MONITORING OF CONCRETE STRUCTURES BY MEANS OF ACOUSTIC EMISSION AND STRAIN

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ABSTRACT

A concept for monitoring of concrete structures exposed to repeated compressive loadings is proposed. The concept is based on measurements of compressive strain and acoustic emission in combination. It is anticipated that the relative development of strain and acoustic emission can be predicted, and hence that a forthcoming failure can be revealed. To verify the concept, experimental tests have been carried out on both reinforced and plain concrete cylinders exposed to different loading conditions. Tests on reinforced columns subjected to repeated compressive loads have also been done. The anticipated development of strain and acoustic emission was verified in the cylinder tests, while the column tests showed that the anticipated behaviour is a local phenomenon connected to the area where final failure occurs. Further investigation on acoustic emission is proposed.

Key words: monitoring, strain, acoustic emission

1. INTRODUCTION

Seeing that the exploration of oil and gas offshore will take place at increasing depths, there is a need to replace visual structural inspection with instrumental systems. The concern for automatic monitoring is also due to a desire for reducing expenditure.

The Cement and Concrete Research Institute (SINTEF, div FCB) has for several years been working on a concept for monitoring of marine structures in concrete. The concept is based on measurements of acoustic emission and strains in combination.

Deterioration of strength, caused by static or dynamic loading, is accompanied by acoustic emission and strains proceeding in a certain course of events. Hence, it is possible to give an early warning of collapse.

To verify the concept, one has carried out several tests on plain and reinforced columns of concrete, both in large and small scale and under various kinds of loadings. The issue of this article, is to outline the concept and to summarize the test results.

However, it is natural to start with a presentation of acoustic emission as a phenomenon.

2. ACOUSTIC EMISSION IN CONCRETE - AN INTRODUCTION TO THE SUBJECT

Acoustic emission (AE) is a general expression for the stress waves that are generated when solid materials are stressed in the non-elastic region.

Consider an elasto-plastic/hardening material like concrete, and imagine a specimen exposed to an increasing load curve. Until the elastic limit is reached, all the energy in the specimen is stored as elastic deformation. Beyond this limit the supplied energy is turned into different states as elastic strain energy, plastic dissipation and dynamic energy.

The plastic deformation in concrete is due to microcracking. When a microcrack occurs, a sudden release of strain energy is converted into stress waves. These stress waves, or the acoustic emission, can be recorded as ultrasonic pulses.

The inhomogeneous nature of concrete implies that the ability to sustain deformation varies, both throughout the matrix, the aggregates and in the interface between them, as well as in the bonding zone between concrete and reinforcement. Thus, if a microcrack occurs in one area, the internal equilibrium is maintained by a redistribution of stresses in neighboring areas.

The formation of microcracks, or sources in AE-terminology, is a continuous process when a specimen is subjected to an increasing load. Even if this deterioration is most dominant in the plastic range, the propagation and formation of microcracks is also taking place beneath the elastic limit, although without any significance on the overall modulus of elasticity. The presence of microcraks in the elastic range can be revealed by AE, see Birac et.al /1/,/2/ and /3/.

The AE-signals depend on the source mechanism, that is the fracture mode. According to Scruby et al. /4/, the sourcemechanisms can be classified in three distinguished modes: dilatation, shear and tension. The three modes are shown in Fig 1.

The AE-signals can propagate from the source and throughout the surrounding solid either as a dilatation wave, as a distortion wave or in both forms. The associated deformations at a distance x from the source at time t can be expressed with Greens function. These are well-known formulations in seismology which can also be applied to AE waves /5/. The attained radiation pattern for the dilatation wave of a point force, a shear-crack and a tension-crack are shown in Fig 2.In addition, Fig 2 shows the results from experimental studies on concrete, in which the sources were introduced in a controlled way.

The three source modes are usually called primary sources. While primary sources are due to the formation and propagation of microcracking, secondary sources originate from sliding between fracture-surfaces.

When the volume waves, that is the dilatational and distortional waves, reach a boundary, they are divided. One fraction moves across the boundary into the surrounding medium, while the rest is reflected at the surface. A surface wave, mentioned the Rayleigh wave is generated if the angle between the boundary and the direction of wave propagation exceeds a specific value.

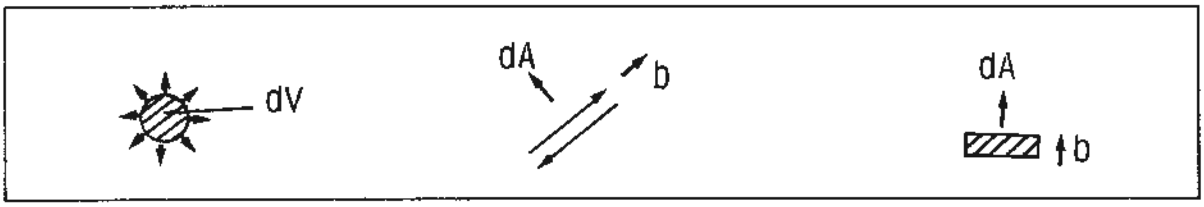

Fig 1. Source mechanisms for AE /4/. dV denotes dilatation, dA areal extension and b Burgers vector. Burgers vector defines the dislocations of translation. a) dilatation, b) shearcrack and c) tension-crack

