FATIGUE STRENGTH OF CABLE COUPLERS IN PRESTRESSED CONCRETE BEAMS

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Fatigue tests have been carried out on ten prestressed concrete beams. Six of the beams were furnished with a cable coupler in the mid-span and four beams had no cable coupler. The uncoupled beams could in some cases sustain 9 times as many load cycles as the coupled beams. Some probable causes to the coupled beams lower fatigue strength are discussed in the paper.

Keywords: Prestressed concrete, cable coupler, fatigue strength, crack propagation, prestressing force, local bending, stress range, stress concentration, friction forces.

1. INTRODUCTION

During the erection of prestressed concrete bridges it is common to use cable couplers in the construction joints to transfer the prestressing force. In an examination of prestressed bridges in the Federal Republic of Germany /1/ damage was observed on many of the bridges in the coupling sections. Out of 4000 examined bridge spans about 2200 showed some form of damage, mainly in the form of a zone of cracking close to the coupling sections. Among other things these cracks give rise to an increased stress range in the tendons. The cracks also increase the risk of corrosion in the steel. So far, at least one serious failure of a prestressed bridge has occurred. Most of the tendons broke in a construction joint with a cable coupler in a ten year old bridge in Heerdter Dreieck in Düsseldorf.

In Sweden no damage has yet been observed in the construction joints of prestressed bridges. One reason for this may be that practice has been to limit the number of coupled cables in one section to half of the total number of cables. In the prestressed bridges in Germany often all tendons have been coupled in the same section. Another reason for the lack of observed damages in Sweden might be the relatively small number of prestressed bridges - about 400.

However, the potential risk with cable couplers has motivated the Swedish National Road Administration to look into the problem. An investigation has therefore been initiated at the University of Luleå /2/, /3/. This investigation is comprised of fatigue tests on coupled and uncoupled prestressed concrete beams. Those types of tendons which are most commonly used in Sweden are studied. This paper presents results from the experiments carried out so far. Ten beams have been tested, four of the type VSL and six of the type BBRV.

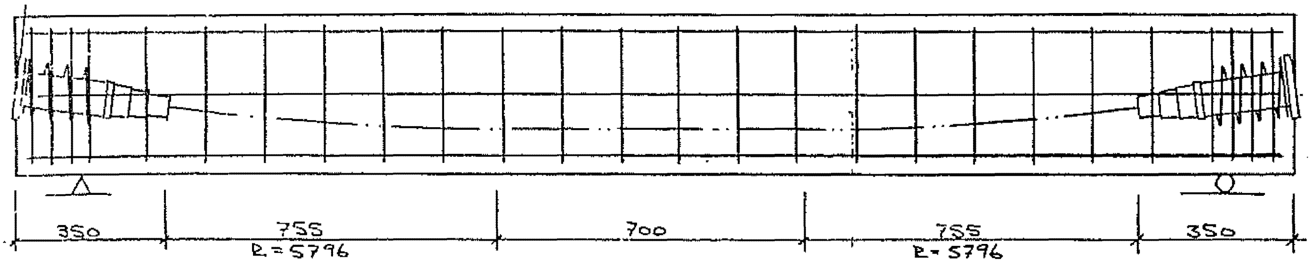
2. TEST PROGRAM

2.1 Test specimen

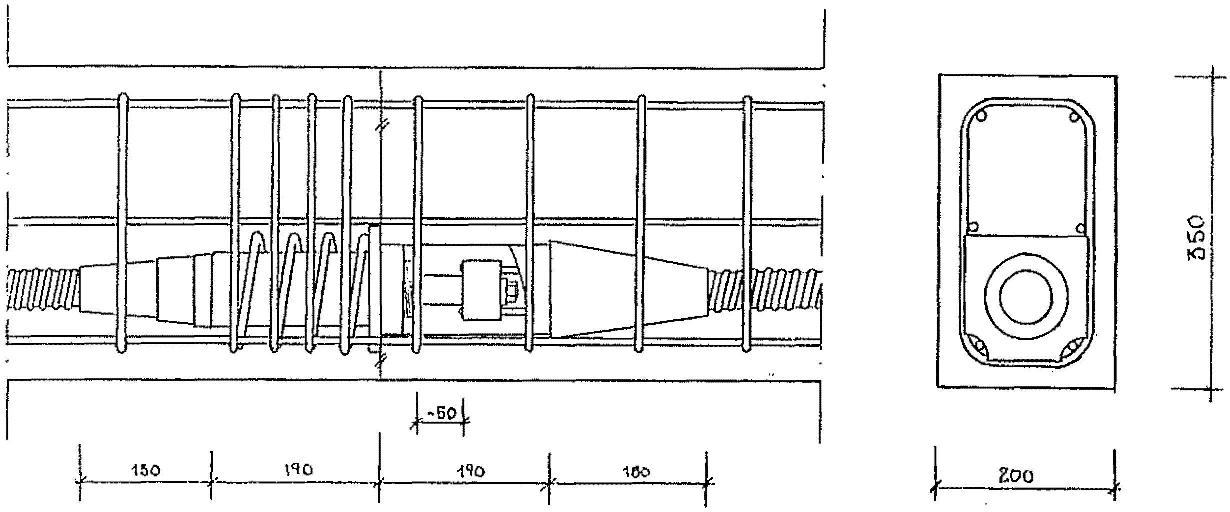
The test beams were designed with the objective of imitating the conditions in a prestressed bridge. In order to facilitate the testing the dimensions 2,90 x 0,35 x 0,20 m^3 were chosen, see Fig. 1. The concrete strength, f_{cc}, was chosen to 40 MPa. The non-tensioned reinforcement consisted of ribbed bars with the yield stress, f_{yk} = 400 MPa. The longitudinal, non-tensioned reinforcement was not spliced in the construction joint.

