

High strength joints for precast bridge slabs

Introduction

A joint project between Strängbetong, Sweden and Aalborg Portland, Denmark has investigated the use of a special high performance concrete called CRC JointCast for joining precast bridge slabs. The proposed joint is fully moment resisting as well as simple to prepare and cast on site. The investigation has included a number of static and dynamic tests carried out at Chalmers University, Sweden a summary of which is presented in the following. More detailed information can be obtained from the publications shown in the list of literature.

Precast bridges

Mixed construction is used increasingly for bridges, where steel is used in combination with either precast or in-situ concrete. In one such type of bridge steel beams provide the spanning action while the bridge deck is made in concrete. In the cases where composite action can be achieved – where a shear connection between concrete and steel can be established – the concrete deck can resist compressive forces while the steel resists tensile forces. This provides improved moment capacity and stiffness compared to the situation where there is no shear connection between the bridge slab and the supporting steel beams. The composite action can obviously be achieved with an in-situ cast bridge deck, but in a number of cases – if the bridge is very high, above water or possible traffic delays favours a short erection time – it is simpler, faster and more economic to use precast bridge slabs with an in-situ cast joint. A composite bridge of this type and with traditionally formed joints is shown in figs. 1 and 2.

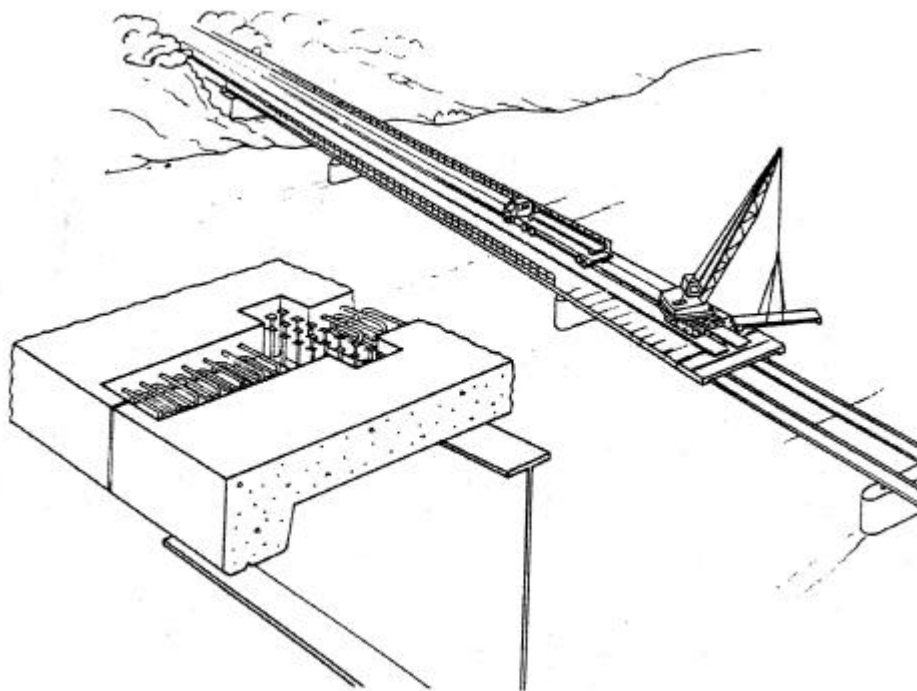


Figure 1 Composite bridge with bridge deck of precast slabs.

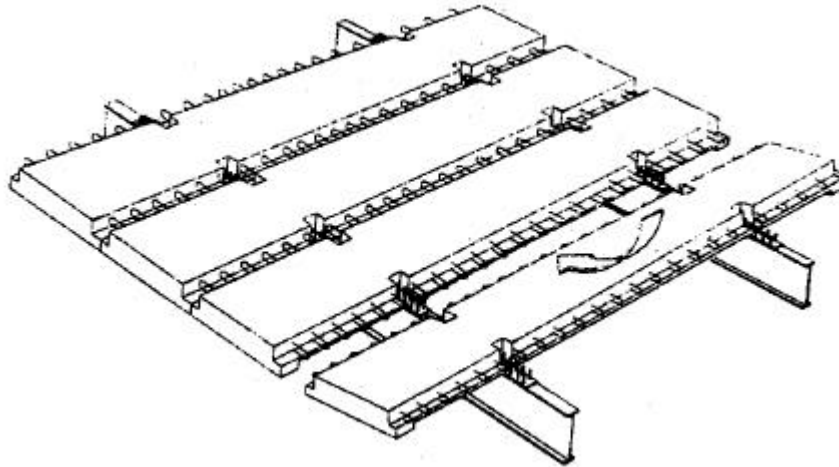


Figure 2 Precast slabs placed on supporting steel beams.