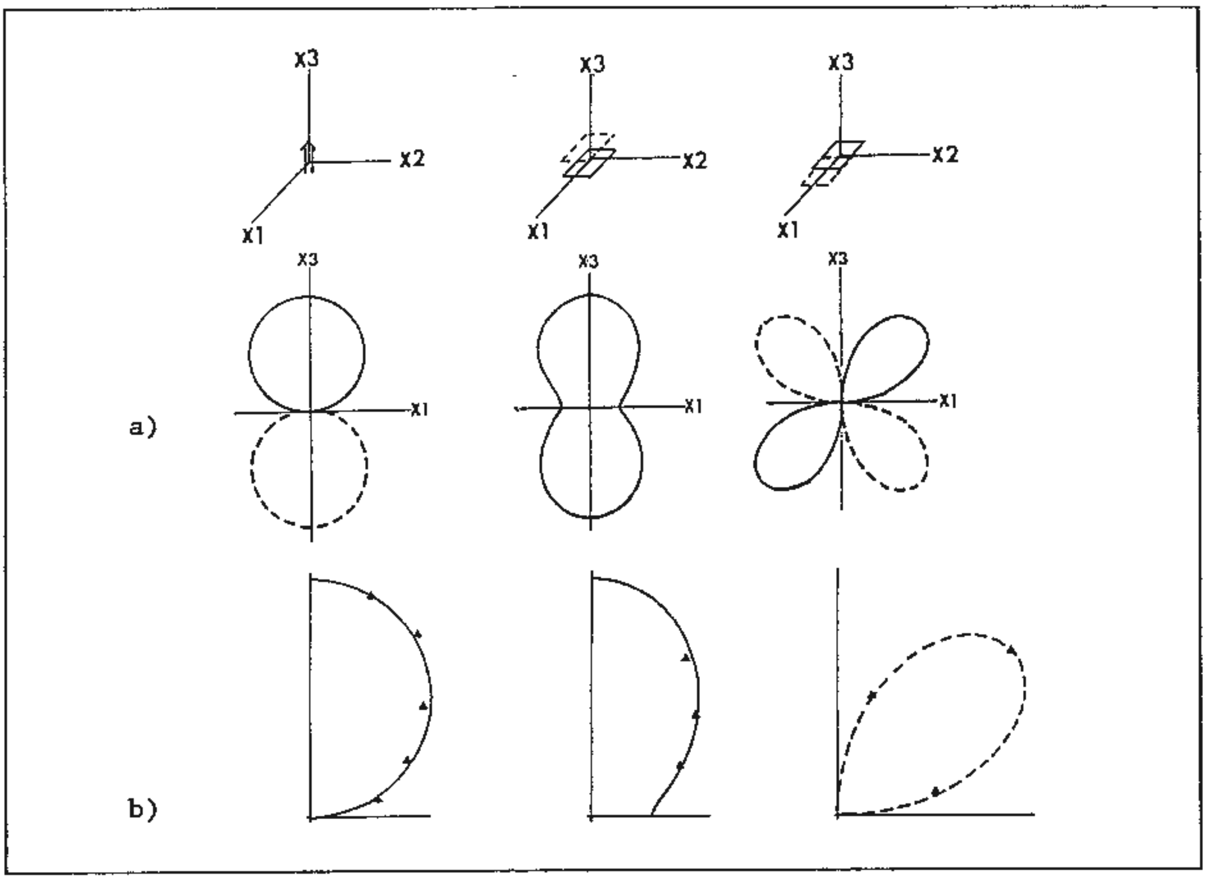

Fig 2. Radiation pattern for dilatation-wave due to a point-force, a shear-crack and a tension-crack.
a) Calculated pattern, b) Results from experimental tests /6/. ▲ denotes measured values.

Due to the hysteresis, the internal friction in all materials, the wave energy decreases as the distance from the source increases. The volume waves suffer an amplitude decay proportional to the inverse of the travelling distance. The amplitude of Rayleigh waves is proportional to the inverted square root of the distance of motion. Hence the surface waves are dominant at a certain distance from the source.

Fig 3. gives a picture of the damping in concrete /7/. These are results from tests on a 3 x 1 m square reinforced concrete plate, 0.2 m in thickness. The AE signals were generated with a controlled point force. Tests were carried out on several concrete plates, which revealed that the reinforcement, in this case, had neglibile effect on the damping.

The AE signals in concrete depend, apart from the damping, on the source mechanism, the rate of microcracking, the concrete composition and the load level.

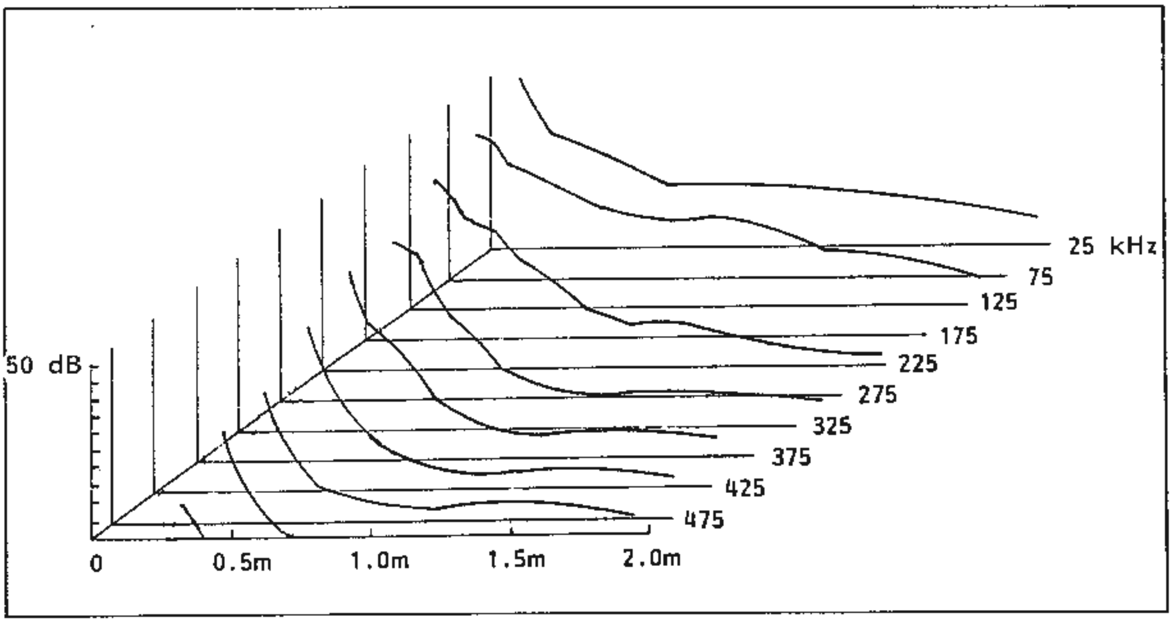

Fig 3. Damping of AE signals in a 1x3x0.2 m concrete plate /7/

Based on the experimental tests that are described in the proceeding chapters, the frequency seems to be mainly in the range 30-150 kHz, with amplitudes rarely exceeding 80 dB.

3. A CONCEPT FOR MONITORING OF CONCRETE STRUCTURES

As outlined in the previous chapter, the nature of AE is quite well described. It is possible to discover and locate microfracturing, and to get an impression about the governing source mechanisms. However, this requires careful planning regarding localization of AE transducers combined with presumptions on the course of events. These are conditions suited for laboratory testing, but even under controlled circumstances it is difficult to predict a forthcoming severe damage on the basis of measured AE signals.

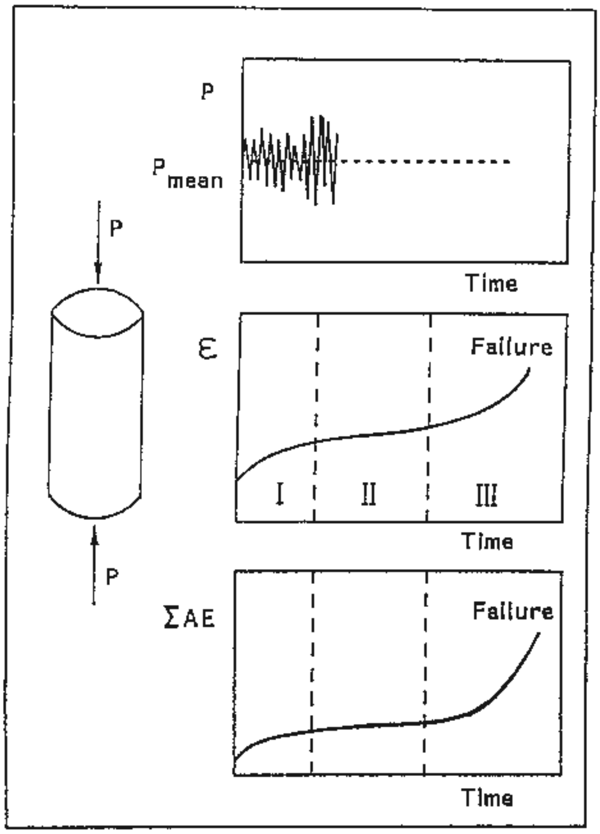

Fig 4. Development of measured strain and AE intensity in concrete under fatigue loading
a) Loading conditions
b) Development of mean strain in the loading direction
c) Accumulated number of AE events

Taking these considerations into account, a concept has been developed where just the AE intensity is used to reveal possible deterioration. Besides monitoring the AE intensity, strains are measured.