Beams No. 1-4 were prestressed with VSL 3 ϕ 13 mm strands ($f_{0.2}/f_u$ = 1560/1830) and beams No. 5-9 were prestressed with BBRV 12 ϕ 6 mm wires (1520/1770). For both types of beams, the prestressing force was taken to 400 kN. Beam No. 10 was prestressed with BBRV 16 ϕ 6 mm wires up to a force of 533 kN.

Six of the beams had coupled tendons and a construction joint in the mid-span. The two investigated types of cable couplings are shown in Fig. 2.



a) Reinforcement in an uncoupled beam



b) Detail over coupling section (BBRV coupler)

Fig. 1 Test beam

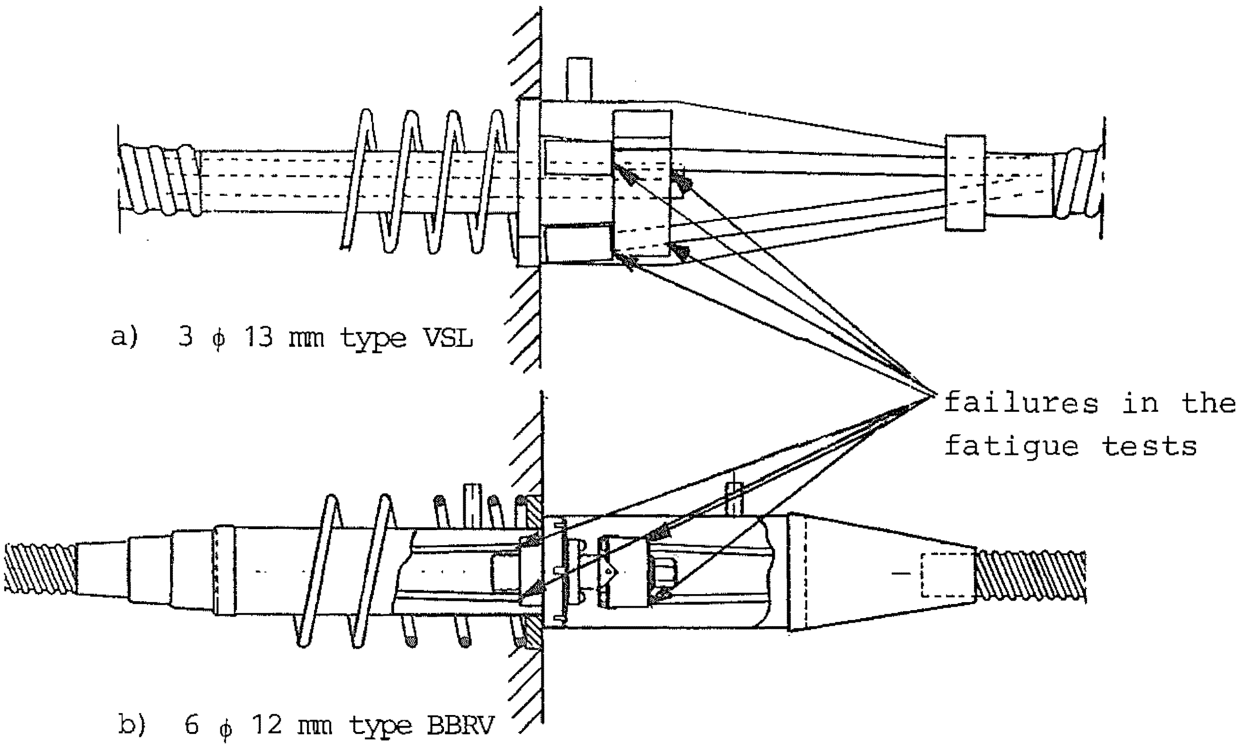


Fig. 2 Cable coupling units

To study possible methods of improving the fatigue strength of the beams, beam No. 9 was furnished with increased non-tensioned reinforcement and beam No. 10 was designed with an increased area of prestressing steel. Furthermore, in order to check the influence of a construction joint on fatigue strength one of the uncoupled beams (No. 7) was furnished with such a joint in the mid-span. Different data for the beams No. 1-10 are summarized in Table 1.

The stressing of the tendons was performed with hydraulic jacks with due consideration to relaxation, friction losses, anchor losses and long-term losses. The left half of a coupled beam was concreted and prestressed two weeks before the right half (see Fig. 1.)

