TESTING OF FIBREOPTIC CRACK-DETECTORS IN CONCRETE

S. Rosseland
Cement and Concrete Research Institute, SINTEF div FCB, N-7034 TRONDHEIM, Norway
M.Sc., Research engineer

ABSTRACT

Four fiberoptic crack-detectors with different sensitivities to crack widths were produced and placed in reinforced beams (100x150x1200 mm). Before casting, the detectors were placed between the reinforcement and the surface of the concrete on the tension side. In addition, all the beams were instrumented with inductive displacement transducers both on the tension and compression faces. The beams were tested by three-point-bending. The tests were deformation regulated to attain controlled crack-propagation.

This investigation showed that the theoretical principle of the fibreoptic crack-detector can be utilized in real concrete structures.

Key-words: Fibreoptic sensors, Fibreoptic, Structural monitoring, Concrete

1 INTRODUCTION

The lifetime for the offshore structures on the Norwegian continental shelf in the North Sea, is usually stipulated at a minimum of 20 - 30 years. Documentation of the safety and integrity of the structures is provided by condition monitoring by the operators during this period. Such monitoring may also be requested by the Petroleum Directorate /1/.

Monitoring the condition of offshore structures gives information about possible damage and can be used to assess whether repair work is required.

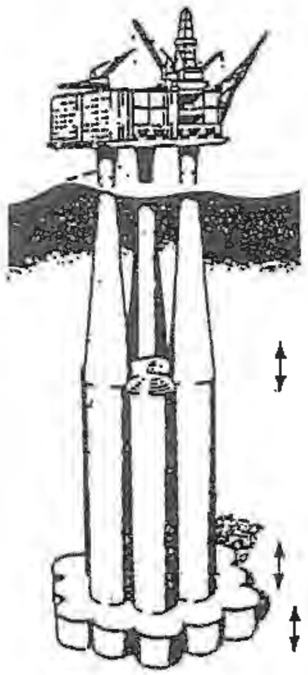
Annual inspection of these structures today is mainly carried out by means of submersible remotely operated vehicles (ROV) or a combination of ROV and divers. Such means of inspection is time-consuming, weather-dependent and expensive.

Oil is being produced at ever-increasing depths. Divers should not be used in the inspection work due to factors such as costs, effectiveness and safety. Therefore, it is necessary to find alternative inspection methods monitor the condition of structures. During the last few years various sensors and systems for monitoring offshore structures have been developed.

One such device is a fibreoptic crack-detector. Possible locations of the sensor in a concrete platform are shown schematically in Fig 1. The arrows in the figure mark the parts of the structure which are most severely loaded during storms. Therefore careful attention will be paid to monitoring the crack propagation in these parts of the structure.

The reinforcement in concrete is normally protected against corrosion by the chemical properties of the pore water in the concrete. If, however, cracks propagate towards the reinforcement in a marine environment, chloride ions might penetrate to the steel surface and destroy the protective effect of the concrete /2/. Consequently the reinforcement may become corroded, which could result in structural damage.

The corrosion process of the reinforcement is dependent upon several parameters. In the tests reported in /2/ and /3/ these parameters are varied and discussed, and both these investigations show that when the crack width exceeds a particular limit, the risk of corrosion is high. Therefore, we should be able to detect where and when such cracks occur.