The concept should be suited both for structures exposed to long-term static- or fatigue loading conditions. It is based on the following observations:

- The compressive strains in uniaxial loaded structures undergo a given relative development before the endurance limit is reached.
- Likewise, that the intensity of AE can be forecasted. The AE-intensity can be measured either as the rate of events, or as the number of events per loadcycle.

A typical development of strains and AE intensity is shown in Fig 4. The curves are characterized by three distinguished regions: a decreasing rate of strain to start with, a subsequent period with constant rate and the last region with an increasing rate, which gives a warning of coming failure.

The main scope of the concept is thus to make it possible to decide whether a load-carrying component is going to sustain the loading or if failure is possibly approaching.

4. VERIFICATION OF THE CONCEPT

4.1 INTRODUCTION

To verify and develop the concept for practical use, an experimental test programme has been conducted at SINTEF. A main scope in the programme was to check the validity of the anticipated development of strain and AE intensity:

- for various uniaxial load conditions
- for reinforced and plane concrete
- for possible scale dependency

In this investigation all specimens were cast in the same concrete composition and cured under comparative conditions. This was done in order to limit the variables involved, and to secure that test results could be compared. A moderate strength concrete with a cube strength equal to 52 MPa was used.

4.2 TESTING OF CONCRETE CYLINDERS

4.2.1 SCOPE

A series of both plain and reinforced concrete cylinders were tested to investigate the development of strain and AE intensity due to different loading conditions.

4.2.2 DESCRIPTION OF TESTS

The test series is summarised in Table 1. It consisted of 11 specimens, concrete cylinders with dimensions 145x300 mm. Five specimens were reinforced with 4Ø8 TS400 notched bars, see Fig 5.

The various load cases are shown in Table 1. The cylinders were consequently exposed in the following manner: a quasistatic load, which carefully raised the compressive stress from zero to the stress level that was to be the mean stress, was set on. Afterwards, the dynamic component was gradually applied.

Table 1. Test programme

Ref	Unreinf	Reinf	Loading (min/max)	Mean stress
A	1	1	$(0.10 - 0.90)f_{cyl}$	$0.55f_{cyl}$*
B	2	2	$(0.15 - 0.85)f_{cyl}$	$0.55f_{cyl}$
C	1	1	$(0.20 - 0.80)f_{cyl}$ Gauss distribution	$0.55f_{cyl}$
D	1	1	$(0.54 - 0.96)f_{cyl}$ Gauss distribution	$0.75f_{cyl}$
E	1		$(0.45 - 0.27)f_{cyl}$	$0.36f_{cyl}$

* f_{cyl} is the mean compressive strength measured on three 145 x 300 mm cylinders prior to testing

The alternating load component was provided with a sinus wave generator. The frequency was held constant in each test, and was in the range 0.1 - 3.0 Hz for different specimens.

For all specimens, the mean stress was held constant until fatigue failure occurred, that is, apart from the specimen marked E in table 1. This cylinder was tested against stresses in the service state and thus did not suffer fatigue failure.The loading scheme was governed by stresses which were measured in a prestressed offshore structure operating in the North Sea.

In Fig 5, the instrumentation of specimens are shown. Regarding the plain concrete cylinders, four strain gauges were applied in the midmost cross section. Three were mounted symmetrically along the periphery, while the last was cast in the centre. In the reinforced specimens, the bars were additionally instrumented with two strain gauges each.

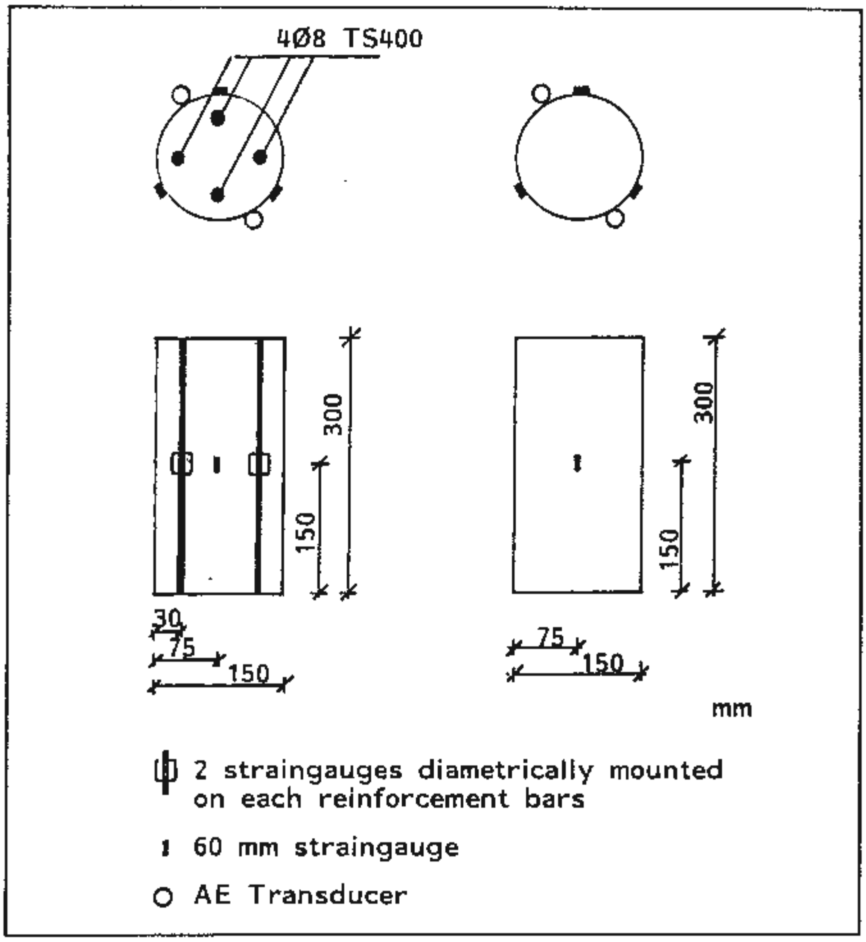

Fig 5. Test specimens with instrumentation

On each specimen, two AE transducers were glued to the surface. These were resonance transducers with a 50 - 500 kHz measuring range. The AE-signals were filtered through a 30 kHz highpass filter. In the test of loading in the service state, one of the transducers was coupled to a 100 kHz highpass filter. This was due to some problems regarding noise from different sources in the laboratory.

4.2.3 TEST RESULTS

The Figures 6, 7 and 8 show the development of strain and AE intensity for respectively a plain and a reinforced specimen exposed to a sinus wave loading with constant amplitude, and a plain cylinder subjected to a sinus wave with random distribution of amplitude.

The curves are representative, and confirm the anticipated development of strains and AE intensity. The measured strains and the number of AE events differed from test to test. Nevertheless, the relative history, i.e. the shape of the curves, were as expected.