TABLE 1 Fatigue tests with coupled and uncoupled prestressed beams

Beam No.	Coupled	Prestress force F_o	Load range P	Stress range theoret. $\Delta\sigma_{th}$	Stress range actual $\Delta\sigma_a$	Number of cycles before failure	Notes
		kN	kN	MPa	MPa	Kilocycles	
1	-	400	170±40	250	240(a)	595.2	
2	Yes	400	170±40	250	255(a)	87.0	
3	-	400	100±40	≈25	40(a)	>3000.0	
4	Yes	400	100±40	≈25	65(a)	356.2	
5	-	400	170±40	250	225(a)	460.8	
6	Yes	400	170±40	250	225(b)	59.5	
7	-	400	170±40	250	225(a)	434.3	(c)
8	Yes	400	100±40	≈25	80(b)	392.2	
9	Yes	400	170±40	250	224(b)	177.0	(d)
10	Yes	533	170±40	250	85(b)	185.3	(e)

Beams Nos. 1-4 were of type VSL with 3 ϕ 13 mm strands, while beams Nos. 5-10 were of type BBRV with 12 ϕ 6 mm (beams Nos. 5-9) and with 16 ϕ 6 mm. (a) Calculated value, (b) Measured value, (c) Beam No. 7 had a joint in the midspan, (d) Beam No. 9 had an increased area of nontensioned reinforcement, (e) Beam No. 10 had an increased prestressing force

2.2 Test setup and fatigue loads

The beams were tested with a 250 kN servo-hydraulic actuator. The load was applied close to the mid-span and the beams were simply supported. A view of the test setup is shown in Fig. 3.

During the course of loading, data were recorded regarding cracks, mid-span deflection, and strains in the concrete, the cables, the coupling unit, and the longitudinal non-tensioned reinforcement.

The load levels in the fatigue tests were determined in order to obtain a stress range of 250 MPa in the tendons (ultimate load stage). This stress range for up to 2×10^6 cycles is the requirement set forth by the Swedish National Road Administration for all tendons. This requirement implied a load level of 170 $\pm$ 40 kN for the test beams. In the working load stage, the load levels were chosen to 100 $\pm$ 40 kN. This load level corresponds to a stress range of approximately 25 MPa.

The tests began with a stepwise loading of the beam up to the upper load level. During this procedure the static properties of the beams were studied. Then the fatigue test was started, continuing without interruption until the beam collapsed. Depending on the stiffness of the beams, frequencies between 1 and 5 Hz were used.

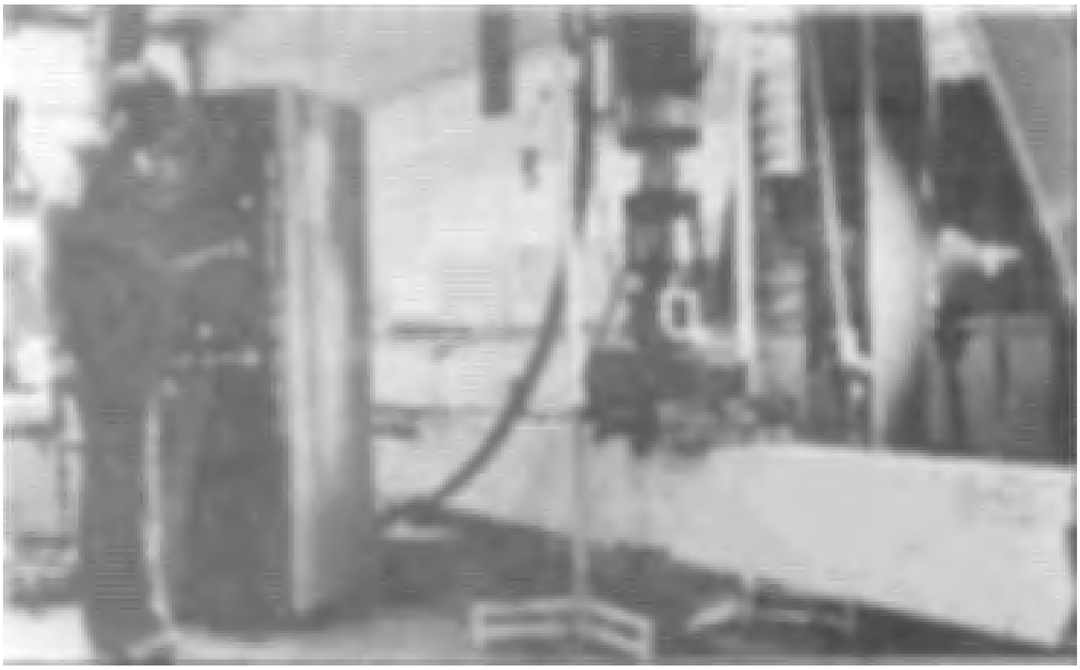


Fig. 3 View of the test setup

3. TEST RESULTS

3.1 Static loading

In the stepwise loading, the uncoupled beams showed noticeably higher bending stiffness than the coupled beams. In Fig. 4 the deflection-load curves are plotted. From this figure it can be seen that the coupled beams display deflections up to 50 per cent larger than the uncoupled beams.