The precast bridge slabs are typically produced with a length corresponding to the full width of the bridge and a width of 1.8 meters. A typical bridge would thus require a large number of joints and with a traditional type of joint using conventional concrete a full one fourth of the bridge would actually be cast in-situ. Furthermore the traditional type of joint requires the use of looped bars as well as a large amount of transverse reinforcement. By using a special concrete – CRC JointCast - for the joints a much more simple type of joint can be used. A comparison of the traditional type of joint and the new CRC joint is shown in fig. 3.

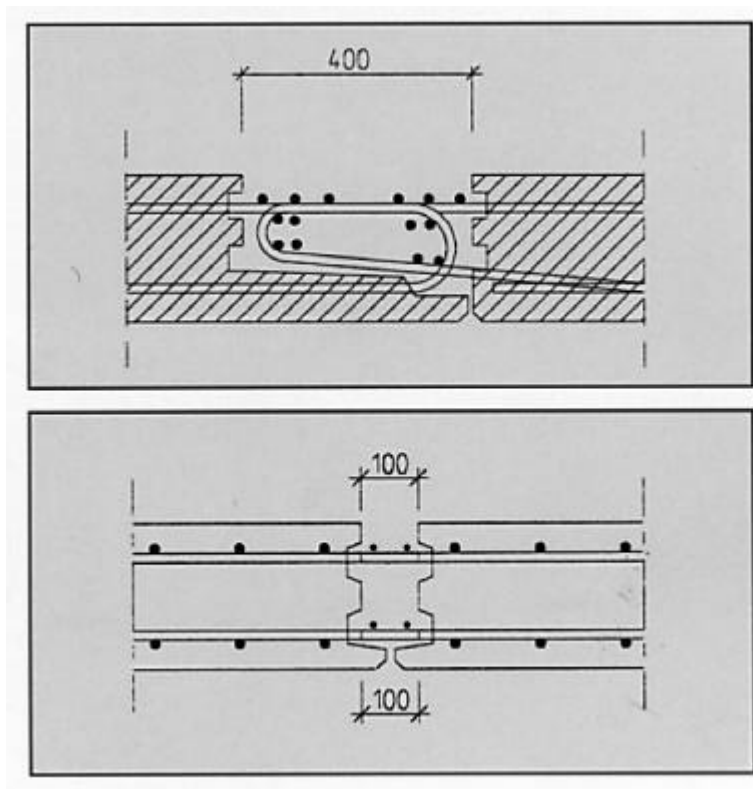


Figure 3 Traditional joint between precast bridge slabs (above) and CRC joint.

The width of the CRC joint is only one fourth of the traditional joint and only straight bars are used. The transverse bars are placed on top of the protruding reinforcing bars. As for the traditional joint shear keys are used and these have the added benefit of providing a slightly longer embedment length for the reinforcing bars. Obviously, a very special type of concrete is needed for the joint in order achieve full moment-resistance.

CRC JointCast

CRC – or Compact Reinforced Composite – is a fibre reinforced high performance concrete developed at Aalborg Portland in 1986. It has been the subject of a large number of research projects and has been used for a number of precast applications ranging from drain covers in the tunnel of the Great Belt Link in Denmark to tunnel linings in a mine in Scotland. As CRC elements are often quite slender even though they are used for structural applications – as shown in fig. 4 – it has been necessary to provide extensive documentation on material properties such as durability, fire resistance, fatigue etc /4/.



Figure 4 Cantilevered balcony slabs produced in CRC.

The high compressive strength of CRC – typically 150 MPa – in combination with a large content of steel fibres – typically 6% by volume or more than 450 kg of fibres per m³ of concrete – provides CRC with exceptional bond properties. This has led to a special type of application where CRC is used for small, simple and strong joints between precast elements. The first of these applications have been slab/slab connections in buildings but other applications of this type have been in repair

or in frames. As only small amounts are used a special dry mortar mix called CRC JointCast is provided where only water has to be added on site.

