FIBER REINFORCED HIGH PERFORMANCE CONCRETE FOR IN-SITU CAST JOINTS

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ABSTRACT

CRC (Compact Reinforced Composite) is a special concept for high performance concretes, where ductility is achieved through incorporation of a large content of short, stiff and strong steel fibers (6 vol.%). This ductility combined with high strength (150-400 MPa) - and the ability of the small fibers to provide an effective reinforcement against even small cracks makes it possible to obtain exceptional bond properties for ribbed reinforcing bars. The paper describes a number of tests carried out on bond properties of CRC as well as some of the applications for in-situ cast full-strength joints.

INTRODUCTION

Generally, bond is improved with higher strength of the concrete, but the pull-out failure in HSC is usually also more brittle than for conventional concrete[1,2]. Condensed silica fume provides a moderate improvement of the bond properties[3], while the use of steel fiber reinforcement improves ductility rather than ultimate bond stresses, unless fiber contents are very high - as in SIFCON (Slurry Infiltrated Fiber reinforced CONcrete) - in which case also ultimate stresses are improved[4]. In a special type of concrete called CRC (or Compact Reinforced Composite) these factors - high performance, silica fume and fiber reinforcement - are combined, and a number of tests have been carried out to investigate the effect on bond properties of ribbed reinforcing bars using this type of concrete. These tests have included investigations of direct pull-out as well as bending tests and based on the results achieved CRC has been used for in-situ cast full-strength joints in a number of applications.

COMPACT REINFORCED COMPOSITE (CRC)

CRC - developed in 1986 at Aalborg Portland, Denmark - is a special concept for high performance concretes, where ductility is achieved through incorporation of a large content of short, stiff and strong steel fibers (typically 3-6 vol.%). This ductility combined with high compressive strength (150-400 MPa) and exceptional durability makes it possible to utilize a large amount of reinforcement, thus giving new structural possibilities compared to conventional concrete[5].

The properties of CRC are often indicated as a range, as the properties depend on type of aggregate, fiber type and content and type of main reinforcement. E.g. for compressive strength a range of 150-400 MPa is given, as a strength of 150 MPa measured on cylinders is achieved with quartz aggregates, but with calcined bauxite aggregates and heat curing a compressive strength of more than 400 MPa can be achieved.

The typical mix composition - which could be called the standard composition - of CRC includes a binder with a large content of micro silica, a water/cementitious materials ratio of 0.16, quartz sand up to 4 mm and 6% by volume of steel fibers with a length of 12.5 mm and a diameter of 0.4 mm. This typical composition will give a compressive strength of 150 MPa and a bending strength – or modulus of rupture - of the matrix of 25 MPa. This composition can be mixed and placed with standard equipment, whereas some of the more exotic compositions - such as mortars with 12% by volume of small steel fibers - would require special equipment.

CRC is used for slender structures such as balcony slabs, walk-ways and staircases or structures where special properties are required such as high strength lining blocks for mines – typically as precast products - but a special application of CRC is for in-situ cast joints between precast members.

PULL-OUT TESTS

A number of tests have been carried out regarding bond properties of reinforcing bars in CRC over the past ten years. Some of the results have already been reported in detail[6,7], and in the following will be given a few examples of the tests carried out, which should give an indication of the combined effect achieved with high strength, silica fume and fiber reinforcement.

A type of pull-out specimen with a relatively small cover to the reinforcement is shown in fig. 1. For this type of specimen, lateral pressure could be applied during the test, to investigate the influence on bond properties. Other specimens included transverse reinforcing bars. Testing showed that to achieve yielding in the reinforcing bar with a diameter of 8 mm before pull-out, an embedment length of 50 mm is necessary. If, however, confinement pressure is applied or transverse reinforcing bars are used, an embedment length of only 30 mm is adequate for achieving full anchorage. A lateral compressive stress of only 5% of the compressive strength of the concrete resulted in an increase in the bond strength of more than 60%. With the small cover to the reinforcement the mode of failure in pull-out will be formation of a crack as shown in the figure and this is counteracted by the confining pressure. Compressive strength of the concrete in this case was 165 MPa.