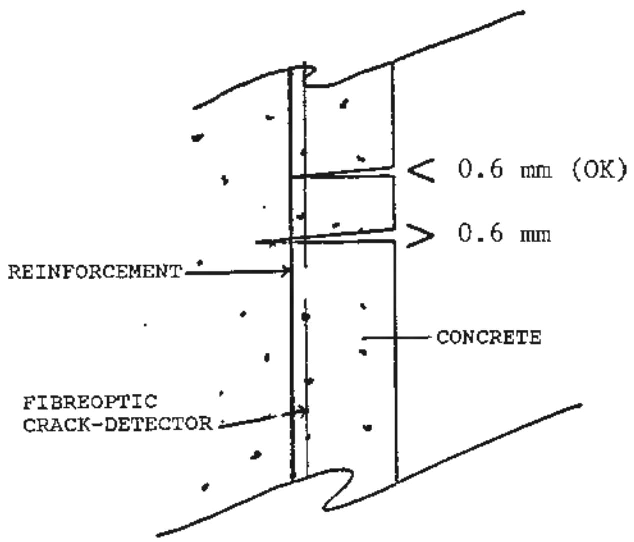


Fig 1. Location of the fibreoptic crack-detector and a sketch showing the principle /4/

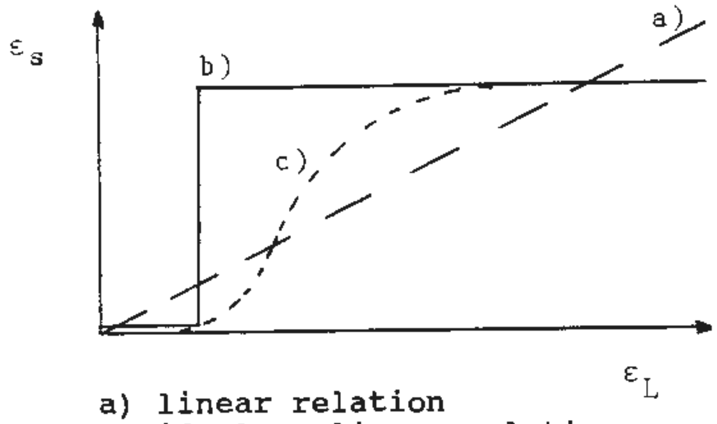
The fibreoptic crack-detector has been developed by a Trondheim company Optoplan a.s. The development work was done during "Instrumented structural monitoring", a project which was initiated and supported by Statoil.

The present investigation by the Cement and Concrete Research Institute both tests and measures properties of the detector. The purpose of the tests was primarily to determine whether the theoretical principle could be utilized in real concrete structures, and secondly, evaluate the crack-width sensitivity of different detectors.

2 FIBREOPTIC CRACK-DETECTOR

2.1 General

The detector has to fulfill several requirements. It must distinguish between high uniform strains and cracks. If the detector accumulates the tension over a particular length, it can give false crack-width alarms if the total tension is larger than the contribution from a possible crack. Therefore, the detector should act in a nonlinear fashion, as shown in Fig 2.



a) linear relation
b) ideal nonlinear relation
c) realistic relation

Fig 2. Elongation of the detector (ε_S) as a function of the elongation in the concrete (ε_L) /5/

Small elongations in the concrete under tension (ε_L) should be eliminated in such a way that they do not contribute to the signal from the detector (ε_S). This will reduce the risk of false crack-width alarms. A crack in concrete represents a very large relative elongation i.e. a jump in the curve of relative elongation along the detector.

Three different monitoring principles are of current interest for the fibreoptic crack-detector. These can be summarized as follows /4/:

a) Warning/alarm principle: if the intention of the monitoring is to detect cracks which are larger than a particular crack width, only warnings above this crack-width are needed.

b) Step-by-step principle: warnings are given when the crack-width is between one of several predetermined crack-widths.

c) Continuous monitoring: this is the most ambitious means of monitoring crack widths.

Regardless of the selection of the monitoring principle, the detector should be able to report repeated alarms without any kind of repair or maintenance.

2.2 The chain principle

The fibreoptic crack-detector is based on micro/macrobendings of a chain. When the chain is stretched, bending of the fibre occurs. This will induce loss in the fibreoptic light passing through the fibre which will be a function of amplitude, periodicity and the number of bendings. The bendings in the fibre are generated as shown in Fig 3.

