LOAD CARRYING CAPACITY OF STRUCTURAL MEMBERS SUBJECTED TO ALKALI-SILICA REACTIONS

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ABSTRACT

The influence of ASR on the shear-, the anchorage- and the punching-shear-strength was investigated in four test series with ASR-damaged specimens. All the specimen were cast with alkaline-susceptible aggregates and subjected to accelerated ASR.

The shear strength of beams and slabs are not reduced even by serious ASR-deterioration.

ASR deterioration reduce the anchorage strength. The relatively few tests indicate a reduction of 20-25%.

INTRODUCTON

During the early 1950's a number of Danish concrete bridges were found to be suffering from alkali-silica reactions (ASR). An investigaton was carried out in order to

- determine and classify the types of alkali reactive aggregates in Denmark,
- study the behaviour of ASR in concrete in relation to the main types of reactive aggregate in Denmark,
- evaluate the importance (risk) of ASR for concrete structures in Denmark.

Several road bridges of concrete suffering from ASR have been repaired. As a routine procedure a petrographic examination of cores drilled from the concrete bridge is always carried out. Along with the inspection of the crack pattern and the disintegration of the concrete in the field, the petrographic examination provides the background for the choice of repair and maintenance.

However, even on the basis of this detailed information, it has been difficult to decide if the bridge needed repair because the decrease in the load carrying capacity was supposed to be critical. This is mainly because the research in ASR in the past focused on the pathological behaviour of ASR rather than to what extent ASR will affect the strength of structural members found in typical road bridges in Denmark.

In order to link the observations in the field the results found in the laboratory and the theory of structural design, the Road Directorate decided to carry out laboratory tests with structural members damaged by ASR in a controlled environment and strictly monitored.

This paper gives the main results of this investigation. For more detailed information and results are referred to (1).

TEST SERIES

The purpose of the tests is to discover a relationship between the extent of concrete deterioration due to ASR and the load carrying capacity of the bridges.In a more specific way the project aims at answering the following questions:

- Is there any correlation between the extent of deterioration and the reduction in the load-carrying capacity?
- Which parameters can characterize this correlation, if any, taking the various structural members and various modes of failure into consideration?
- Is it possible - with these parameters - to establish a limit of deterioration beyond which a critical reduction in the load carrying capacity might be expected?

The project includes four test series:

Series A: **Shear test** on beams without shear reinforcement.
Series C: **Anchorage tests** on beams.
Series D: **Anchorage tests** on pull-out specimens.
Series E: **Punching tests** on slabs.

The geometry, reinforcement and loading for the test specimens are given in Figure 1.

Concrete Proportions, Casting, Curing and Exposure

The concrete mixes for the test series are given in Table 1.

TABLE 1. Concrete mix-design.

Constituents / Series	Aa,Ab,Ac,C,D,E [kg/m^3]	Ad [kg/m^3]
Cement (RPC)	300	300
Water	150	150
Fine aggregate (0-4 mm)	805	805
Coarse aggregate (3-6 mm)(alkali-susceptile)	0	215
Coarse aggregate (8-16 mm)(nonsusceptible)	1150	840

The cement used in the test series are rapid hardening Portlandcement (RPC) with an eqv.-Na_2O of approx. 0.8%. The fine aggregate and coarse aggregate (3-6mm) contain approx. 10% and 55% opaline cherts respectively. The coarse aggregate (8-16mm) is crushed granite. For each beam nine ø100 × 200 mm concrete cylinders were cast from the same mix. In the main series, three 100 × 100 × 600 mm concrete prisms were cast in addition.

In some beams the eqv.-Na_2O was increased by adding NaOH and KOH to the water in a ratio of high alkali cement. The total amount of eqv.-Na_2O is given in Table 2, which also gives the air content. Details are given in (1).