The three distinguished regions are clearly observed. Certain drops in strain in Fig 6 and 7 are noticeable. They are due to breakdown of strain gauges and a minor stress gradient in the cross section.

Fig 9 shows the results from the service state loading test. The figure shows clearly what was expected, namely a decrease in AE activity closely connected to the decreasing creep during the 38 days of testing.

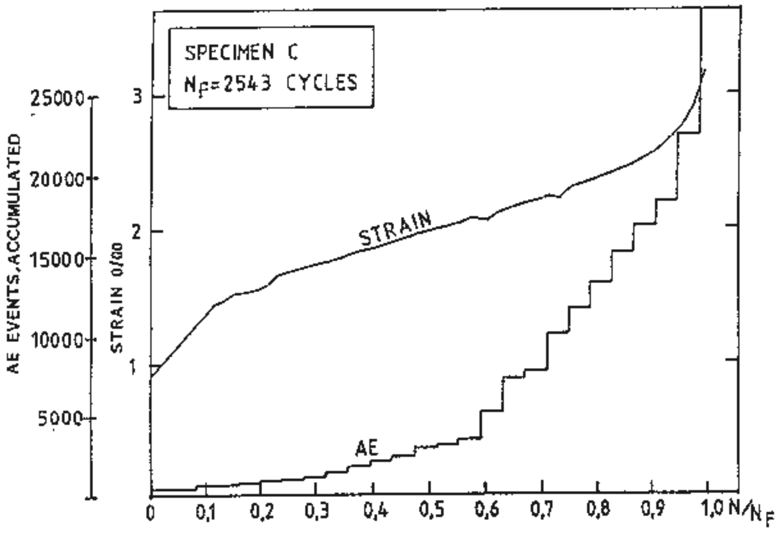

Fig 6. Development of strain and AE in an unreinforced cylinder

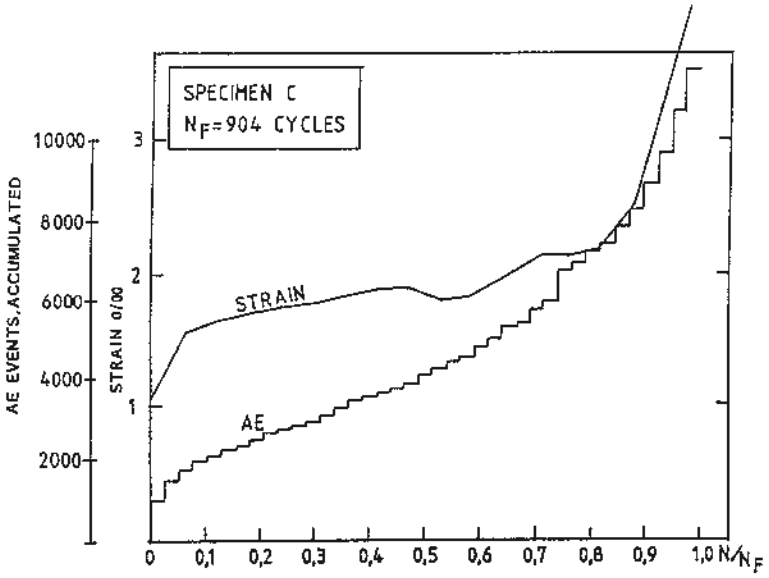

Fig 7. Development of strain and AE in a reinforced cylinder

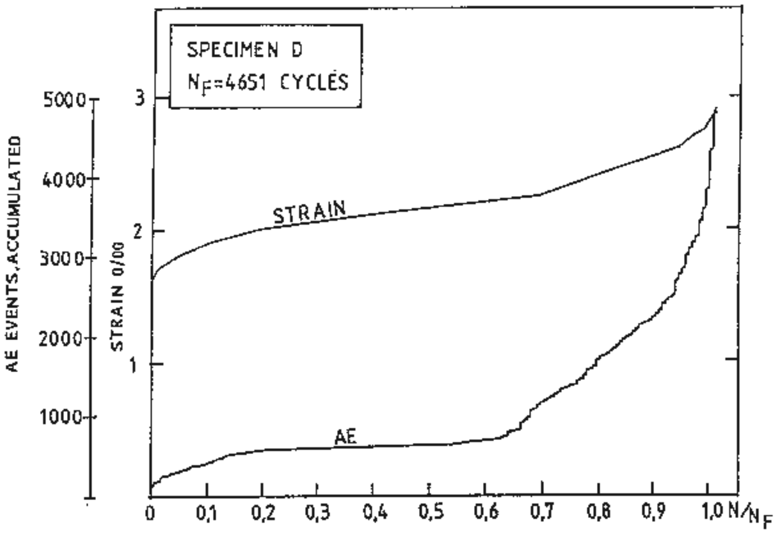

Fig 8. Development of strain and AE in a plain cylinder exposed to Gauss distributed amplitude of loading

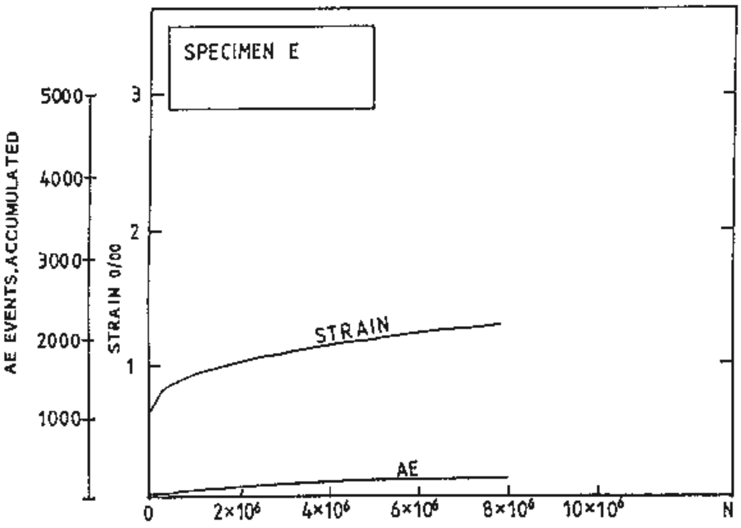

Fig 9. Development of strain and AE in a plain cylinder exposed to stresses in service state loading

4.3 TESTING OF COLUMNS

4.3.1 SCOPE

As shown in the previous chapter, the proposed method of monitoring worked on small specimens where the measurements of strain and AE were done in the failure area, or at least close to it.

By doing similar tests on columns, one wished to investigate if the anticipated development of strain and AE intensity is a local behaviour connected to the area where the final failure occurs.

4.3.2 DESCRIPTION OF TESTS

The test series consisted of three 150 x 1750 mm columns. As shown in Fig 10, they were reinforced with 4Ø10 K400TS bars in the axial direction supported by stirrups.