Both the chain and the fibre are cast within an elastic material /5/. This material controls the position of the chain and pulls the chain back to the initial position when tension is released. The detector will act nonlinearly because the bending of the fibre is related to the chain deformation. The start-point for the fibre bending, and hence the loss in the fibre-optic light, can be adjusted by placing the fibre in a hole with a larger diameter then the fibre. Loss of fibreoptic light will not be recorded until the fibre makes contact with the wall of the hole.

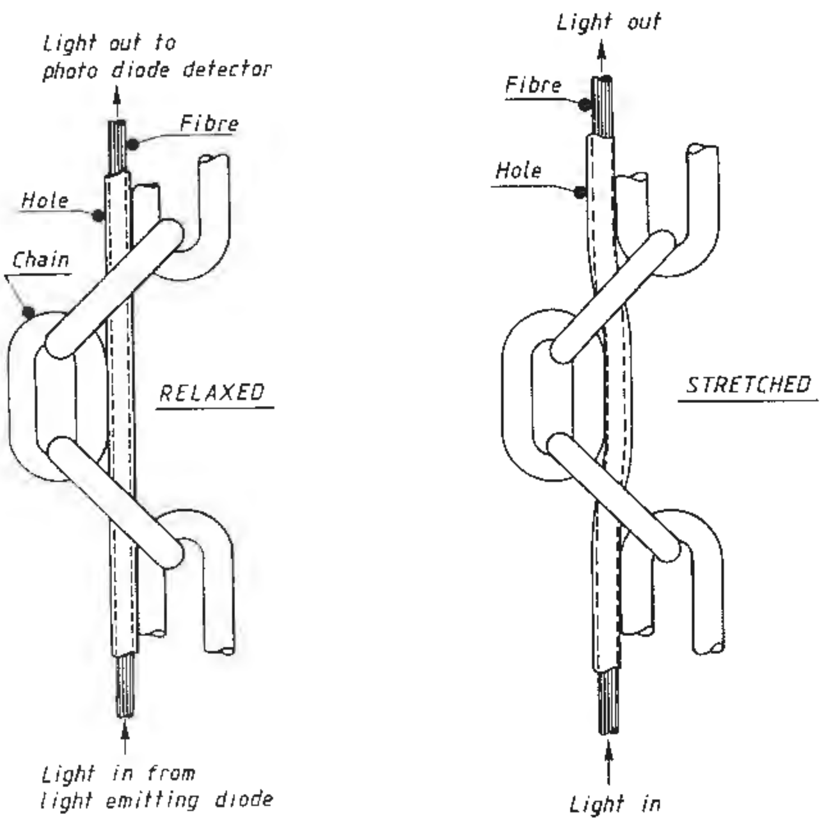


Fig 3. The chain in relaxed and stretched conditions /5/

3 TEST PROGRAMME

3.1 Production of crack-detectors

Four different fibreoptic crack-detectors with different sensitivities to crack-width were produced by varying the diameter "a" of the hole, see Fig 4. The diameters of the holes were 0.25 mm, 0.30 mm, 0.35 mm and 0.40 mm respectively, while the diameter of the fibre (0.25 mm) was equal for all the crack-detectors.

A steel wire with the selected diameter was pulled into the chain and cast within silicon-rubber to make the hole. After the silicon-rubber had hardened the steel wire was pulled out of the chain and replaced by the fibre. The steel-spring, see Fig 4, acted both as formwork for the silicon-rubber and provided a bond between the concrete and the silicon-rubber /5/. The length of the detectors was 100 mm. The different parts of the detector are shown separately in Fig 5.