Under increasing load, cracks opened in the mid-span. In the uncoupled beams the cracks had a rather uniform distribution along the beam, see Fig. 5. The length of the cracks agreed rather well with the calculated length up to the neutral axis.

In the coupled beams the cracks were concentrated to the coupled section. In these beams the first cracks appeared for lower loads than in the uncoupled beams and the cracks overstepped the calculated location of the neutral axis.

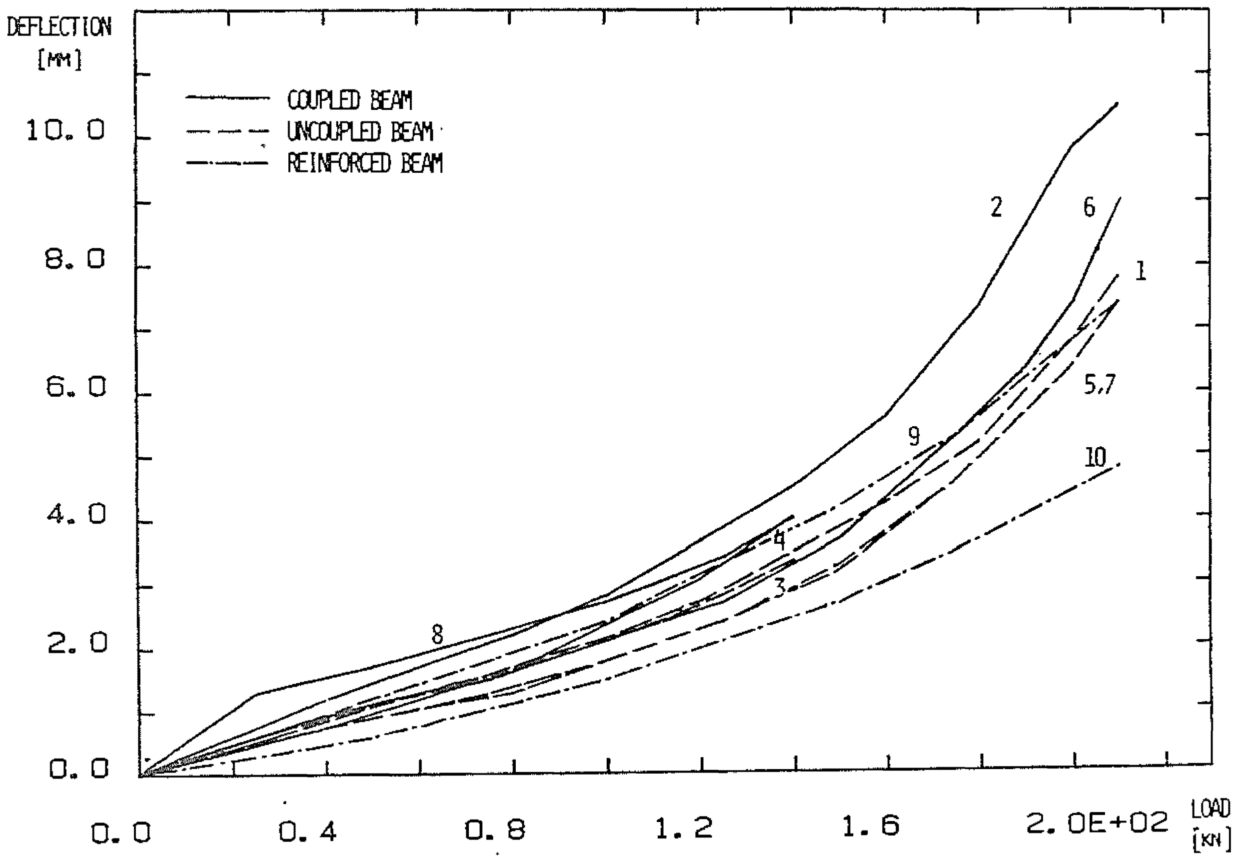


Fig. 4 Deflection-load curves at the monotonous loading to the upper load limit

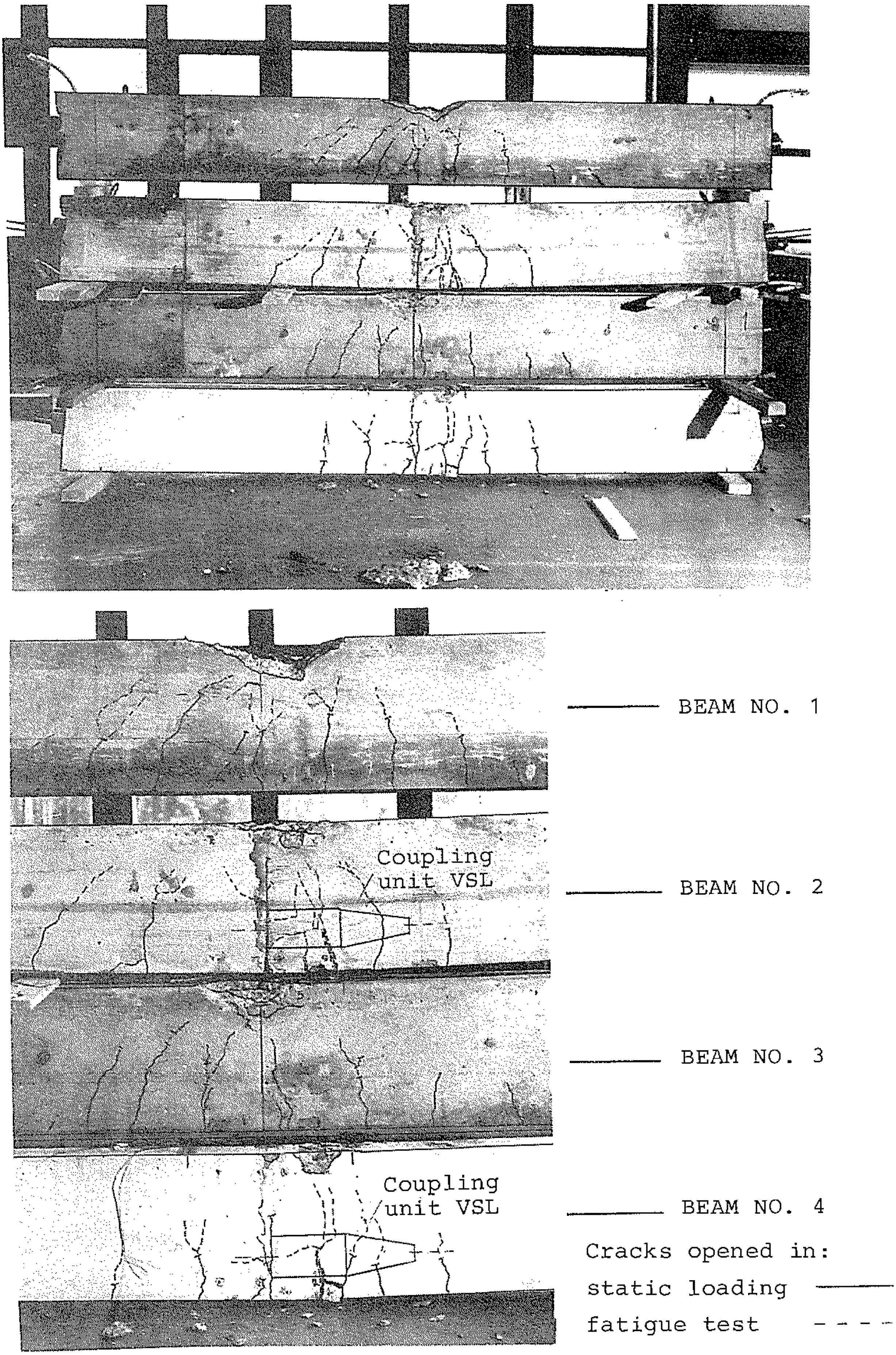


Fig. 5 Typical crack propagation of some tested beams

3.2 Fatigue tests

The results of the fatigue tests are summarized in Table 1. A significant difference in the number of cycles before failure can be seen between the coupled and uncoupled beams. The uncoupled beams could in some cases sustain 9 times as many cycles as the coupled beams.

The actual stress ranges $\Delta\sigma_a$ in Table 1 are based on theoretical calculations using actual material properties (from material tests). In some cases the stress ranges are based on measurements in the coupling units. The difference between $\Delta\sigma_a$ and the required stress range $\Delta\sigma_{th}$ depends mainly on deviations in material properties and in the prestressing force.

Beams No. 9 and 10 with improved joints lasted about three times as long as those with ordinary joints. Beam No. 7, which had a construction joint in the mid-span, had the same fatigue capacity as a corresponding beam without a joint (beam No. 5).

The locations of the fractures in the cable coupling units are marked in Fig. 2. In Fig. 6 failures of wires and strands in VSL and BBRV couplers are shown. In the uncoupled beams the failures of strands or wires occurred close to the mid-span.

Figs. 7 and 8 show the growth of the mid-span deflection and the stresses in couplers. Although larger values, the deflections of the coupled beams showed similar growth compared to the uncoupled beams, see Fig. 7. The growth of mid-span deflection of the beams was very small in the beginning of the tests. In the last part of the tests the deflections increased markedly (see beam Nos. 5, 7, and 8). According to the growth of the stresses in the couplers, Fig. 8, a similar course can be seen. It is only in the last part of the tests where the stresses change. Especially for beam No. 8 the stress decreased markedly. This probably depends on failures of the strands.

The crack propagation in the fatigue tests is shown in Fig. 5. It can be seen that the propagation of cracks in the fatigue tests is concentrated to the area of the cable couplers.