TABLE 2 - Air-Content, Alkali-content and Curing

Series	Beam No	Air content [%]	Eqv.Na_2O [%]	NaCl-submersion Duration [Weeks]	Notes
Aa	A4	10.0	2.0	9	High air content
	A8	10.0	2.0	98	High air content
Ab	A0	4.5	0.8		Reference beam
	A1	5.6	0.8	10	
	A3	2.5	1.0	76	
	A5	5.6	0.8	42	
	A6	2.6	0.8	76	
	A7	2.5	1.0	88	Dried for 42 weeks before testing-
	A9	3.3	0.8	104	Freeze/thawcycles after 88 weeks.
	A10	2.6	0.8	236	
Ac	A11	3.7	0.8		Reference beam
	A12	3.1	0.8	52	Dried for 18 weeks before testing
	A13	4.5	0.8	183	
Ad	A14	0.8	0.8		Reference beam
	A15	0.8	0.8	99	
	A16	1.1	0.8	99	
	A17	1.1	0.8		Stratified shear zones
C	C1	2.6	0.8		
	C2	2.6	0.8	86	
	C3	3.3	0.8	127	
	C4	3.3	0.8	80	
D	Da	1.2	0.8	47	
	Db	1.2	0.8	47	
	Dc	1.2	0.8	47	
	Dd	2.6	0.8	47	
E	E1,E5	1.1	0.8		
	E3,E4	1.4	0.8		
	E2,E6	1.2	0.8	47	
	E7,E8	1.0	0.8	47	
	E9,E10	0.9	0.8	47	

Curing and Exposure, Series A

The beams of series Aa and Ab were stored for approximately 3 weeks at 100% RH and 20°C before submersion in a saturated NaCl-solution at 50°C. The beams of series Ac and Ad were not given any kind of curing before submersion in the NaCl-solution. The unprotected beams were exposed to outdoor conditions for approximately three weeks.

In order to accelerate the deterioration, the beams of series Ac were given a thermal shock. Still in the form the temperature of the beam were raised to 80-90°C in 15 hours. After removing the form the beam was splashed with cold water (10°C) for four hours. After the "curing" period, all beams (except the reference beams) were stored in a saturated NaCl-solution at 50°C, see Figure 2.

Cylinders and prisms cast with the beams were exposed as follows. **Six** cylinders were stored as the beam. **Three** cylinders were stored at 20°C and 100% RH. **One** of the prisms was stored as the beam, **one** at 100% RH, 50°C and **one** was exposed to outdoor conditions.

Curing and Exposure, Series C, D and E

After stripping of forms the test specimens are left unprotected in out-door conditions for approx. 4 weeks. After the curing period all test-specimen (except the reference-specimen) were stored in saturated NaCl at 50°C. All specimens are tested in a wet condition. The reference specimens i.e. C1, one of each of the subseries of series D, E1 and E5 are stored in lab.-conditions. These specimens are submerged in water three to four weeks before testing. The free parts of the bars of the pull- out prisms were epoxy-coated to prevent corrosion.

Evaluation of Damage

Longitudinal and transverse expansions of the beams and longitudinal expansions of the prisms, were measured during the submersion period. The system for the measurement of expansions is described in more detail in (4).

To follow the strain in the bars during the expansion the beams A15 og A16 were supplied with electrical strain gauges on the corner bars of the longitudinal reinforcement.

For the evaluaton of the deterioration a grading scale ranging from 0 to 4 is used. 0 corresponds to no deterioration, and 4 means deterioration to the point where "the safety against failure is dubious or eliminated".

The registration comprises the concrete surface as well as the interior of the concrete. The surfaces are visually registered in number, extent and appearance of gel-deposits, pop-outs and crack system. The interior of the concrete is evaluated on the basis of a structural and micro-structural description of reacting sand particles, crack systems, gel-deposits, etc.

The structural and micro-structural analysis is performed on a 50 mm core, horizontally drilled at right angle to the beam axis. From this core one polished section and generally **two** thin sections are produced, see Figure 3. The compressive strength (and in a few cases the modulus of elasticity) is evaluated from 100 mm cores drilled from the anchorage zone of the beam. Generally **two** cores are drilled vertically and **one** horizontally, see Figure 3.

RESULTS

Expansion

The results of the expansion measurements on the beams are given in Table 3. The table lists the expansions measured just before the end of the NaCl-submersion. For each beam the longitudinal expansions as well as the transverse expansion are given. The results of the strain measurement on the longitudinal reinforcement of beam A15 and A16 due to the expansions are shown in Figure 4.