Based on a large number of pull-out tests carried out in a EUREKA project and a Brite/EuRam project a formula for calculation of the bond stress between CRC and a reinforcing bar has been developed. This formula is used to provide an estimate of the necessary bond length to achieve full anchorage.

$$\frac{\tau_u}{\sqrt{f_c}} = 0.5 + 0.7 \frac{c}{d} \sqrt{\frac{d}{L}} + 17 \mathbf{f}$$

where τ_u = bond strength (MPa)
 f_c = compressive strength (MPa)
 c = rebar cover (mm)
 d = rebar diameter (mm)
 L = embedment length of rebar (mm)
 $\phi_t = \frac{n \cdot A_{st}}{d \cdot L} < 0.1$ = transverse reinforcement ratio
 A_{st} = area of tranverse reinforcement
 n = number of transverse reinforcing bars

The formula was obtained as a curve fit for data based on testing at 28 days, but in order to take advantage of also the high early strength of CRC – typically 110 MPa at 3 days – the joints are often designed in order to achieve full moment resistance or full anchorage in 3 days. An example of this is shown in fig. 5, which shows the results of pull-out tests performed on 2 specimens tested at 3 days. The 12 mm bars had an embedment length of 80 mm and they failed before they were pulled out of the matrix. The failure occurred at loads of 81.165 and 81.175 kN corresponding to stresses in the reinforcing bar above 715 MPa.

If the reinforcing bars are sufficiently anchored in the joint, the joint will be stronger than the adjoining elements due to the higher compressive strength and tensile strength of the fibre reinforced matrix and the total system can be considered as a monolithic system. Continuous decks, slabs or beams can thus be constructed using precast members connected by strong and ductile joints.

In addition to the static pull-out and bending tests carried out on CRC, a number of pull-out fatigue tests have also been carried out /5,6/.



Figure 5 Pull-out specimens with 12 mm bars after testing at 3 days.

Chalmers, static tests

The first study of the actual type of joint was made at Chalmers University as a diploma work reported in / 1 /. In these tests both bending and shear capacity of the joint was tested. The result from the bending tests gave some indications on how to further improve the joint geometry to avoid anchorage failure before rebar ultimate strength was reached. Even though the minimum CRC cover was very small of the most active rebars, yielding in bending was reached before anchorage failure. The shear tests performed with the same joint geometry gave quite satisfactory results. It was concluded that no further static shear tests were needed to demonstrate the shear capacity of the joint. Improvements of the bending capacity and a check of the influence on joint capacity from small variations of joint geometry were selected as subjects for further investigations.

A new set of tests was thus carried out at Chalmers University investigating the behavior of the CRC joint shown in fig. 3 and the effect of small variations in design /2/. These variations included the effect of forgetting to put in transverse reinforcement and the effect of making the joint too small. Instead of joining and testing full slabs the tests were carried out on beams with a reinforcement similar to what would be used in the slabs. Two beam ends were cast with protruding reinforcing bars and placed opposite each other after which the joint was filled with CRC. A beam end and the joint before casting is shown in figs. 6 and 7.

Beam ends were produced at Strängbetong's factory in Veddige. The compressive strength at 28 days was 73 MPa measured on cubes and 57 MPa measured on cylinders. The 16 mm reinforcing bars had a yield stress of 564 MPa and failed at approximately 660 MPa.

The joints were cast at Chalmers using a poker vibrator. Casting of all joints took about 20 minutes. Compressive strength of the CRC JointCast at 28 days was 198 MPa measured on cubes and 150 MPa measured on cylinders.

The beam-ends that have been joined in this project have all been smooth as this has been the easiest way of preparing the precast units. In other projects, especially where there has been a special emphasis on durability, a retarder has been placed on the moulds where the joint is to be. When the precast units are stripped a water spray is used to prepare a surface with exposed aggregate to ensure a good bond between CRC and the conventional concrete used in the precast units. The need for this type of preparation is determined based on the overall structure.



Figure 6 Beam end with 20 mm cover to the rebars at the bottom.



Figure 7 Detail of the joint prior to casting.

The protruding "lip" at the bottom of the joint is used to avoid having to place moulds under the joint. The thickness of the lip has been minimised under the reinforcing bars in order to provide as much CRC cover under the bars as possible. A rubber sealing or gasket is used where the 2 "lips" meet in order to form a tight joint. As the beams are tested with a positive moment the most critical part of the joint is tested. If the beam was loaded with a negative moment the top bars would have larger cover and the transverse bars would be in a better position with regard to preventing the formation of splitting cracks. Height of the beam is 260 mm, width is 440 mm and 16 mm bars are used. The extent of testing and the results are shown in table 1 and a picture of the loading arrangement is shown in fig. 8.