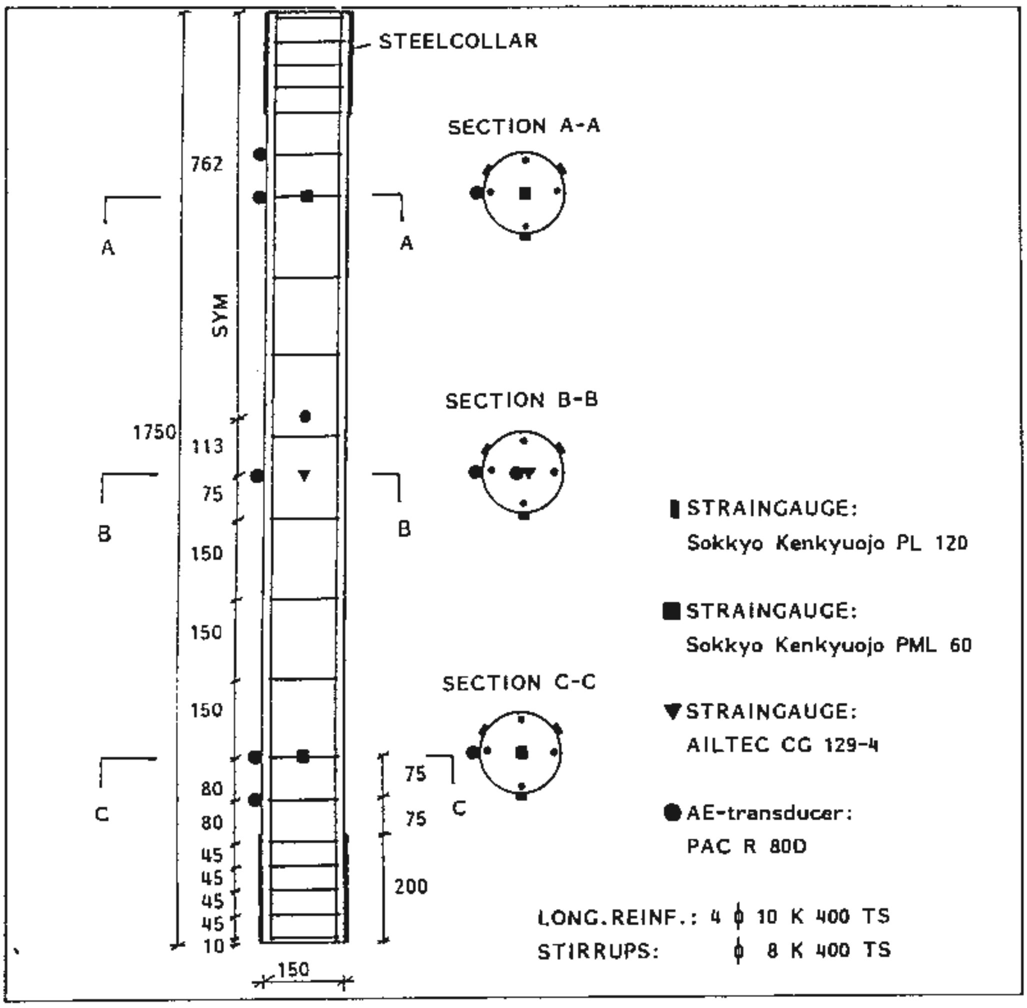

Fig 10. Testcolumns with instrumentation

Two columns were instrumented as shown in Fig 10. The third column was used to get hold of the load-bearing capacity, and hence serve as a basis to determine a proper loading scheme. This one was only instrumented with three strain gauges to provide

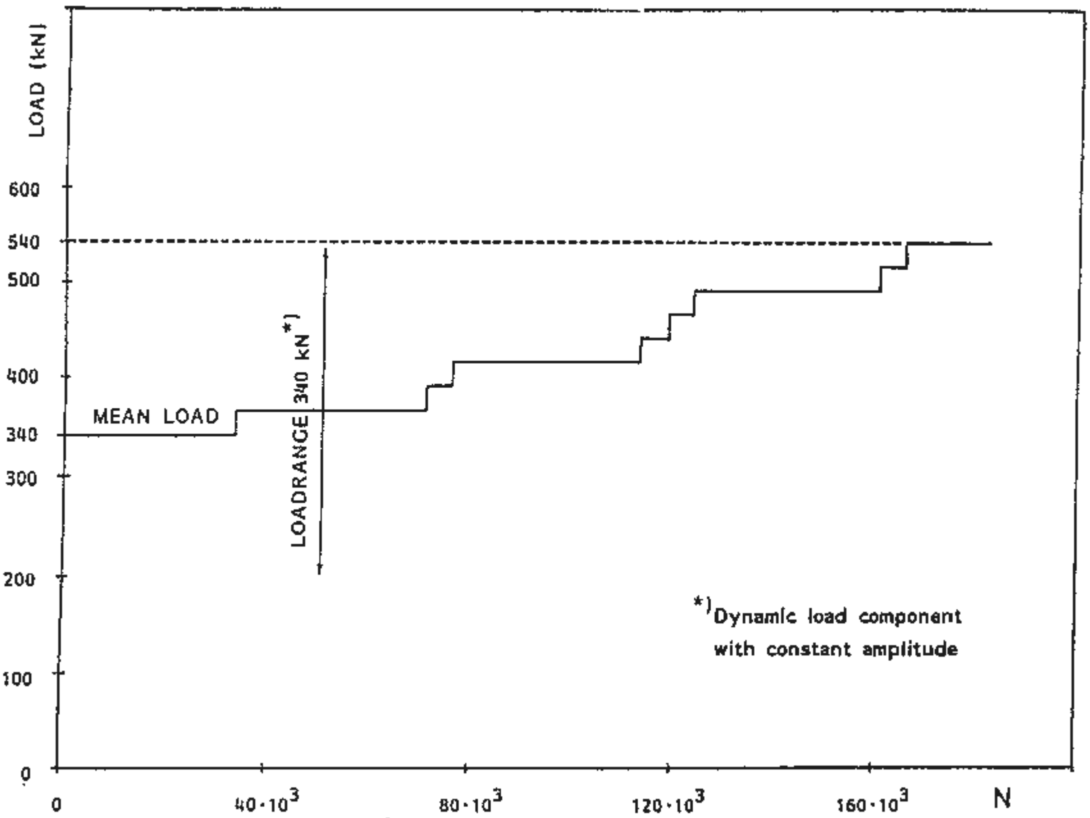

Fig 11. Loading scheme for the second test

informations about the strain level.

The instrumentation in Fig 10 shows that three sections were monitored. Each section was equipped with:

- one strain gauge cast in the column's centerline
- three strain gauges glued to the surface
- one AE transducer glued to the surface

In addition, one AE transducer was cast in the centerline in the midmost section.

The uppermost and lowest AE transducer in Fig 10 served as guard transducers which should reveal possible signals from the boundaries.

All AE transducers were coupled to a 100 kHz highpass filter.

The loading scheme was originally planned as a repeated sinus shaped load with a constant amplitude. The amplitude was chosen to give max and min values equal to 80% and 20% of the static capacity in compression. Due to scatter in the endurance limit, the first column sustained this loading for only approximately 450 load cycles. Thus in the second test, one started out with a reduced static offset in combination with a reduced dynamic component. Throughout this test the mean load was raised in levels, while the dynamic load was held constant. The static level was raised when the development of creep terminated. This was done to obtain failure within a reasonable amount of load-cycles.