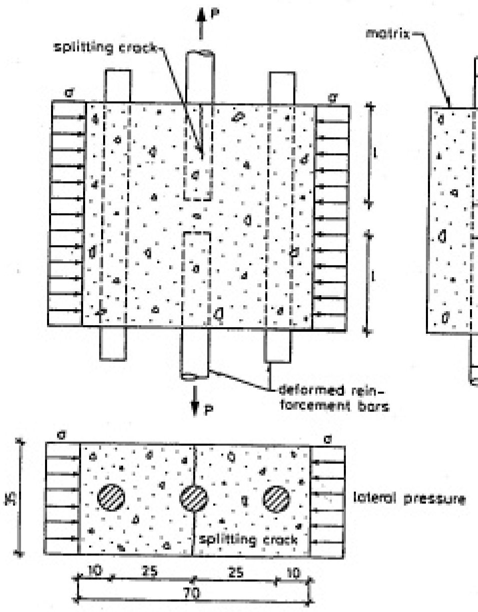

Figure 1. Test principle for pull-out of reinforcing bars with varying lateral pressure and embedment length. All measures in mm

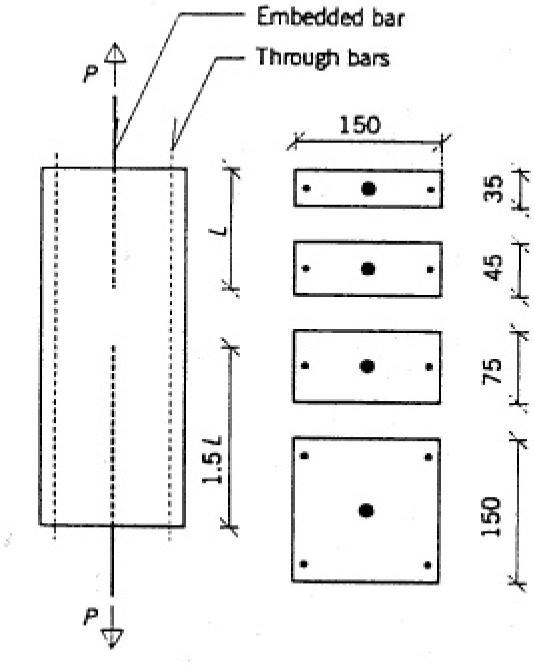

Figure 2. Concrete prisms with varying thickness for pull-out tests. All measures in mm.

Another type of specimen is shown in fig. 2. In this case the cover to the reinforcement can be varied from a specimen similar to the one shown in fig. 2 to very large concrete covers, in which case if pull-out occurs, this will typically be as a cone pull-out for short embedment lengths.

The test results mentioned above were achieved at 28 days. To speed up erection times in construction and minimize the need for temporary supports it is preferable if full anchorage can be achieved in a shorter time than 28 days, so often joints are designed to achieve full anchorage at 3 or 7 days depending on the construction schedule. A test of this type has also been performed with the test specimen shown in fig. 2. In this case 16 mm bars were tested with an embedment length of 100 mm and 140 mm. The cover to the reinforcement was 29 mm, considerably larger than in the first test described, but better suited to actual site conditions. Results are shown in table 1.

As can be observed, the conventional matrix was not sufficiently strong to achieve full anchorage with an embedment length of 100 mm. The rebars pulled out shortly after yielding at stresses of about 550 MPa. When the term full anchorage is used, it means that the test is continued until failure of the rebar, and in no cases should pull-out occur. Mode of failure is shown in fig. 3 for one of the specimens tested at 3 days with 140 mm embedment length.

In order to demonstrate the importance of compressive strength of the matrix the composition of the matrix was changed slightly by replacing quartz sand with bauxite sand while maintaining the fiber content. In this case full anchorage was achieved also at an embedment length of 100 mm and tested at 3 days.

Compressive strength of the bauxite matrix at 28 days was 240 MPa compared to 150 MPa for the quartz matrix, and strength at 3 days is approximately 70% of the 28-day strength.

Table 1 - Results of Pull-out Tests on 16 mm Diameter Bars

Specimen type	**Failure type**	**Load at failure (kN)**	**Stress in rebar (MPa)**	**Bond stress (MPa)**
140 mm, 3 days	rupture	136.7	680	19.4
140 mm, 7 days	rupture	136.6	679	19.4
100 mm, 3 days	pull-out	110.1	548	21.9
100 mm, 7 days	pull-out	118.8	591	23.6
100 mm, 3 days*	rupture	139.1	692	27.7

Each result given is a mean value of three tests.
* These results were obtained for a matrix with bauxite and the bars were from another delivery than the other specimens tested.