The final longitudinal expansions of the prisms of series Ab are 7.3-9.4 o/oo for NaCl-stored prisms, 0.8-3.7 o/oo for the prisms stored at 100% RH, 50°C and 0.01-0.04 o/oo for the prisms exposed to outdoor climate. The results of prisms of A10 are given in Figure 4. For more detailed results of the expansion measurements the reader is referred to (1).

TABLE 3 Expansions of Beams and Prisms in o/oo

Series	Beam No.	NaCl-submersion [weeks]	Expansions of beams		Expansions of prisms
			Longitudinal	Transverse	
Aa	A4	9	0.6	1.7	
	A8	98	0.8	13.5	
Ab	A1	10	1.1	6.8	7.3
	A3	76	0.6	18.3	9.7
	A5	42	0.4	5.5	7.5
	A6	76	0.7	3.3	9.4
	A7	88	0.6	8.5	9.1
	A9	104	0.6	7.8	8.2
	A10	236	0.8		9.2
Ac	A12	52	0.6	8.3	
	A13	183	0.5	6.7	
Ad	A15	99			11.1
	A16	99			11.1

Evaluations of Damage

Structural and micro-structural analysis of cores from the beams shows a crack system parallel to the surfaces moving inwards. The beams are thus subdivided into a damaged outer zone and a more or less undamaged inner zone as illustrated in Figure 5.

From the inspection of the beam the following general observations can be made:

- On the beam faces two to four continuous cracks are generally seen. The cracks run parallel to and usually near the edges.
- The crack widths vary from 0.1 - 3.0 mm
- On the topface one contiuous crack is generally seen. The crackwidth is always 3 mm.
- The fine cracks only penetrate the surface layer. The wider cracks go deeper and probably through the beam.
- Om all the faces 10-15 pop-outs per 100 cm2 (diameter : 5-15 mm) are typical. In the bottom of each pop-outs a reacted grain is seen.

- On most of the beams white, threadlike salt precipitations are seen.

The results of the evaluation of the damage degree are given in Table 4.

Shear Tests.

Table 4 gives the results of the evaluation, the main results of the compression tests on cast water-stored cylinders ($f_{c,cyl}$) and drilled cores ($f_{c,core}$) and the failure loads of the beams (V_u). The table also shows the ratios V_u/V_{01} and V_u/V_{02}. V_{01} and V_{02} are the theoretical shear capacities calculated on the basis of ($f_{c,cyl}$) and ($f_{c,core}$) respectively. In the last mentioned case the compressive strength is taken as $f_c = 1.26\ f_{c,core}$. V_{01} thus represents the expected shear capacity of a corresponding undamaged beam, while V_{02} gives the theoretical shear capacity of the actual, damaged beam. The calculation of the theoretical values is based on the theory of plasticity (2) & (3).