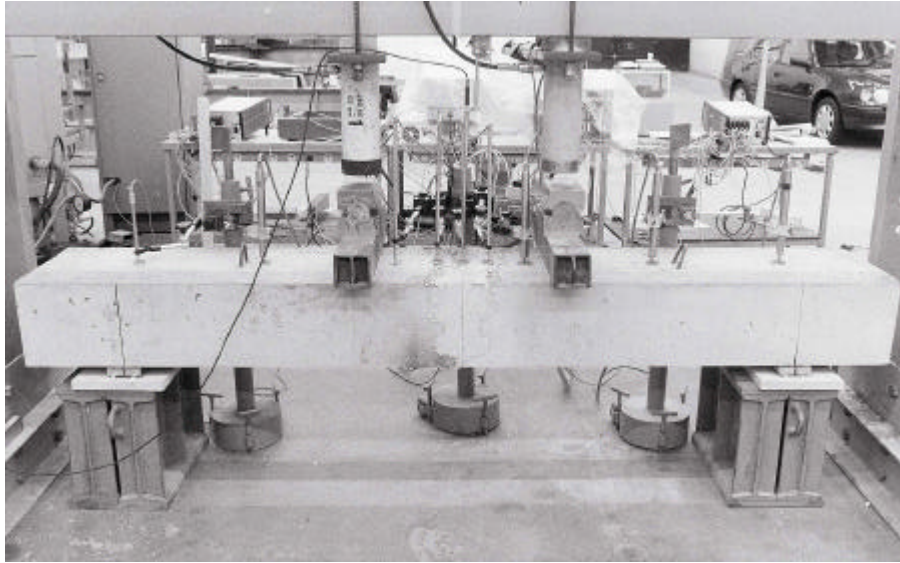


Figure 8 Loading configuration for the static beam test. The beam is subjected to symmetric loading by two point loads. Span of the beam is 2000 mm and the distance between the 2 loading points is 600 mm.

Specimen no.	Width of joint (mm)	Bottom cover (mm)	Transverse bars	Maximum load (kN)	Type of failure
1	80	20	ø8	81.6	B*
2	80	20	ø8	78.6	A
3	100	15	ø8	82.9	B
4	100	15	ø8	83.9	B
5	100	20	none	77.9	A
6	100	20	none	76.7	A
7	100	20	ø8	79.8	B
8	100	20	ø8	82.9	B
9	100	20	ø10	84.9	B
10	100	20	ø10	86.9	B

Table 1 Results of static tests. Width of the joint is the same as lap length of the bars. In the cases where transverse bars were used, there were always 2 bars. Maximum load is given as the load for only one of the two loading points. B indicates bending failure and A indicates anchorage failure. * indicates a less ductile behavior after bending failure has occurred.

In the cases of bending failure the failure always occurred away from the joint and there were no cracks in the joint itself. In all cases failure occurred after yielding of the reinforcement, but in the cases where no transverse reinforcement was included – specimens 5 and 6 – the failure load was the lowest in all the tests. Also the effect of reducing lap and width of the joint – specimens 1 and 2 – resulted in a lower failure load. In this case the 2 specimens failed in different manners indicating that 80 mm is close to the smallest lap length that can be used for the 16 mm bars. 2 of the beams are shown in figs. 9 and 10 after failure.