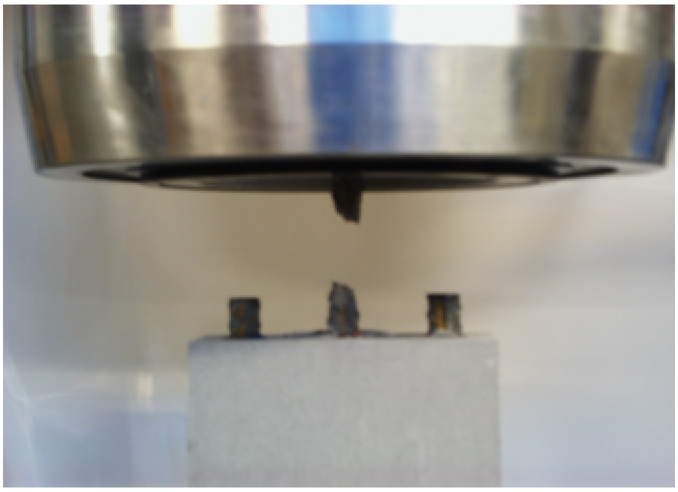

Figure 3. Failure of 16 mm rebar with 140 mm embedment length tested at 3 days.

It is generally observed that higher bond stresses can be achieved with shorter embedment lengths and with smaller diameter bars. This has been demonstrated in a number of tests – the last one of these carried out at the Institute of Concrete Technology, Shimizu, Japan – where different bar sizes were tested in pull-out. The largest bar diameter was 51 mm, and all bars were tested with an embedment length of 3 bar diameters. The maximum bond stress measured was 85 MPa.

Also fatigue tests have been carried out[8], demonstrating that if a static test can show full anchorage, then the fatigue failure will be failure of the rebar rather than pull-out.

BENDING TESTS

The direct pull-out tests provide good information on the bond properties, but as the object of using CRC for an in-situ cast joint is mostly to obtain a joint that is able to transfer full moments, a bending test is more readily applicable. A typical joint would be as shown in fig. 4, where the joint would be able to transfer full moments at 3 days after casting. The precast elements are produced with straight bars protruding a length of 140 mm, and as the width of the joint is 160 mm, the lap length will be 120 mm. In order to achieve full anchorage at an early age, it is necessary to use longer lap lengths than if full anchorage was to be achieved at 28 days, but this is usually more than compensated for by achieving rapid construction.

Most of the bending tests on CRC have been carried out at Aalborg University[9] , but other tests have been carried out at the Institute of Concrete Technology, Shimizu, Japan[10] and Chalmers University, Sweden. The tests at Chalmers were carried out together with Strängbetong, Sweden. The performance of the joint in fatigue has also been tested at Chalmers, and as for the pull-out tests it has been demonstrated that if the strength of the joint is adequate in static loading, it will also perform as well in fatigue as a monolithic structure.