TABLE 4. Results of beam shear tests * marks the first failure

Series	Beam No	Degree of damage	$f_{c,cyl}$ [MPa]	$f_{c,core}$ [MPa]	V_u [kN]	V_u/V_{01}	V_u/V_{02}	V_{cr} [kN]	E_{deflec} [kN]
Aa	A4	2	15.7	17.2	N* 49.0 S 51.1	0.82 0.85	0.70 0.73	38.2	1.9 10^4
	A8	1	16.4	20.2	N* 62.8 S 62.8	1.03 1.03	0.83 0.83	62.8	2.4 10^4
Ab	A0		45.4	37.4	N 58.3 S* 58.8	0.58 0.58	0.57 0.57	58.8	2.1 10^4
	A1	1	43.6	37.8	N 116.6 S* 89.2	1.18 0.90	1.12 0.85	65.7	2.0 10^4
	A3	4	58.2	38.2	N* 127.4 S 112.5	1.13 1.09	1.21 1.17	98.0	3.0 10^4
	A5	3	47.1	20.5	N* 98.0 S 111.3	0.95 1.08	1.29 1.46	73.5	
	A6	3	60.1	32.2	N* 107.8 S 102.9	0.95 0.91	1.12 1.07	85.8	3.1 10^4
	A7	2	62.5	45.7	N* 142.1 S 142.1	1.23 1.23	1.27 1.27	58.8	3.2 10^4
	A9	3	55.3	38.5	N* 88.2 S 127.4	0.80 1.16	0.84 1.21	88.2	3.7 10^4
	A10	3	60.7	32.2	N* 132.3 S 142.1	1.18 1.27	1.38 1.48	78.4	3.8 10^4
Ac	A11		43.7	32.0	N 78.9 S* 64.9	0.80 0.65	0.82 0.68	58.8	2.9 10^4
	A12	2	50.4	35.6	N - S* 134.3	1.27	1.33	78.4	2.8 10^4
	A13	3	42.5	30.6	N* 147.9 S -	1.51	1.59	84.2	4.3 10^4
Ad	A14		44.9	28.0	N 73.5 S* 63.7	0.73 0.64	0.83 0.72	58.8	2.8 10^4
	A15	4	47.1	16.2	N 112.7 S* 102.9	1.09 1.00	1.63 1.49	63.7	5.2 10^4
	A16	4	51.7	14.4	N 117.6 S* 112.7	1.10 1.05	1.81 1.73	68.6	3.0 10^4
	A17		52.0	34.6	N S* 38.2	0.36	0.38	29.4	2.2 10^4

Table 4 finally lists the load level of the first shear crack V_{cr} and the modulus of elasticity, E_{deflec}, calculated on basis of the midspan deflection of the beam at an uncracked load level (V=10kN). Typical deflection curves are given in Figure 6. Several beams (A1,A9, A12, A13 and A16) show a jump in the deflection at a load level corressponding to the load of the first shear crack.

Anchorage Tests

Table 6 lists for the beam tests the results of the evaluation of the damage degree, compression test results ($f_{c,cyl}$ and $f_{c,core}$) and the results of the beam tests (V_u). The table also lists the ratios V_u/V_{o1} and V_u/V_{o2}, where V_{o1} and V_{o2} are the theoretical failure loads calculated on the basis of $f_{c,cyl}$ and $f_{c,core}$ respectively.

TABLE 5. Test results of series C

Series	Beam No.	Degree of damage	Concrete strength [MPa] $f_{c,cyl}$	Concrete strength [MPa] $f_{c,core}$	Failure load, V_u [kN]	V_u/V_{o1}	V_u/V_{o2}
C	C1		51.0	39.1	49.0	0.98	1.00
	C2	3	51.0	22.6	35.0	0.70	0.93
	C3	2	46.0	40.2	40.1	0.83	0.80
	C4	1	41.9	44.2	54.9	1.20	1.06

The results of the pull-out tests (P_u) are given in TABLE 6. The table also lists the ratio P_u/P_{o1}, where P_{o1} is the failure load calculated on basis of $f_{c,cyl}$. The compression strength $f_{c,cyl}$ was measured to 38 MPa for series D_a, D_b and D_c and for series D_d to 33.9MPa.

Only the damage degree of D_{a-2} and D_{d-2} are evaluated. The values for these specimens are 3 and 0 respectively.

TABLE 6. Tests results of series D

Series	Specimen No.	Failure load P_u [kN]	$\frac{P_u}{P_{o1}}$	Concrete cover	Transverse reinforcement
Da	Da - 1	118.9	0.97	30	
	Da - 2	90.0	0.73		
	Da - 3	85.0	0.69		
	Da - 4	85.0	0.69		
Db	Db - 1	125.0	1.01	50	
	Db - 2	90.0	0.73		
	Db - 3	100.0	0.81		
	Db - 4	85.0	0.69		
Dc	Dc - 1	90.0	0.73	10	
	Dc - 2	75.0	0.61		
	Dc - 3	70.0	0.57		
	Dc - 4	70.0	0.57		
Dd	Dd - 1	125.0	0.89	30	Ø7 per 75 mm
	Dd - 2	151.6	1.08		
	Dd - 3	145.0	1.03		
	Dd - 4	155.0	1.10		