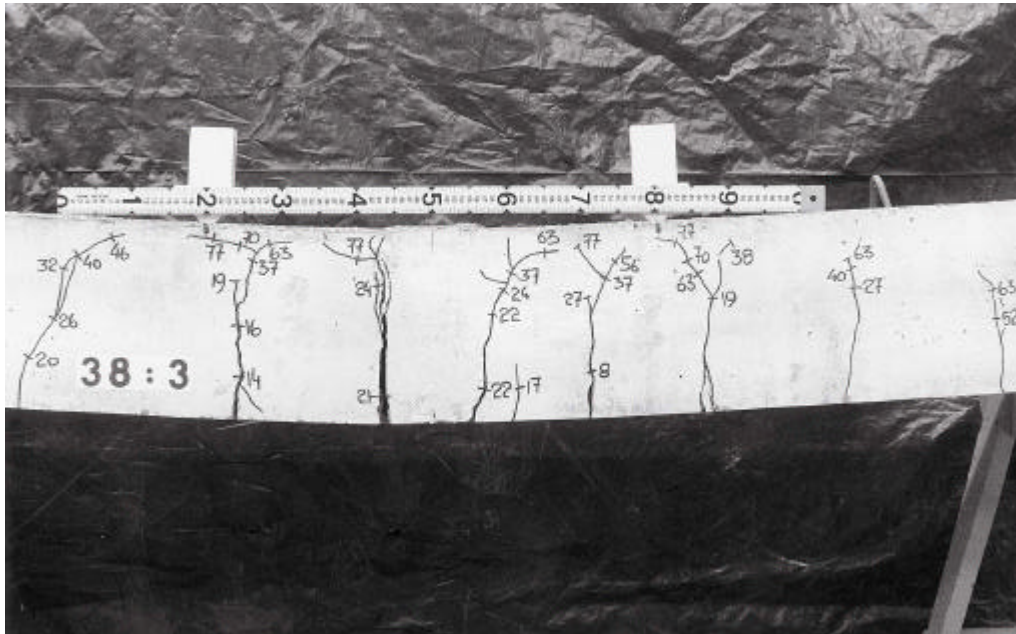


Figure 9 Specimen no. 1 after loading to failure.

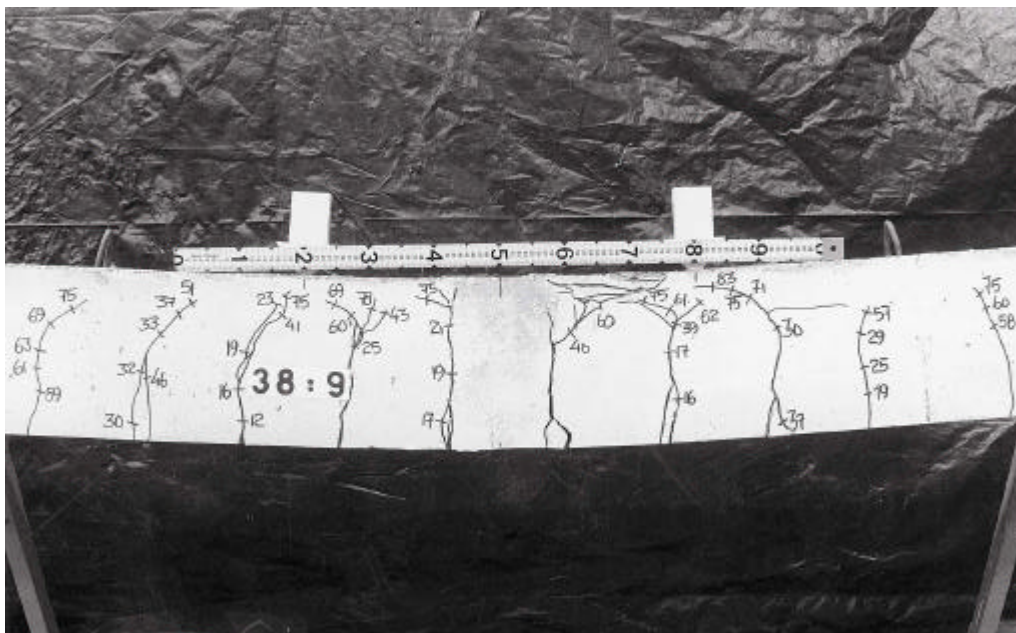


Figure 10 Specimen no. 8 after loading to failure.

Chalmers, fatigue tests

Based on the results of the static tests an optimal joint design was chosen as having lap length (and width of joint) of 100 mm, 8 mm transverse reinforcing bars and a 20 mm cover in the bottom. The beams with only 15 mm cover also showed good performance in the static tests but to facilitate proper compaction around the bottom rebars the 20 mm cover was maintained.

But in order for the joint system to be used on bridges, it is necessary to establish that the performance in fatigue is as satisfactory as the performance under static loading. For this reason another series of tests were carried out at Chalmers, investigating fatigue performance of 3 different types of specimens. The test loads were established based on the Swedish standard for bridges Bro94 to verify that the specimens could resist the maximum allowable stress range for similarly reinforced in-situ cast slabs. According to the Swedish regulations for bridge design BRO 94 the fatigue life is set to 400 000 cycles assuming the stress range based on a specific loading configuration. The maximum point load in this configuration due to the wheel pressure on a loading area of 200 x 600 mm is set to 90 kN. The maximum stress range allowed for reinforcement according to the Swedish concrete code is for 400 000 cycles set to $216 \text{ Mpa} / \gamma_n$, where γ_n is the partial safety factor ($= 1.2$ for safety class 3, applicable for bridge design)

The aim with test FAT1 and FAT2 was to demonstrate that the joints with medium and high reinforcement content has sufficient strength to, with certain marginal, withstand the highest level of fatigue loading in pure bending. The reinforcement stress range was set to about 1.15 times the characteristic code value, resulting in 250 MPa. The maximum bending moment was set to 70% of the design strength in bending and the minimum load was calculated to achieve the stress range selected.