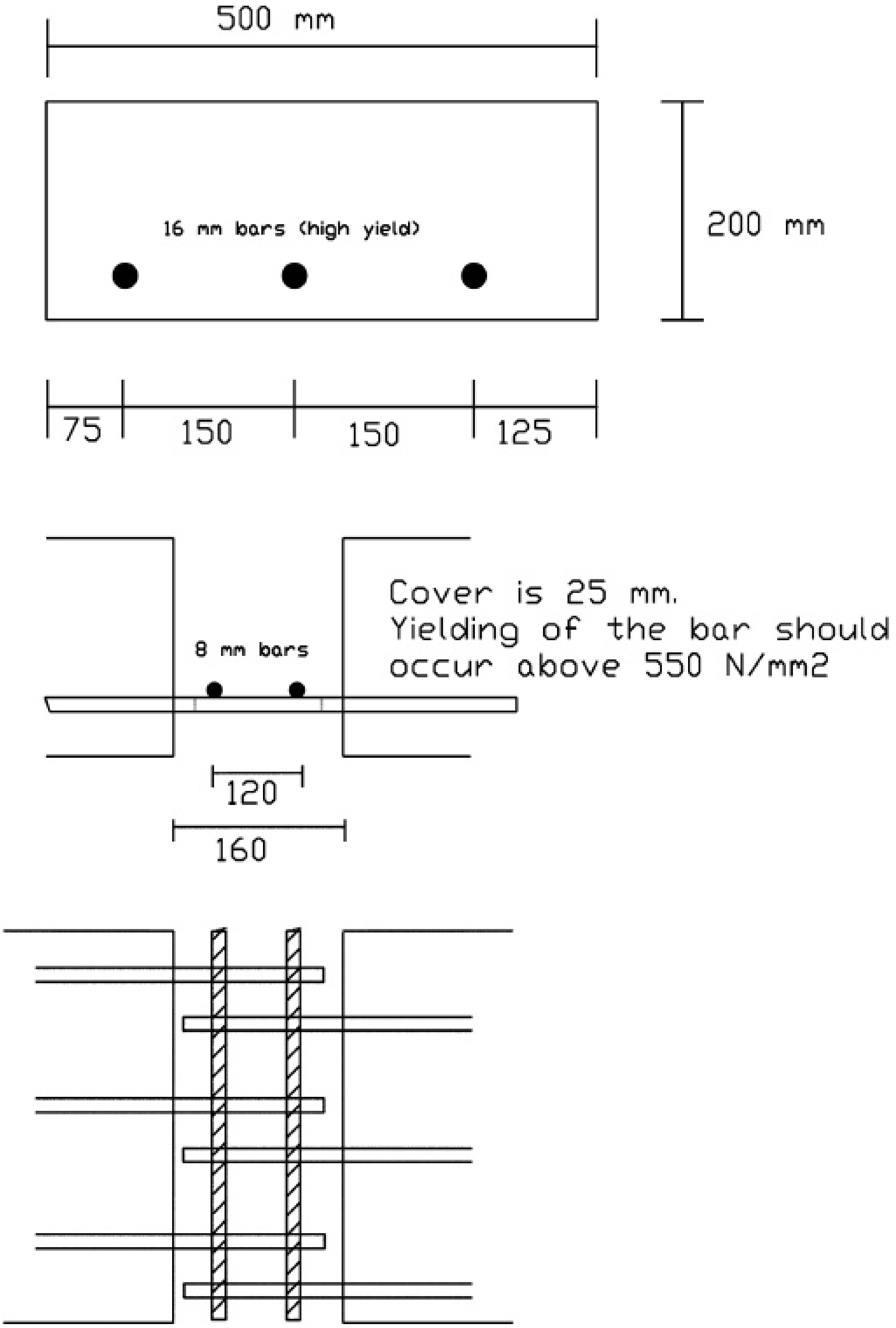

Figure 4. Typical joint for beam or part of slab, designed for achieving full moment resistance after 3 days. All measures in mm.

APPLICATION

The superior bond properties of CRC have been utilized in a new, flexible building system that has recently been used for new buildings at the University in Aalborg, Denmark.

A column/beam/slab system had previously been used for university buildings, but in order to have more flexibility with regard to changes in the interior of the building the Ministry of Education wanted a column-slab system with fewer restrictions on changes in the facade and the layout of the rooms in the building. This could be accomplished with an in-situ cast slab, but the builder also wanted the speed of construction and the degree of quality control, which can be achieved with a precast system.

A research project sponsored by the Ministry of Education was initiated, and it soon turned out that the objectives of the project - to design and implement a flexible building system in a 6x6 m grid - could be achieved with conventional columns and 3x6 m slabs - in connection with the use of CRC as a jointing material.

The slabs - with a depth of 200 mm - were cast with 80 mm of protruding ribbed 8 mm reinforcing bars and placed at a distance of 100 mm from each other as shown in fig. 5. 2 transverse reinforcing bars with 6 mm diameter were placed in the joint. The joint - with a width of 100 mm - was poured with the standard CRC mortar and compacted with a poker vibrator to ensure that the system would have the strength and stiffness of an in-situ cast slab. That way the architect would not have to consider the placement of load-bearing walls or beams in designing the layout of the building, but could simply disregard the joint and consider the slab as being monolithic.

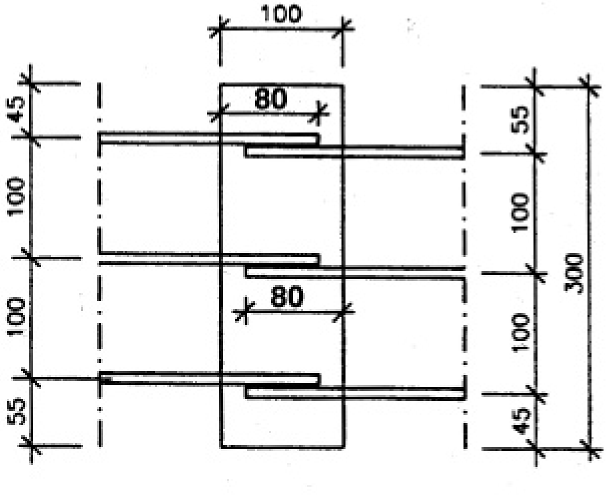

Figure 5. View from above of part of the slab connection for Aalborg University. All measures in mm.