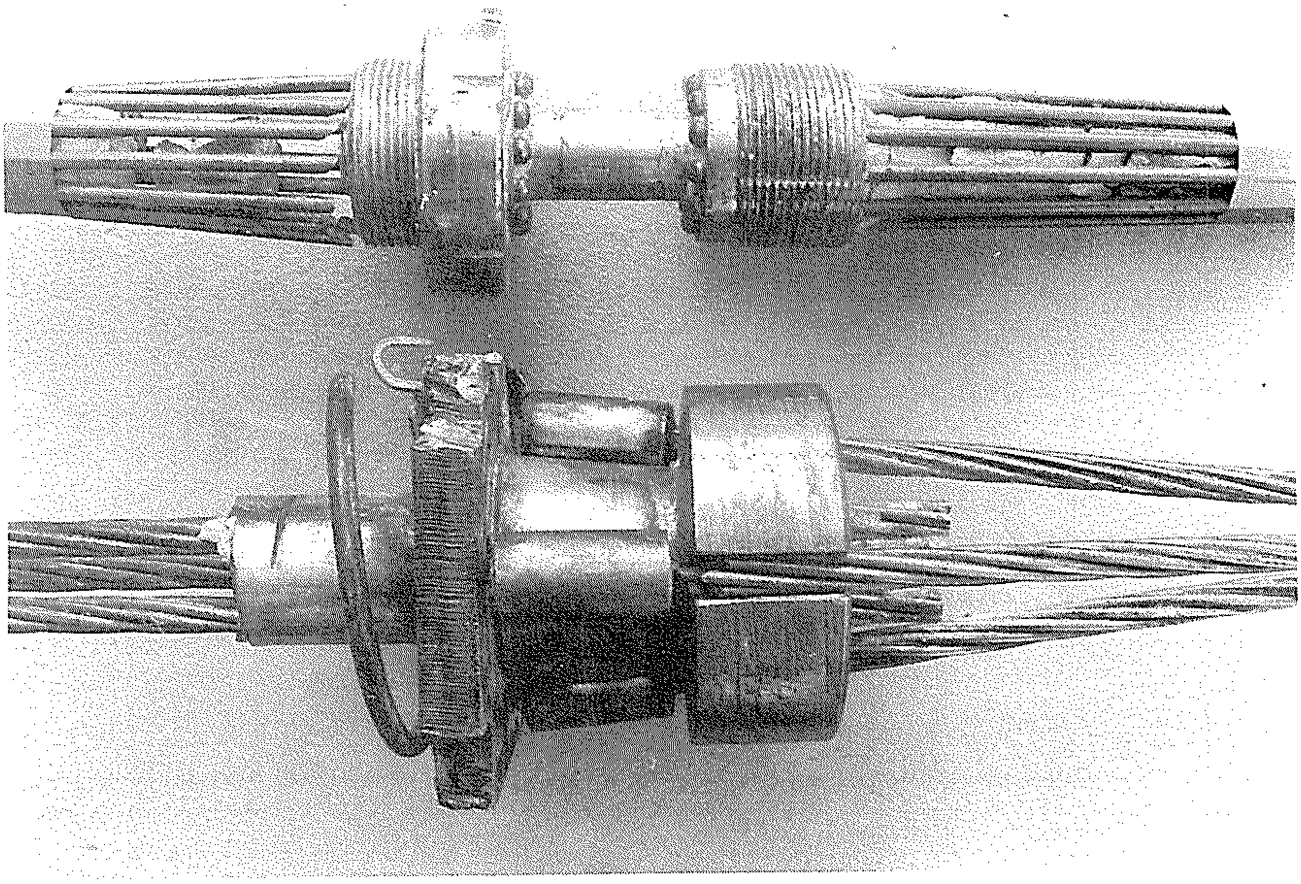


Fig. 6 Failures of a strand in a VSL coupler and of wires in a BBRV coupler

4. DISCUSSION

4.1 Cracking

In the coupled beams cracking started earlier than in the uncoupled beams. The cracks were concentrated in the coupling sections. This cracking reduced the bending stiffness and increased the deflections. The stress range in the tendons increased after cracking as the tendons had to take care of the tensile forces that were earlier carried by the concrete. The increased stress range in the tendons reduced the fatigue strength of the coupled beams.

Why, then, did these cracks appear in the coupled beams?