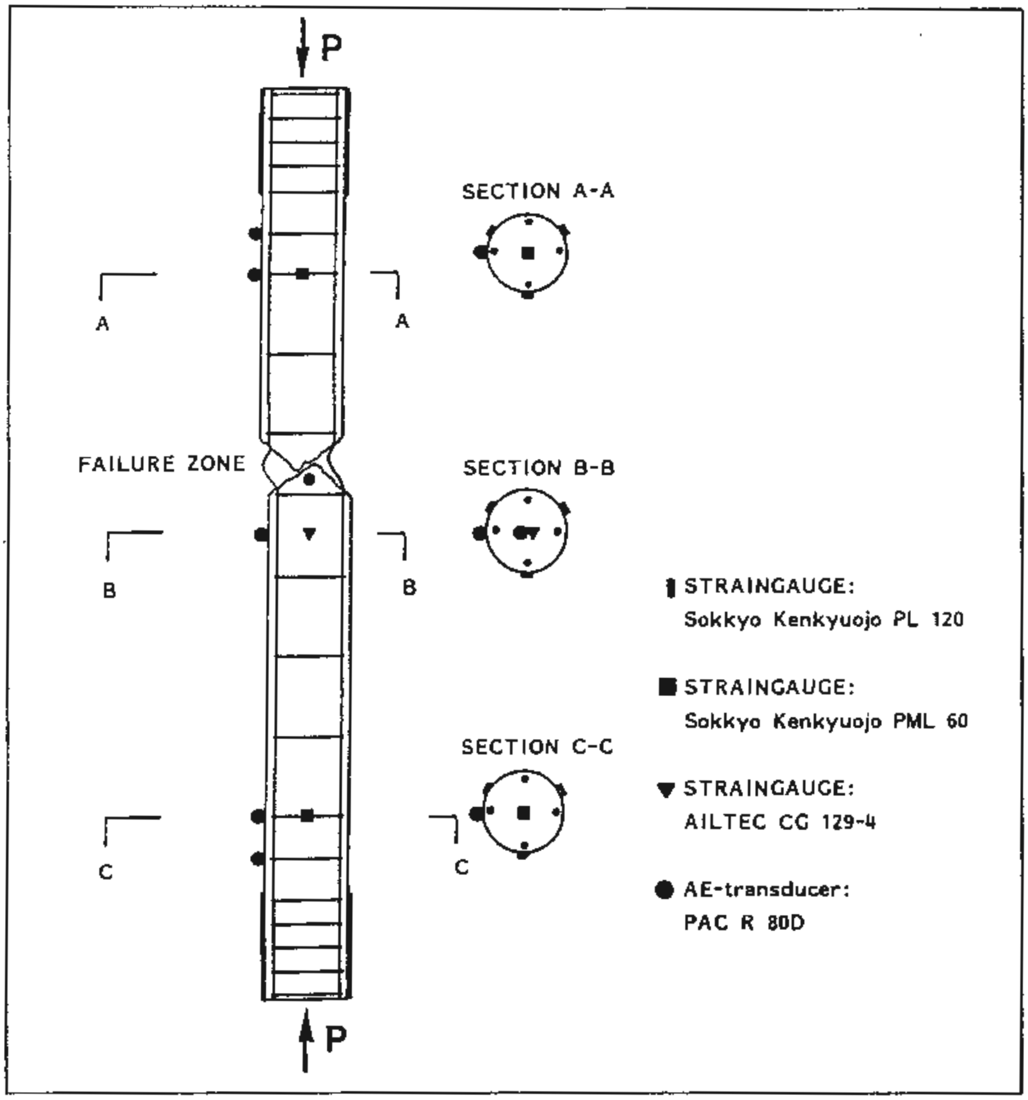

Fig 12. Localization of sensors with respect to the failure zone for the second test

4.3.3 RESULTS

Due to the low endurance limit in the first test, the AE registration unit suffered saturation. The proceeding figures are thus related to the second test.

As shown in Fig 11, this column was exposed to an increasing load curve. The last load level before failure was the most interesting one regarding verification of the concept. The test was successful in the sense that the column sustained a number of load cycles on the last level sufficient to reveal whether the final deterioration is a local or a global phenomenon. The evaluation of test results is thus concentrated about the registrations on the last load level prior to failure.

Unto the last load level, the development of strain was as expected, i.e. an elastic strain component followed by a decreasing rate of creep was measured whenever the load was raised.

Concerning the AE activity, different registrations were made with the transducers mounted on the surface from the one that was cast in the concrete. On the surface, totally 2-3 events were recorded instantly in connection with new load levels, while only occasional signals appeared afterwards. The AE transducer cast in the concrete registered a somewhat higher and continuous activity that increased as the load was raised. As shown in Fig 16, many counts were due to secondary sources.

The registrations on the last load level prior to failure are shown in Figs 13,14 and 15, for sections A-A, B-B and C-C respectively. The figures should be viewed together with Fig 12 which shows the instrumented sections with respect to the ultimate failure area.

The strain curves represent the mean values of the measured mean strain in each section. In section B-B and C-C the rate of creep was nearly constant. In section C-C the increase in strain was somewhat higher than in section B-B, but at the time of failure the absolute values were approximately the same, namely 2.5 0/00. At the time when the load was raised to the final level, the largest strains appeared in section C-C. At this time of testing one felt sure that this was the area were the failure would occur. During the proceeding load cycles, the strain in section