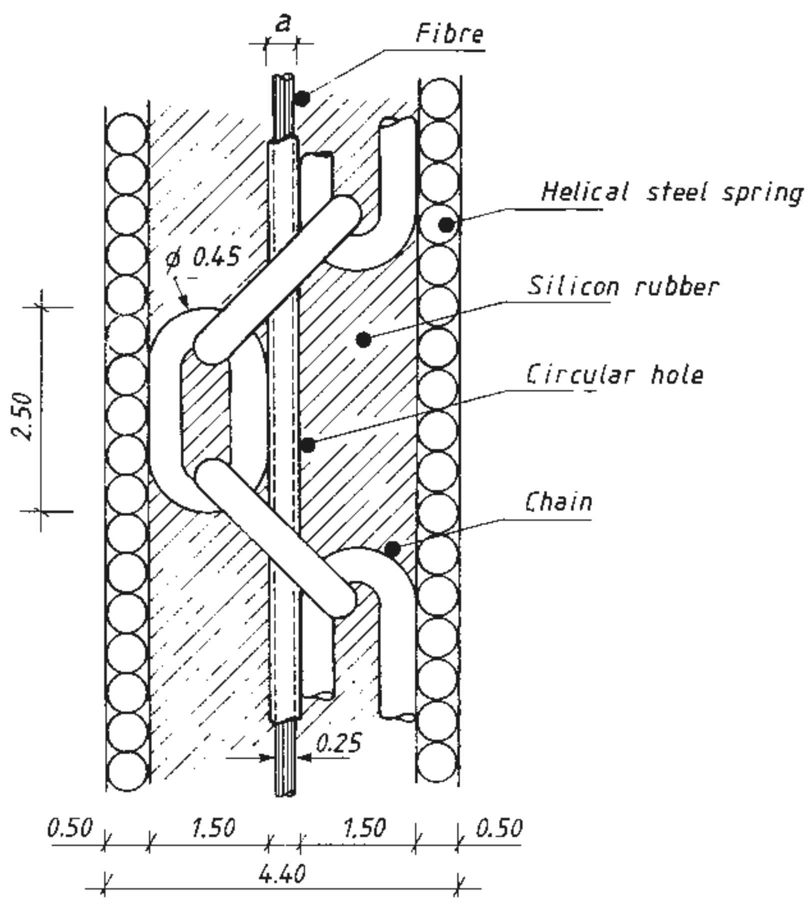
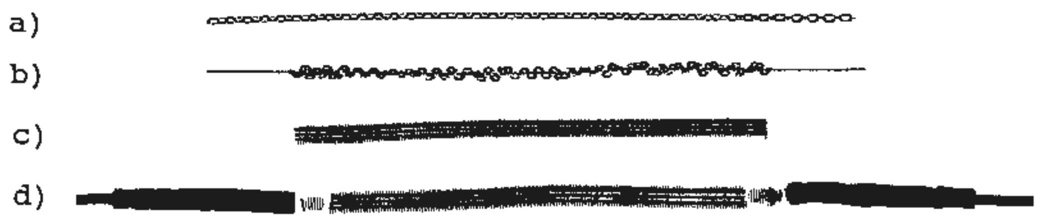


Fig 4. Construction of the fibreoptic crack-detector, measured in millimetres



a) chain
b) steel wire pulled into the chain
c) helical steel spring
d) fibreoptic crack-detector

Fig 5. The different parts of the detector

3.2 Specimens and test set-up

The four fibreoptic crack-detectors were each placed in their respective reinforced beams of concrete, quality ND 50.

The detectors were placed close to the middle rebar between the reinforcement and the surface of the concrete on the tension side in the middle of the beamspan, see Fig 6. The concrete cover over the rebars was 20 mm. Besides that, the beams were instrumented with an inductive transducer, which had the same measuring-length as the length of the fibreoptic crack-detector, 100 mm, on both the tension and compression faces. The inductive transducer on the tension side directly measured the crack-width on the surface and was used as a reference for the crack-detector.