The main reason for this premature cracking of the coupled beams

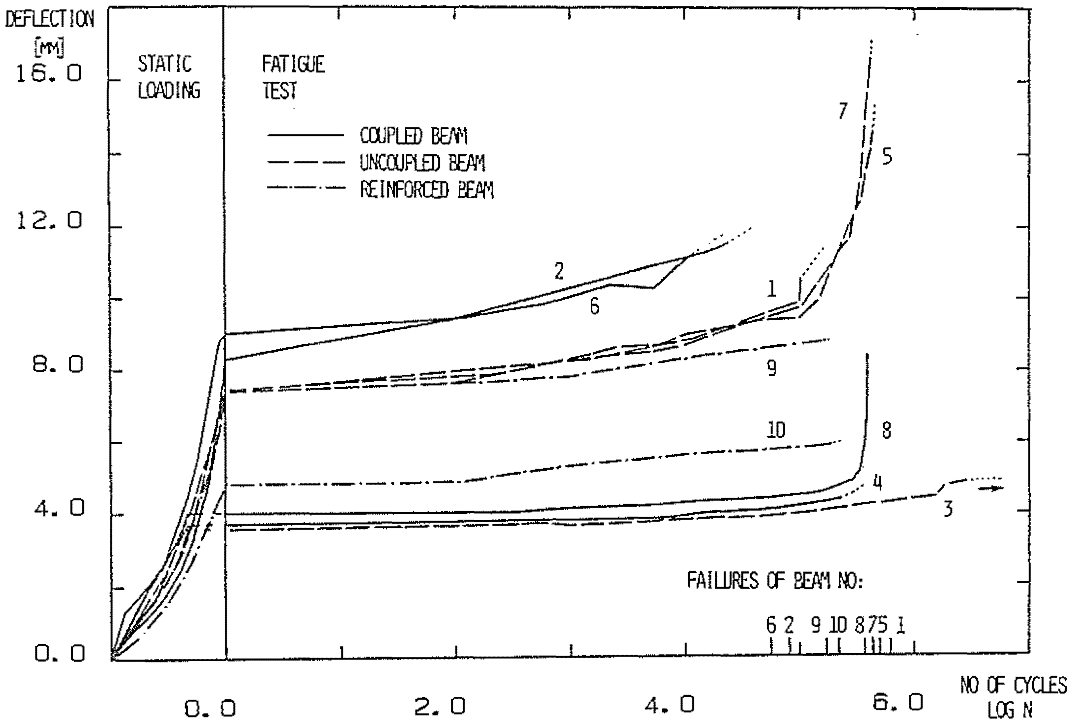


Fig. 7 Growth of the mid-span deflections in the fatigue tests

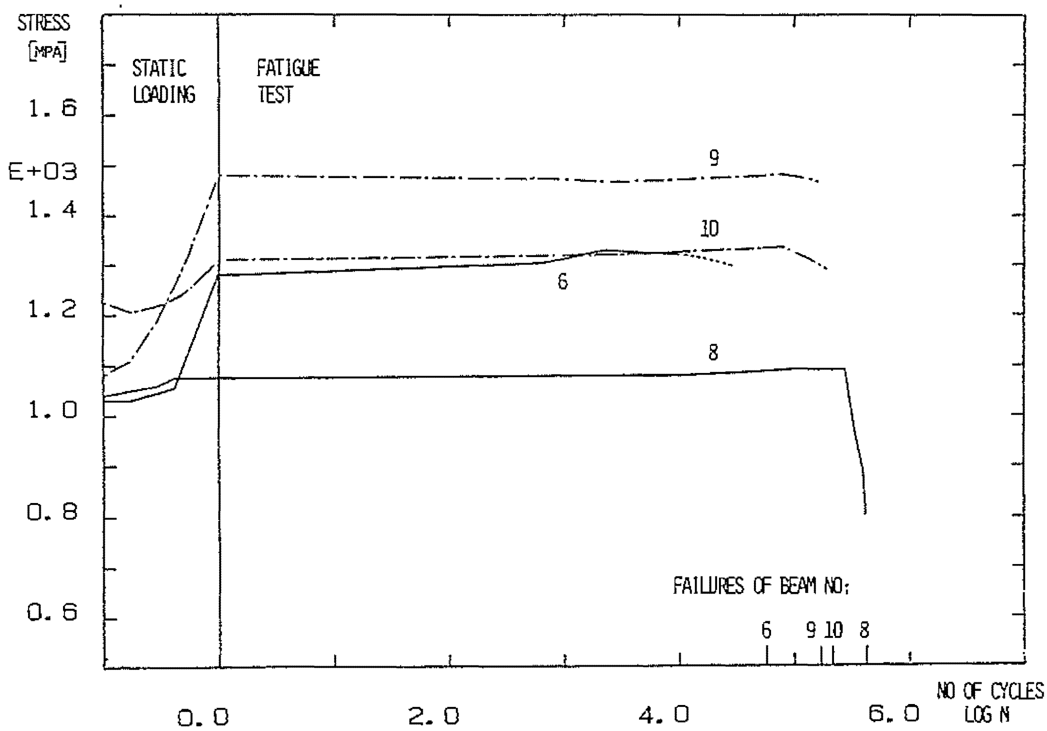


Fig. 8 Growth of the stresses in some couplers in the fatigue tests

seems to be that the prestressing force locally decreases in the region of a couple. This results mainly from increased creep caused by high compressive stresses in a coupled section where the concrete area is reduced by a considerable amount due to the coupling. Measurements /2/ in the mid-span of the beams show creep values that are twice as high in the coupled beams as in the uncoupled beams.

Calculations /2/ show the strong effect of a decrease in the level of the prestressing. For instance, a reduction of the prestressing force by 10% causes that stress range to increase about 100% in the working load stage (100 ± 40 kN) and about 30% in the ultimate load stage (170 ± 40 kN).