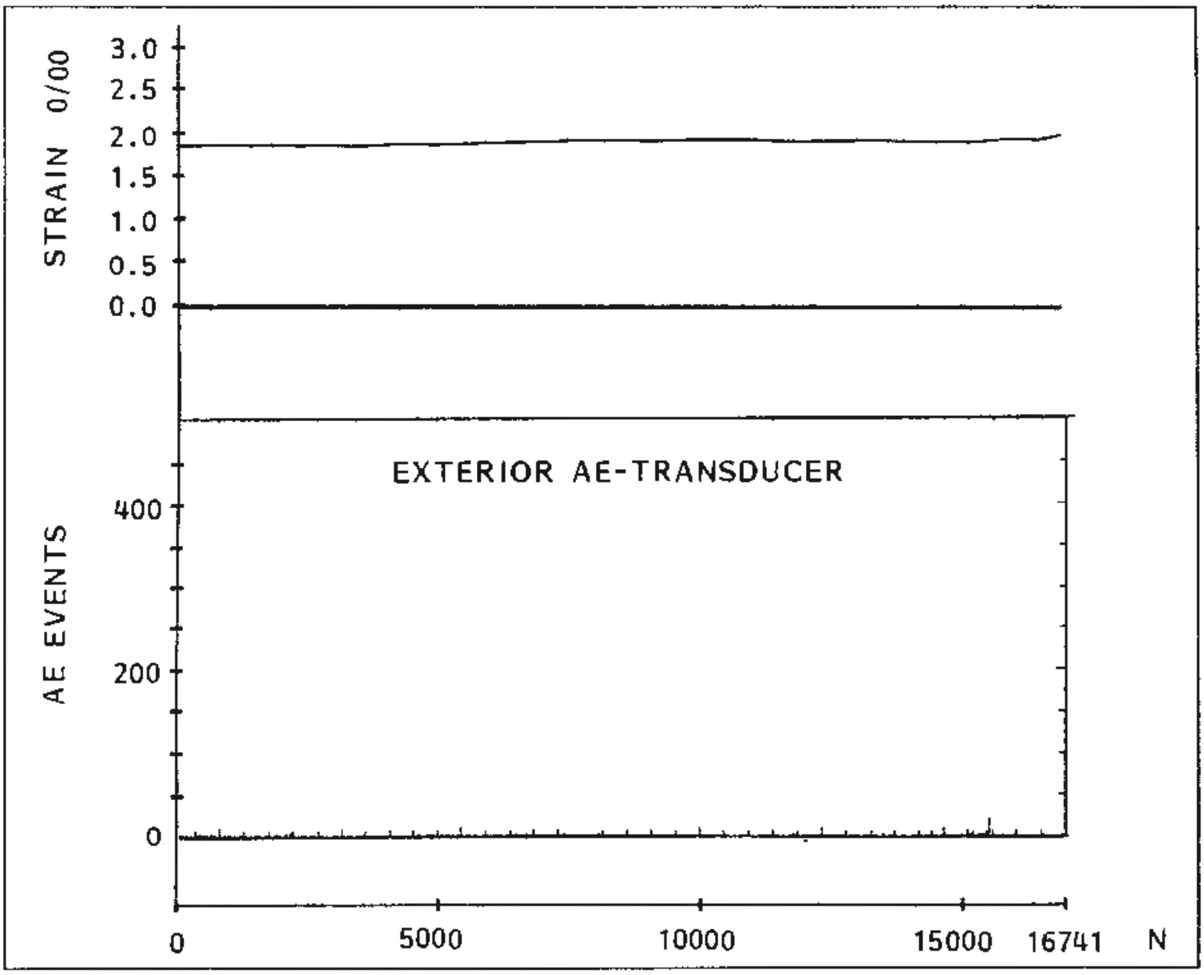

Fig 13. Strain and AE in section A-A for the last load level

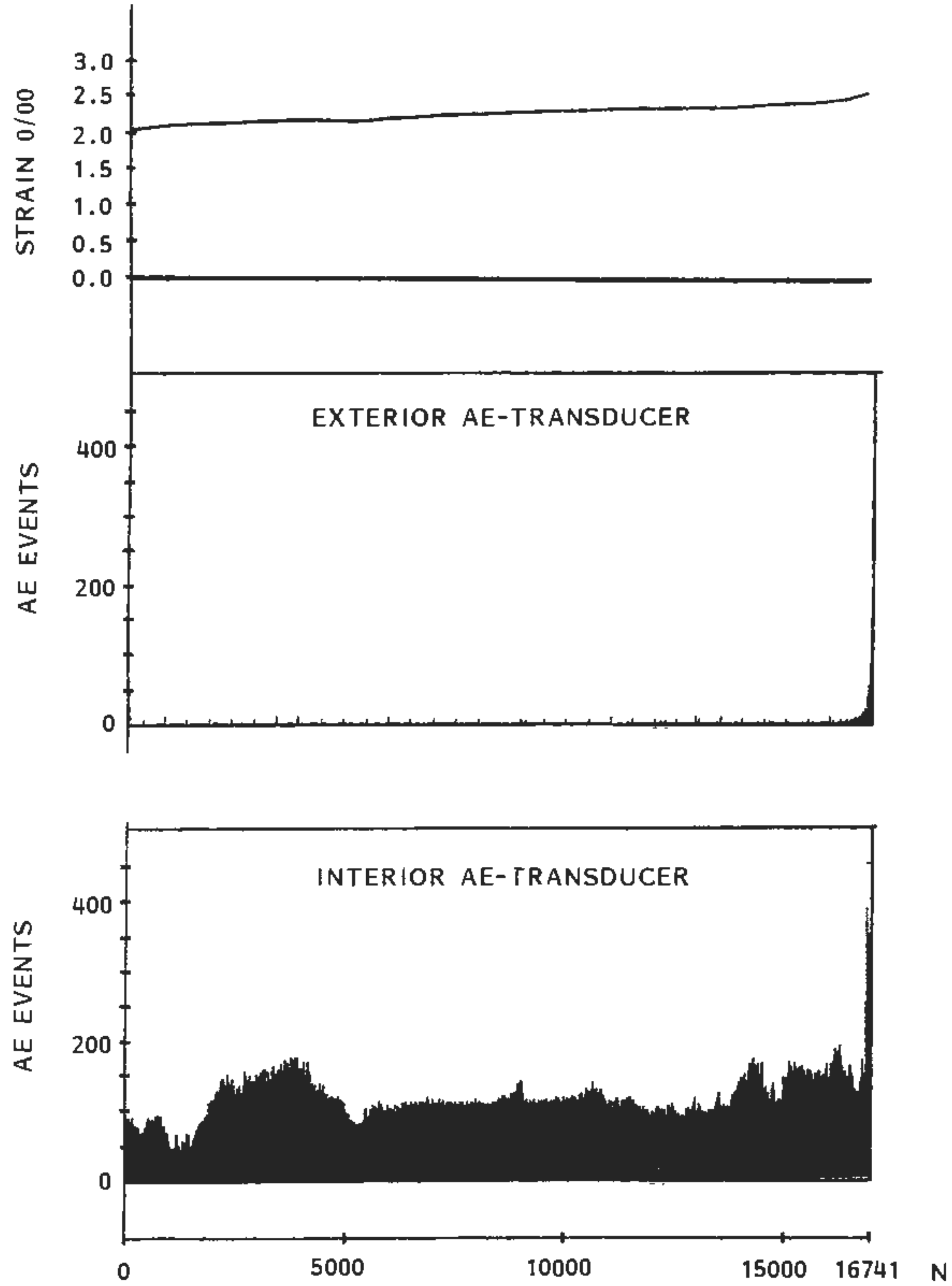

Fig 14. Strain and AE in section B-B for the last load level

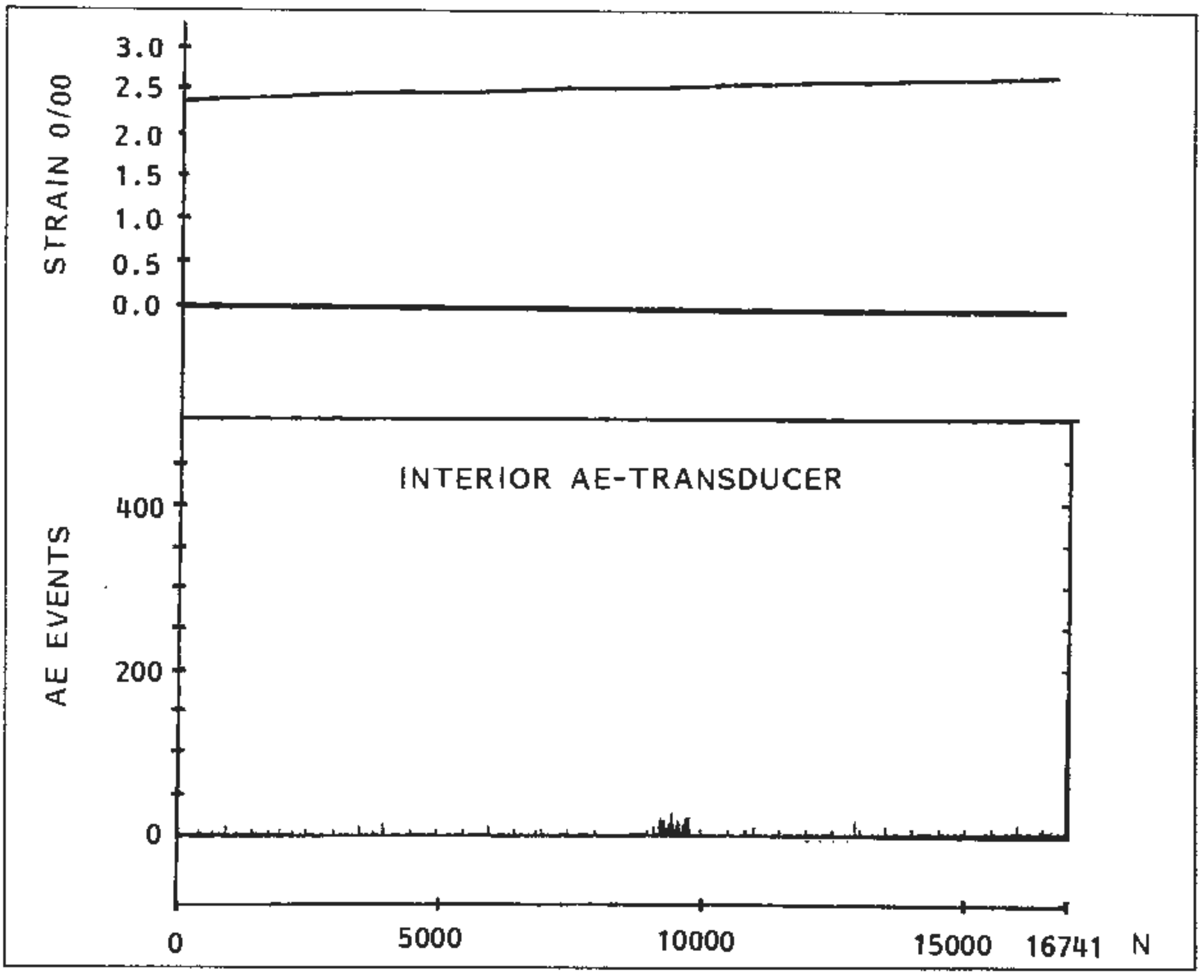

Fig 15. Strain and AE in section C-C for the last load level

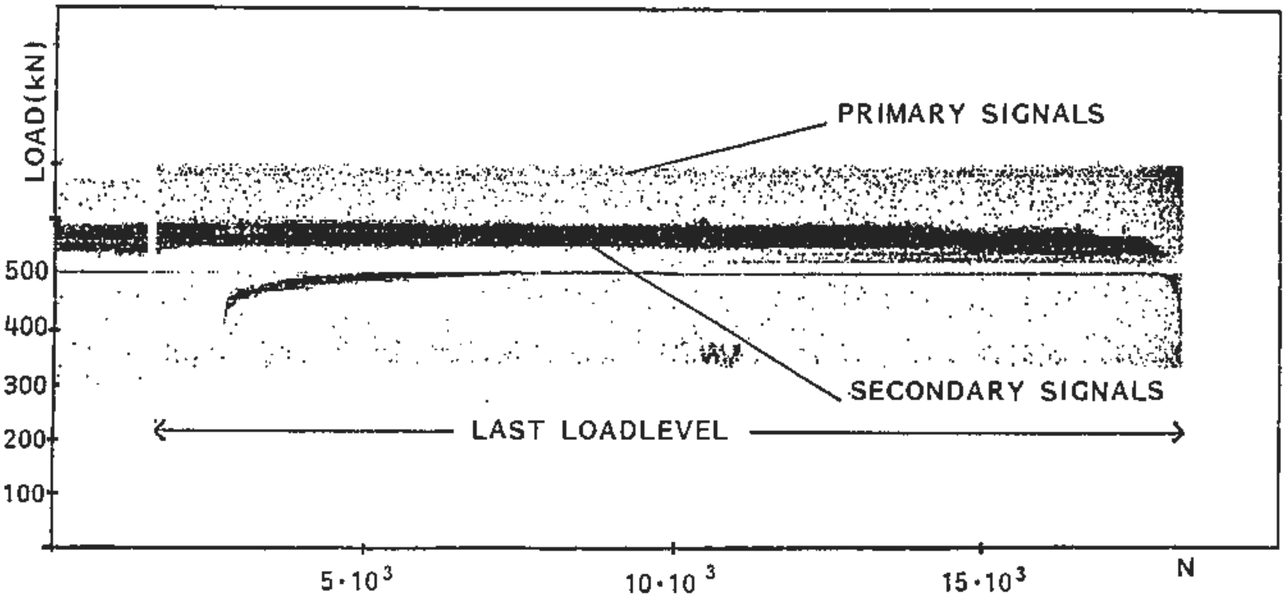

Fig 16. AE activity versus load for the last load level

B-B increased faster, and ended up closer to the failure area. That is probably due to a larger distance between stirrups in this area than in section A-A and C-C. In section A-A hardly any creep was discovered.

The anticipated development of strain, that is the third stage in Fig 4, was not observed in any section, even though a small increasing gradient can be seen in section B-B, see Fig 14. This is probably because the measuring range of the strain gauges in this section went into, or touched the failure zone.

The development of strains shows that the ability to withstand microcracking and the ability to recover, to maintain the load-carrying capacity varies throughout the specimen. Consequently, the increasing strain rate prior to failure, as shown in Fig 4, must be considered to be a local development connected to the failure area.

These considerations are consistent with the AE registrations. As shown in Figs 13, 14 and 15, the AE activity was very low except in the area of failure, which was registered with the interior AE transducer. Notice that the AE curves are presented in a non-accumulated manner.

With the interior AE transducer one registered a continuous high AE intensity during the last load level. The anticipated increased intensity prior to failure was covered by secondary signals, see Fig 16.

Even though the exterior AE transducer in section B-B recorded an increased intensity just prior to failure, unexpectedly few signals reached the AE transducers mounted on the surface. This is probably due to the choice of coupling the transducers to a 100 kHz highpass filter, but it also indicates that the amplitude of the signals above this frequency is low. As shown in Fig 3, the damping ratio is proportional to frequency and hence is also a reason for the few registrations.

5. CONCLUSIONS

The proposed concept has been verified through experimental tests on both plain and reinforced concrete cylinders exposed to different compressive loading conditions.

Tests on reinforced concrete columns has revealed that the anticipated development of strain and AE intensity is a local phenomenon connected to the area were final failure occurs. Thus, so far, practical use of the concept demands that the area of a possible failure can be predicted.

Measurement of strain is useful in cases where structural parts are stressed at levels that cause concern. As a final failure is caused by a local deterioration, strain measurements have to be done in the failure area to give a warning of a forthcoming failure.

To overcome this restriction regarding localization of sensors, a future development of the concept should therefore be focused on investigation of the AE signals originating from a failure zone. The goal in such an investigation should be to :

- distinguish primary and secondary signals
- find the optimum combination of frequency and amplitude of primary signals regarding travelling distance

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