The aim with test FAT3 was to demonstrate the joint fatigue capacity in shear loading in combination with bending. The specimen selected is oriented in transversal bridge direction, i.e. spanning between the bridge beams. For this specimen the joint runs along the element but with an eccentric position in the element to force the joint to transfer the shear load from a symmetric wheel pressure in the middle of the span.

The loading area was selected as 200 x 600 mm and the maximum load in the test was set to 1.5 times the fatigue point load of 90 kN, resulting in 135 kN. The span used for the test and the minimum load was selected to achieve a reinforcement stress range in the magnitude of the characteristic level for 400 000 cycles.

For all tests the specimens were loaded in dynamic loading in about 800 000 cycles if possible. The specimens surviving this loading was later subjected to static load until failure, using the same loading configuration.

The three types of specimens tested are shown in table 2 and the load parameters are shown in table 3. Two specimens of each type were tested.

Specimen	Length (mm)	Width (mm)	Height (mm)	No. of active bars
FAT1	2600	440	260	2
FAT2	2600	480	260	3
FAT3	3520	1200	260	8

Table 2 Specimen description for dynamic tests. In FAT1 and 2 the joint is placed perpendicularly to the spanning direction, while for FAT3 the joint is placed parallel to the spanning direction, so that the joint runs the full length of the span. In FAT1 the 16 mm bars are placed with a spacing of 220 mm, so that there are only 2 bars in the cross section. For FAT2 the spacing between bars is 160 mm and for FAT3 the bar spacing is 150 mm.

Specimen	Span (mm)	Max. load (kN)	Min. load (kN)	Max. rebar stress (MPa)	Min. rebar stress (MPa)	Stress range (MPa)
FAT1	2000	68.0	13.0	323.1	73.4	249.7
FAT2	2000	94.0	13.0	300.4	50.7	249.7
FAT3	2880	135.0	24.0	282.8	68.1	214.7

Table 3 Load parameters for dynamic tests.

Beam ends were produced at Strängbetong's factory at Veddige. The compressive strength at 28 days was 80 MPa measured on cubes. At the time of testing of the beams strength was 64 MPa measured on cylinders. The 16 mm reinforcing bars were the same type that was used for the static tests.

The joints were cast at Chalmers using a poker vibrator. Compressive strength of the CRC JointCast at 28 days was 200 MPa measured on cubes. At the time of testing of the beams strength measured on cubes was 214 MPa.

Results of the dynamic tests are shown in table 4 and fig. 11. If failure has not occurred after 800,000 load cycles the specimen is loaded to failure in a static test. All test results demonstrate that the characteristic stress range is obtained with a margin of added safety.

Specimen type	Specimen no.	Failure type	No. of cycles	Failure load (kN)
FAT1	1	F-B	423000	---
	2	F-B	506000	---
FAT2	1	S-B	820000	249
	2	F-A	382000	---
FAT3	1	S-B	802000	373
	2	S-B	800000	385

Table 4 Results of dynamic tests. F indicates fatigue failure, S indicates static failure, B is failure in bending and A is anchorage failure. Failure load is only shown for static failure.