In the discussions in the literature of the causes of deficiencies in coupled bridges, the following reasons for cracking have also been proposed /1/, /4/, /5/, /6/, /7/:

- The cable couplings are often situated in sections which theoretically have a zero bending moment. Due to settlements in the supports, non-uniform temperature stresses, etc., the position of the zero moment can move slightly along the bridge span. This causes non-predicted bending moments to occur in the section with the coupling. These bending moments can give rise to tensile stresses in the concrete.

- The temperature field in a coupled section may disagree with the assumed one. This may cause considerable tensile stresses in the concrete.

- The position of the cables may not be correct. This can also increase the tensile stresses in the concrete.

- Due to bad workmanship and complicated casting conditions in a coupled section the concrete tensile strength may be reduced.

However, in our tests none of these four reasons seems to have been present.

4.2 The coupling unit

There is a big difference in the fatigue strength of coupled and uncoupled beams even if the stress ranges in the tendons are almost the same. One important fact which can explain this has been observed in tests performed by Kordina and Günther /8/. In these tests, beams with coupling units showed no differences in fatigue strength compared to standard tests on bare tendons with a coupling. Therefore Kordina and Günther conclude that the dominating factor causing the lower fatigue strength of coupled prestressed structures is the loss of fatigue strength in the coupling itself. This loss of fatigue strength depends among other things on stress concentration in the strands due to bending and on fretting in the connection between the strands and the coupling units.

4.3 Local bending in the beam and friction between concrete and tendons

How phenomena like local bending and friction between concrete and tendons affect the fatigue strength is not quite clear. It can be seen from photos of the failures of the collapsed beams (see Fig. 6) that local bending probably has an influence on the fatigue life of the coupling. This local bending gives rise to stress concentrations in the connections between the tendons and the coupling unit. The stress concentration seems to have initiated the failures in the strands.

On the other hand, Kordina and Günther suggest /8/ that local bending and friction forces are only secondary effects which do not influence the fatigue capacity of the couplings. However, Kordina and Günther have tested other coupling units than we have (e.g. Dywidag bars), and it is likely that different coupling units produce different stresses.

5. CONCLUSIONS

The tested coupled prestressed beams have a much lower fatigue strength than the uncoupled beams. The number of cycles up to failure are only about 10 to 15% of the number of cycles in an uncoupled beam. The possible reasons for this are summarized below:

- In a coupled section the prestressing force is reduced to high creep strains. This loss of the prestressing force causes cracking to occur in the section and leads to an increased stress range in the tendons in the coupling area. A beam which is loaded in the working stage may for this reason fail although the theoretically predicted stress range (for an uncracked beam) does not indicate any reason for collapse.

- A low fatigue strength of the coupling unit itself. This may explain the observed difference in fatigue strengths between coupled and uncoupled beams with similar stress ranges.

- Local bending in the beams and friction forces between concrete and the strands in the coupling lead to stress concentrations which initiate failure of the tendons.

Based on the results in the project so far, the following steps might be considered to improve the fatigue strength of coupled beams.

- The presence of tensile stresses in the coupled sections could be predicted (and prevented) by means of a more exact theoretical analysis. In this, the effects of the reduced concrete area at the coupling section and of possible temperature stresses should be considered.

- Cracks can also be prevented by an increase in the nontensioned reinforcement and an increase in the prestressing force. The Swedish National Road Administration has recently issued a code revision based on this idea /6/.

- The design of the coupling units can be improved to reduce stress concentrations caused by, for example, local bending between the strands and the coupling unit.

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REFERENCES

/1/ Pfohl: Mitteilungen der Bundesanstalt für Strassenwesen 3/79. Strasse und Autobahn, Heft 12, 1979

/2/ Emborg, Mats: Fatigue strength of cable couplers in concrete beams, tendons type VSL (In Swedish with English summary), University of Luleå, Division of Structural Engineering, Diploma Work No. 1981:075E, Luleå 1981, 98 pp

/3/ Hjärtström, Staffan and Södergren, Björn: Fatigue strength of cable couplers in concrete beams, tendons type BBRV (In Swedish with English summary), University of Luleå, Division of Structural Engineering (to be published)

/4/ Engelke, P: Überblick über Ursachen und Bedeutung von Schäden im Bereich von Spannglied-Kopplungen, Strasse und Autobahn, Heft 11, 1980, pp 492-507

/5/ Kordina, K.: Schäden an Koppelfugen, Beton- und Stahlbetonbau, No. 4, Berlin 1979, pp 95-100

/6/ Ingvarsson, H.: Casting joints in prestressed concrete structures (In Swedish with English summary), Nordisk Betong, No. 6, 1981, pp 21-23

/7/ von Olnhausen, W. and Ingvarsson, H.: Prestressed concrete in Swedish roadbridges, Nordisk Betong, No. 2-4, 1982, pp 205-211

/8/ Kordina, K. and Günther, J.: Dauerschwellversuche an Koppelankern unter praxisähnlichen Bedingungen, Bauingenieur Vol. 57 (1982), pp 103-108