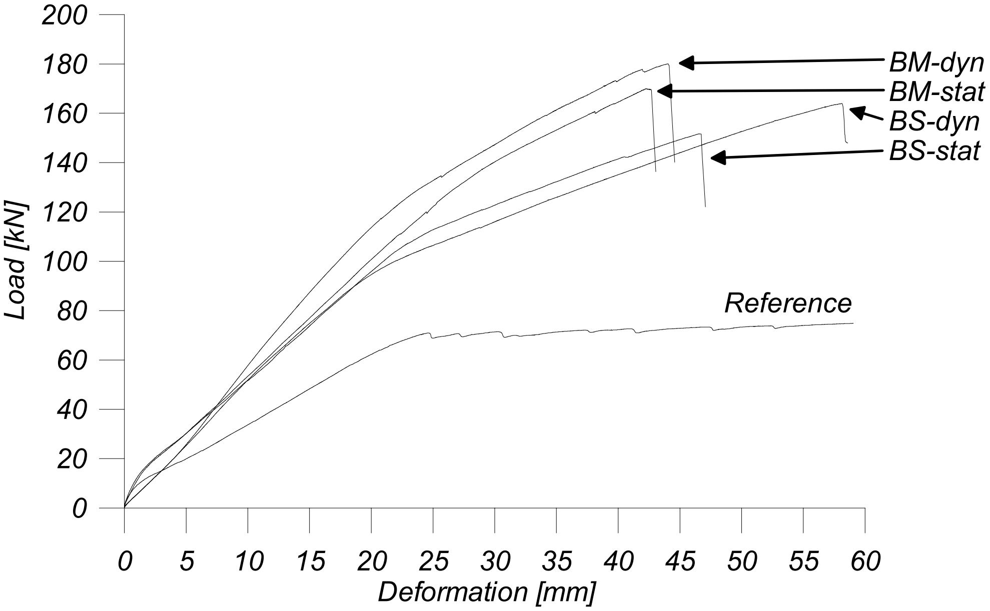


Figure 8. Load-deflection plots for the NSMR strengthened beams.

Figure 8 shows in general that strengthening with Near Surface Mounted Reinforcement is an effective strengthening method. It also shows that the dynamic loads during the curing of the epoxy do not affect the strengthening. Beam *BMdyn* failed by fiber rupture in one rod and anchorage failure in the concrete for the other rod. Beam *BMstat* failed by severe concrete damage where the part of the concrete beneath internal steel was detached, see Figure 9. The other beams failed by normal anchorage failure in the concrete.

Figure 9. Anchorage failure in the concrete for *BM-stat*.

In Figure 10 it is shown that a cementitious mortar also works as bonding agent when the beam is strengthened while unloaded. In fact, it is possible to achieve the same capacity with cement as with epoxy. It is also obvious that the same mortar is not useful if dynamic loads during the strengthening are prevailing.

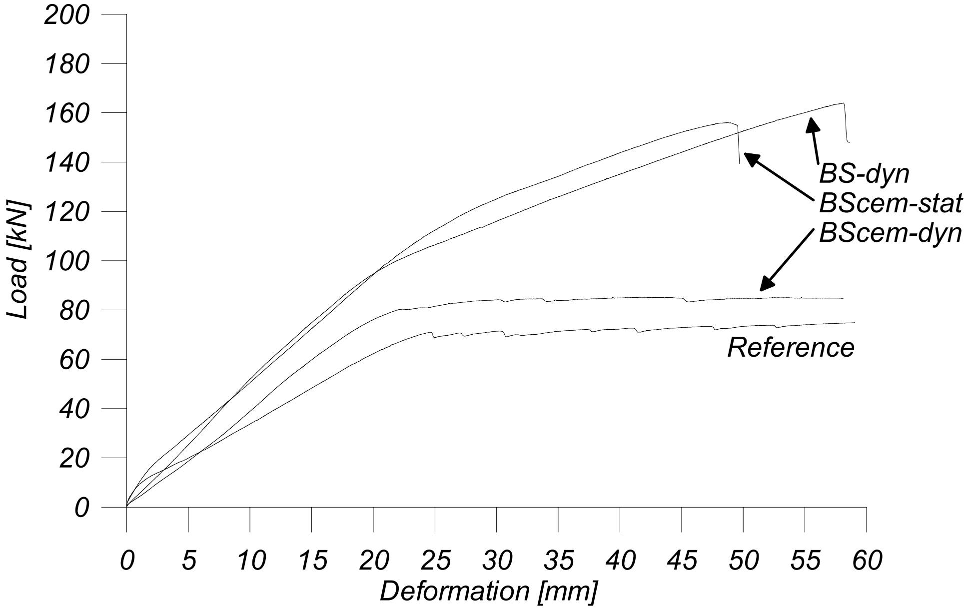


Figure 10. Load-deflection plots for the NSMR strengthened beams with cement adhesive.

Beam *BScem-dyn* was acting like the Reference beam. Even if the rods were almost loose in the groove the roughness was able to transfer forces to the rods that actually became stressed. After the steel started to yield the strain in the rods remained at the same level as the deformation of the beam increased. Beam *BScem-stat* failed by fiber rupture in one of the rods.

Table 4. Summarized results of test to failure

	Ultimate load [kN]	*Deflection at ultimate load [kN]*	*Failure description*
Reference beam	72*	24*	Yielding and large deformation
Plate bonding			
LMstat	150	34	Fiber rupture in one rod. Anchor failure in the other
LMdyn	129	27	Anchor failure in the concrete
LSstat	127	34	Anchor failure in the concrete
LSdyn	127	38	Anchor failure in the concrete
NSMR			
BMstat	169	42	Anchor failure in the concrete
BMdyn	180	44	Fiber rupture in one rod. Anchor failure in the other
BSstat	153	47	Bond slip
BSdyn	164	58	Anchor failure in the concrete
BScem-stat	157	48	Fiber rupture in one rod. Anchor failure in the other
BScem-dyn	80*	22*	Bond slip. Yielding and large deformation

*) yield load

The next step in the evaluation is to compare the test results with theoretical derivations.

Conclusions

For the beams strengthened by laminate plate bonding or NSMR with epoxy, the cyclic loads do not significantly affect the strengthening effect. The small differences noticed in the tests can be due to normal scatter of the failure mode. The use of cementitious mortar together with NSMR is not suitable when cyclic loads are prevailing during hardening of the adhesive. A cementitious bonding agent together with NSMR does work when it cures under static conditions.

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