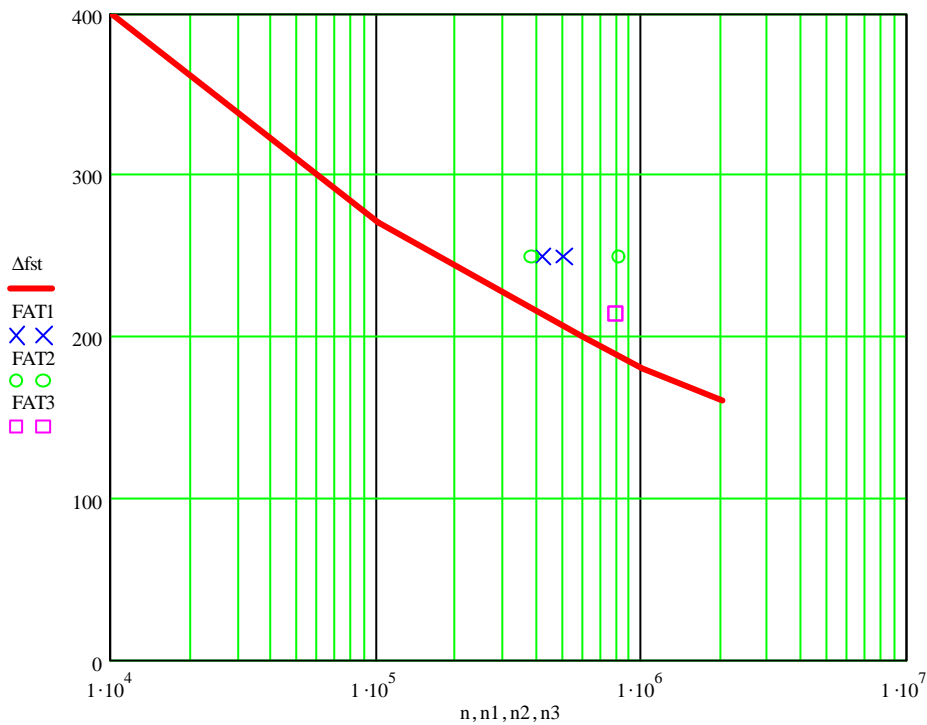


Figure 11 Stress range (MPa) and number of cycles in the fatigue tests in comparison with the characteristic fatigue strength function for reinforcement according to the Swedish code BBK 94. The specimens loaded with about 800 000 cycles were later loaded to failure in static tests.

The specimens were loaded at a frequency of 5 Hz. The first 10 cycles were performed slowly in order to follow crack formation, after which the test was started. The cycles were interrupted at certain intervals, where the specimen was then taken through a slow cycle to follow the change in stiffness and cracking. The first bending cracks appeared quickly, and as loading continued, the number and width of cracks increased. However, no cracks were observed in the CRC joint. For FAT1 specimens a normal type of fatigue failure in bending was observed. An example of this is shown in fig. 12.

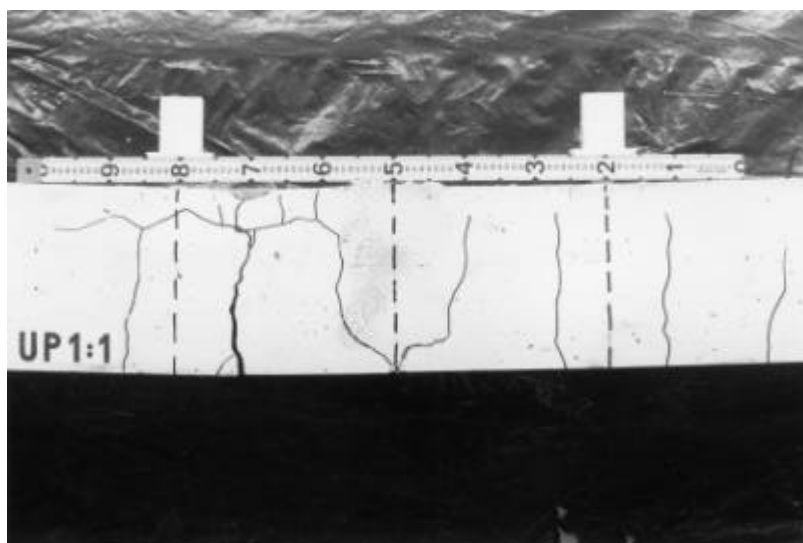


Figure 12 Specimen FAT1-1 after failure at 423,000 cycles.

For FAT2 one specimen sustained more than 800,000 cycles without failure and was then loaded to failure statically, while the second specimen failed in anchorage at less than the 400,000 cycles that were the goal for the test. This particular specimen had not been aligned correctly when the joint was cast, so the beam was twisted in the test rig, causing torsional loads to be introduced. This caused uneven distribution of stresses, leading to premature failure of one of the bars. This bar – the corner bar – had a smaller cover than specified due to the misalignment of the beam ends, which was probably the cause of the anchorage failure. The failed specimen is shown in fig. 13, where the splitting crack over the failed bar can be observed. Also, this specimen failed in the interface between CRC and conventional concrete, the only specimen where the crack that developed into failure was situated at the interface.