In this case the joints are placed in the position where the largest moment is anticipated. As this system had not previously been used in buildings and could not be validated based on existing standards, a rather comprehensive set of tests was carried out[9]. The investigations included pull-out tests, tests on column-slab connections, beam-

beam connections and fire resistance tests. All tests showed that failure would occur as yielding in the reinforcement outside the joints - except for the case when a connection was loaded to failure after one hour of exposure to a standard fire. In this case the surface of the connection was sufficiently weakened by the fire to cause a pull-out failure at 75% of the load sustained on undamaged specimens. This was, however, well above the service load so the system could be classified as BS60 (fire resistant for at least 60 minutes according to the Danish standard). If fire exposure was continued for 97 minutes under service load, failure took place as yielding in the reinforcement[11].

The tests also included an investigation on the robustness of the system - the sensitivity to placing of transverse reinforcing bars, length of embedment and changes in geometry - and it was concluded that a high degree of safety was available in the system. Fig. 5 shows the rebars placed adjacent to each other, but full capacity was also achieved if the rebars were equally spaced.

The first building was finished in 1996 and the cost of the new system was 10-15% less than what would have been the cost of the "old" system with columns, beams and slabs. The system demands a high degree of precision, but the contractor and the producer of the precast slabs achieved this without problems, and no special equipment was used.

Another building was erected in 1997, and in this case the effectiveness of the joints was extended, by making a stiff joint between the columns and the slabs.

Other types of applications have been in repair, where rebars have been accidentally cut, for connecting staircases or for joints in frames.

CONCLUSIONS

A number of tests have been performed on a special high strength steel fiber reinforced concrete called CRC demonstrating that full anchorage of ribbed reinforcing bars can be achieved with embedment lengths of 5-10 bar diameters.

The material has been used for a building system, where the bond properties of CRC were utilized beyond what is commonly accepted in standards, but it was demonstrated in tests that the carrying capacity of the joints was adequate to ensure that the system acted monolithically.

Since then, the jointing system has been used in other applications, and the Building Research Establishment in England is currently testing it for a number of standard joints between precast elements.

References

1. Noghabai, K. & Ohlsson, U. & Olofsson, T., "Bond Properties of High-Strength Concrete", Proceedings from the Third Int. Symposium on Utilization of High Strength Concrete, June 1993, Lillehammer, Norway, pp. 1169-1176.

2. Larrard, F. & Schaller, I & Fuchs, J., "Effect of Bar Diameter on the Bond Strength of Passive Reinforcement in High-Performance Concrete", *ACI Materials Journal*, July-August 1993, pp. 333-339.

3. Gjørv, O.E. & Monteiro, P & Mehta, P.K., "Effect of Condensed Silica Fume on the Steel-Concrete Bond", ACI Materials Journal, November-December, 1990, pp. 573-580.

4. Hamza, Ali M. & Naaman, Antoine E., "Bond Characteristics of Deformed Reinforcing Steel Bars Embedded in SIFCON", *ACI Materials Journal*, November-December 1996.

5. Aarup, B., "Fiber Reinforced High Performance Concrete for Precast Applications", Proceedings from Int. Symposium on High-Performance and Reactive Powder Concretes, August 1998, Sherbrooke, Canada, pp. 113-123.

6. Nielsen, C.V. & Olesen, J.F. & Aarup, B, "Effect of fibers on the bond strength of high strength concrete". BHP96 Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, 29-31 May, 1996, Paris, France, pp. 1209-1218.

7. Aarup, B. & Jensen, B.C., "Bond Properties of High Strength Fiber Reinforced Concrete", Bond and Development of Reinforcement, ACI publication SP-180, 1998, pp. 459-472.

8. Nielsen, C.V., "Presentation of Cyclic Load Tests of Rebars Anchored in Steel Fiber Reinforced High-Strength Composite", Fatigue of Concrete Structures (ed. L.P. Hansen), Department of Building Technology and Structural Engineering, Aalborg University, Aalborg, Denmark, 1993, pp. 65-71.

9. Jensen, B.C., "Applications of Steel-Fibre-Reinforced Ultra-High-Strength Concrete", Structural Engineering International V.9, no. 2, May 1999, pp. 143-146.

10. Jensen, B.C. & Aarup, B, "Fire Resistance of Fiber Reinforced Silica Fume Based Concrete". BHP96 Fourth International Symposium on Utilization of High-Strength/High-Performance Concrete, 29-31 May, 1996, Paris, France, pp. 551-560.

11. Shioya, T. et al, "Pre-cast Concrete Joint using Steel Fiber Reinforced High Strength Mortar and/or H-beam", Proceedings of the Japanese Concrete Institute, Vol. 19, No. 2, 1997, pp. 1305-1310 (in Japanese).