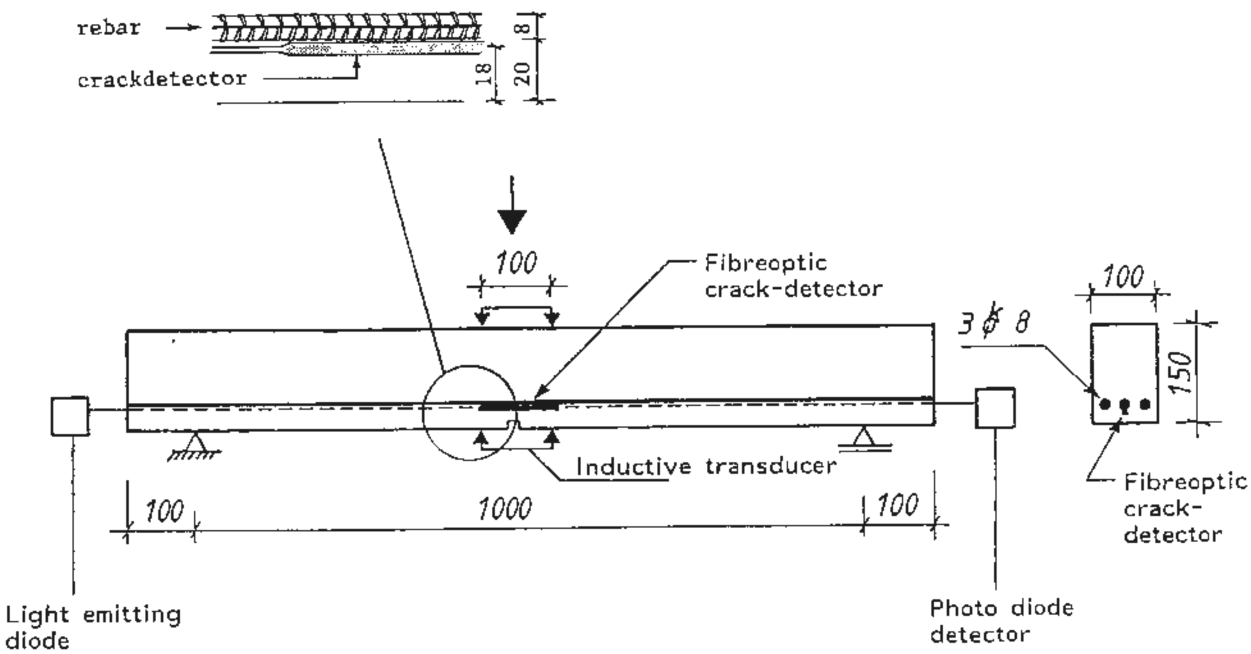


Fig 6. A beam undergoing three-point-bending, measurement in millimetres

The beams were statically tested by tree-point-bending. The tests were deformation regulated to attain controlled crack propagation. During the tests, the load, strains and crack-widths were recorded automatically by a personal computer at regular intervals.

4 RESULTS AND DISCUSSION

The loss in the amount of light passing through the fibreoptic crack-detectors during the tests is shown together with the corresponding crack-widths in Fig 7. The difference between the diameter of the fibre and the surrounding hole is termed a cavity. The fibreoptic crack-detectors with increasing cavities were cast in specimens nos 1, 2, 3 and 4, respectively.