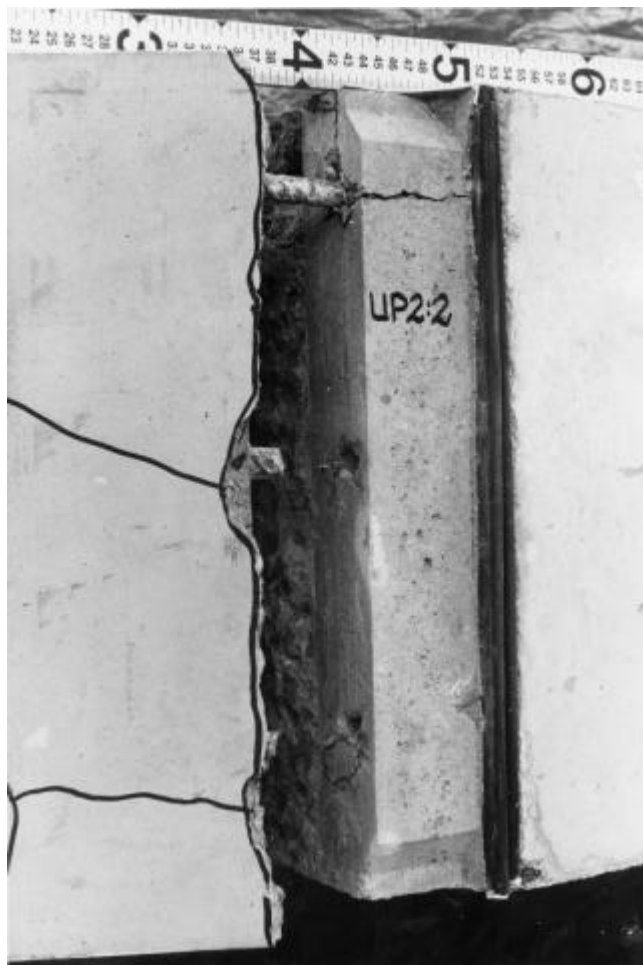


Figure 13 Detail of FAT2-2 after failure.

As can be noted from the tables, the actual failure load of specimen FAT2-1 was more than double the load applied in the fatigue test. For FAT3 specimens the difference between applied load and static failure load was even higher, which explains why both specimens sustained more than 800,000 cycles before they were loaded to failure statically. Pictures of one of the FAT3 specimens after failure are shown in figs. 14 and 15.

Conclusions

A simple, small joint for bridge slabs with full moment resistance has been designed using CRC JointCast. The joint has been tested statically as well as dynamically with good results. In one case for the fatigue tests an anchorage failure was observed, but as the failure occurred only in a corner bar while the other bars performed as expected, this is considered acceptable – especially as the specimen had shown ductile behaviour and had performed quite well. As can be observed in fig. 11 also this test result was on the safe side as compared to the characteristic strength function for reinforcement. The load taken by corner bars will be relatively small in actual bridge slabs.

But the failure in the FAT2-2 test demonstrates that attention must be paid to tolerances and quality control in using this type of system, a fact that was also demonstrated in the static tests, where specimens without transverse reinforcement had pull-out failures.

Provided that proper quality control is maintained, the joint is easily as strong as the adjoining elements and the joined element can thus be treated as a monolithic member in design.

List of literature

1. "Fog av högpresterande fiberbetong i prefabricerad brobaneplatta", examensarbete 97:2, Chalmers Tekniska Högskola, avd. för Betongbyggnad, Helén Broo and Marie Broo. (in Swedish, "Joint of high performance fibre reinforced concrete in precast bridge slabs")
2. "Böjprovning av fog i högpresterande fiberbetong för prefabricerade brobaneplattor, statisk belastning", rapport 99:1, Chalmers Tekniska Högskola, avd. för Betongbyggnad, Peter Harryson. (in Swedish, "Bending test of joint in high performance fibre reinforced concrete for precast bridge slabs, static loading")
3. "Utmattningsprovning av fog i högpresterande fiberbetong för prefabricerade brobaneplattor", rapport 00:2, Chalmers Tekniska Högskola, avd. för Betongbyggnad, Peter Harryson. (in Swedish, "Fatigue test of joint in high performance fibre reinforced concrete for precast bridge slabs")
4. "CRC – a description", note on design of CRC, Bendt Aarup and Jan Karlsen, Aalborg Portland A/S.
5. "Presentation of cyclic load tests of rebars anchored in steel fibre reinforced high-strength composite", Claus V. Nielsen, Fatigue of Concrete Structures (ed. L.P. Hansen), Department of Building Technology and Structural Engineering, Aalborg University, Denmark.
6. "Applications of Steel-Fibre-Reinforced Ultra-High-Strength Concrete", Bjarne Chr. Jensen, Structural Engineering International 2/99, pp. 143-146.