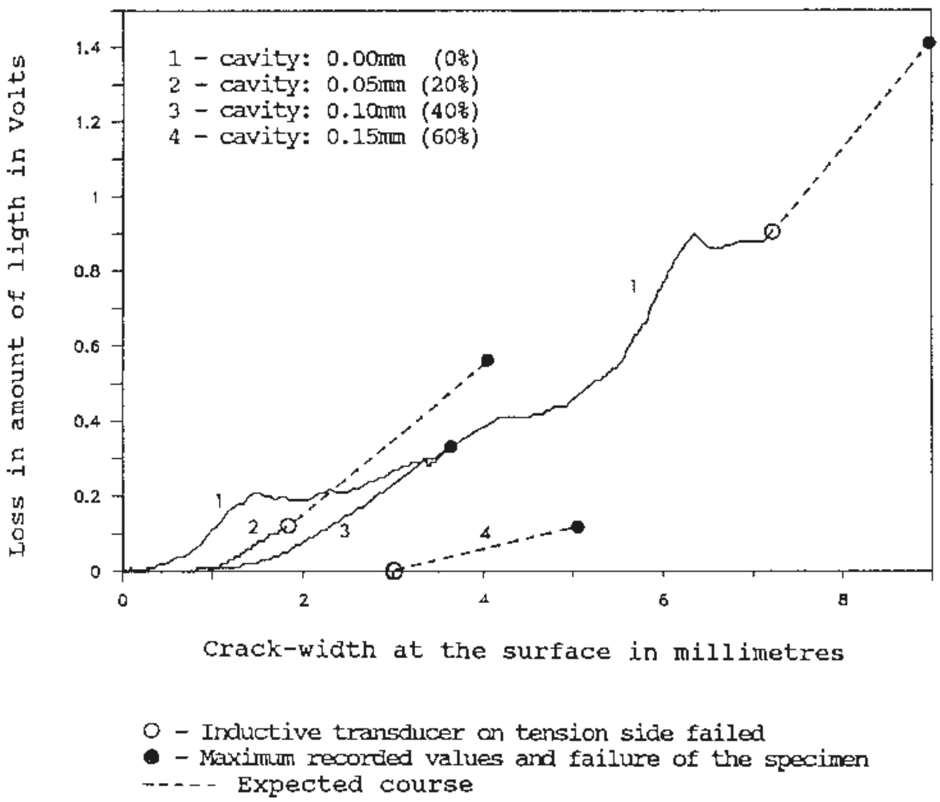


Fig 7. The loss in the amount of light through the fibreoptic crack-detector shown together with the corresponding crack-widths

There was one large crack (crack-width > 1.0 mm) and a few small cracks (crack-width < 0.05 mm) in the measuring area (100 mm) of each beam. The widths of the small cracks were considerably less than the largest cracks, and did not influence the amount of light passing through the fibreoptic crackdetector. Hence, all the detectors were intersected by only one crack, which influenced the amount of light.

The crack-widths were measured by the inductive transducers. The strain inside the measuring area was regarded as small compared to the crack widths, and was thus neglected.

For all the beams the load/displacement relation and consequently the sum of all the crack-widths on the surface were approximately equal. Nevertheless, the maximum crack-widths in the measuring area (100 mm) varied from 3.5 mm in specimen no 3 to 9.0 mm in specimen no 1. This variation in crack-widths is caused by some large cracks which appeared just outside the measuring area.

The initial loss in the fibreoptic light started at crack-widths on the tension face of 0.25 mm, 0.80 mm, 1.25 mm and 3.00 mm for specimen nos 1, 2, 3 and 4, respectively. These results show that the starting-point can be adjusted by varying the cavity, and that the fibreoptic crack-detector with no cavity, i.e. the one with the highest sensitivity, registered a change in the amount of light first through the fibre.

In spite of the zero cavity for the most sensitive detector, the initial loss in the fibreoptic light did not start before the crack-width was 0.25 mm. There are probably two reasons for this. First, this can be due to a clearance of some tenths of a millimetre between the chain and the steel-spring. Since the silicon-rubber is an elastic material, the deformation of the steel-spring was not directly transferred to the chain. Second, this could be caused by the chain elements not being tightly stretched to begin with.

As shown in Fig 7, the average inclinations from the initial loss of the fiberoptic light up to 0.12 Volt for curves no 1, 2 and 3 are approximately equal. These results show that the behaviour of the three detectors in these specimens were equal after the cavity in the detector reached zero.

All the crack-widths were measured on the tension surface, while the crack-detectors were affected by the same cracks at a distance of approximately 18 mm from the tension surface. As mentioned, there was only one crack which influenced the amount of light in the measuring area of each beam. The propagation of this crack in the interior of the beams was not recorded. For specimen no 1 the one crack which intersected the detector was probably divided into several smaller cracks in the area close to the rebar, which affected the loss of light through the crack-detector. This is probably the reason for the variant behaviour of the crack-detector in specimen no 1 compared to the other curves. This is especially evident in the change in inclination at crack-widths 1.5 and 6.3 mm measured on the surface. In addition, the crack-detector with no cavity is more sensitive to a crack division than the other crack-detectors which were tested.

In specimens nos 1, 2 and 4 the inductive transducer on the tension surface failed, see Fig 7, but all the crack-detectors worked satisfactory until the failure of the specimens. After failure the crack-width was measured by magnifying glass. Linear curves were expected from the point the inductive transducers failed up to the failure of the specimens.

In specimen no 4 the inductive transducer failed before any loss was measured in the amount of light. The crack width corresponding to the initial light loss for this specimen was manually measured to be 3.0 mm. For specimen no 3 the initial loss in the amount of light started at 1.25 mm. In spite of the fact that the cavity in the crack-detector in specimen no 4 was only 0.05 mm larger than the cavity in the crack-detector in specimen no 3, the initial loss in the amount of light thus started at a 1.75 mm larger crack-width, see Fig 7. The cavities as a percentage of the diameter of the fibre were 0, 20, 40 and 60, respectively, for the four crack-detectors. The results show that the behaviour of the detector in specimen no 4 strongly differs from the three other crack-detectors. Hence, crack-detectors with cavities from 0 to 40 % are recommended to detect and monitor crack-widths from 0 - 2 mm. To detect and monitor larger crack-widths, crack-detectors with cavities from 40 to 60 % can be used.

The crack-widths by the crack-detector were smaller than at the surface. Assuming a linear variation the crack with the maximum crack-width (9 mm, see Fig 7) measured at the surface, was about 2 mm smaller by the crack-detector. Hence, the crack can be detected earlier than shown in this test by placing the detector directly under the surface. The detector ought to be placed away from the rebars to avoid any disturbance.

In Section 2.1 it was required that the detector should register and behave nonlinearly. A comparison of the results in Figs 7 and 2. shows fairly close agreement to Curve c). In the tests the crack-detectors were not tested at their maximum capacity, hence the results in Fig 7 only represent the lower part of curve C) in Fig 2.

Three different monitoring principles were described in Section 2.1. The results of the tests show that the detectors and the measuring instruments satisfy the most ambitious monitoring principle: continuous monitoring of the crack-widths. This also implies that the two other monitoring principles can be met, depending on the measuring instruments used.

5 CONCLUSIONS

The theoretical principle of the fibreoptic crack-detector can be utilized in real concrete structures.

The fibreoptic crack-detector behaves nonlinearly. By varying the cavity in the fibreoptic crack-dectector, the start-point of initial loss in the amount of light through the fibre can be adjusted.

Crack-detectors with cavities from 0 to 40 % of the diameter of the fibre are recommended to detect and monitor crack-widths from 0 - 2 mm. To detect and monitor larger crack-widths, crack-detectors with cavities from 40 to 60 % can be used.

The crack-detector ought to be placed directly under the concrete surface so that any cracks can be detected as early as possible.

The detectors and measuring equipment used in this investigation, satisfy the most ambitious monitoring principle: continuous monitoring of the crack-widths.

7 REFERENCES

1 Norwegian Petroleum Directorate: Acts, regulations and provisions for the petroleum activity; December 1987

2 Gautefall, O. and Vennesland, Ø.: "Effect of Cracks on the Corrosion of Embedded Steel in Silica-Concrete Compared to Ordinary Concrete", Nordic Concrete Research, Vol 2 (1983), pp 17-28

3 Gautefall, O.: "Effekt av spekkvidde og betongoverdekning på korrosjon av innstøpt stål i armerte betongkonstruksjoner", SINTEF-Rapport STF65 A86080, Desember 1986

4 Nesset E., Berg A.: "Konstruksjonsovervåking ved hjelp av fiberoptikk (D31-1 Fiberoptikk)", ELAB-Rapport STF44 F85190, November 1985

5 Berg A.: "Fiberoptisk distribuert strekksensor, Prototyper basert på induserte bøyetap", Optoplan Rapport 86 108, December 1986