Punching Tests

Table 7 lists the results of the compression tests ($f_{c,cyl}$ and $f_{c,core}$) and the failure loads (P_u). The table also lists the ratio P_u/P_{o1} and P_u/P_{o2}. P_{o1} and P_{o2} are the theoretical punching strength calculated on the basis of $f_{c,cyl}$ and $f_{c,core}$ respectively. P_{o1} represents the theoretical punching load of the corresponding undamaged slab and P_{o2} represents the theoretical punching load of the actual damaged slab.The calculation of the theoretical values is based on the theory of plasticity (3). Table 7 also lists the deflection at the center of the slab corresponding to P=200kN. The damage degree of the slabs are estimated to 3 except slab E9, which was estimated to 2.

TABLE 7. Results of the Punching Tests

Series	Slab No.	Compressive strength [MPa]		Punching failure load			Deflection (P = 200 kN) [mm]
		$f_{c,cyl}$	$f_{c,core}$	P_u [kN]	P_u/P_{o1}	P_u/P_{o2}	
E	E1	47.3	41.7	240	0.91	0.86	1.8
	E5	47.3	36.6	249	0.94	0.95	1.9
	E3	45.0		73	0.28		
	E4	45.0		200	0.78		7.6
	E2	45.6	24.0	283	1.09	1.33	1.8
	E6	45.6	20.1	246	0.95	1.27	2.9
	E7	53.2	21.0	262	0.93	1.32	3.5
	E8	53.2	16.8	241	0.85	1.36	2.3
	E9	50.6	22.0	262	0.96	1.29	2.7
	E10	50.6	17.1	208	0.77	1.17	3.1

CONCLUSIONS

Expansions and Evaluation of Damage

From the registrations of expansions and damages degrees the following observations can be noticed:

- The scatter of the expansion measurements for the beams are rather high.
- The longitudinal expansions are an order of magnitude lower than the transverse expansions.
- The expansions of the beams reach an constant level within 8-15 weeks.
- The expansions of the NaCl-stored prisms are in the same order of magnitude as the transverse expansions of the beams.
- The expansions of the prisms stored in 100% RH at 50°C show expansions of an order of magnitude lower than the NaCl-stored. The expansions of the outdoor stored prisms are almost zero.
- The agreement between the degree of damage evaluated on the basis of visual inspection, structural analysis of polished sections and microstrutural analysis of thin-sections are good.

Test on Cylinders and Cores

From the results of the compressive tests on cylinders and cores the following points can be noticed:

- The strength of NaCl-stored cylinders is generally below 1/3 of the strength of the corresponding water-cured cylinders.
- The strength of the drilled cores ($f_{c,core}$) is always less than the strength of the corresponding water-cured cylinders ($f_{c,cyl}$). For the vertically drilled cores the ratio $f_{c,core}/f_{c,cyl}$ is in the interval 0,28-0,87, and for the horizontally drilled cores in the interval 0,33-0,67.
- In spite of a considerable scatter, a clear tendency of decreasing strength of drilled cores with increasing degree of damage is seen.

Shear Tests, Punching Tests and Anchorage Test

From the shear tests, punching tests and anchorage tests the following main conclusions are drawn.

- The shear strength of beams without shear reinforcement and the punching shear strength of slabs are not reduced by even serious ASR-deterioration.
- Estimates of the shear capacity of ASR-damaged beams and the punching shear capacity of ASR-damaged slabs on the basis of the compressive strength of drilled cores (f_c = 1.26 $f_{c,core}$) - on average - underestimate the failure loads by approx. 20%.
- The ASR-damaged beams and slabs show more ductility than the corresponding undamaged specimens and the ASR-damaged specimens show more extensive cracking before failure.
- ASR deterioration reduce the anchorage strength. The relatively few tests indicate a reduction of 20-30%.

The search for a theoretical explanation of the increase of the shear strength is outside the scope at this paper. However, two hypotheses are mentioned:

- The extensive fine cracking because of ASR leads to a higher ductility and thereby to the possibility of a more efficient stress distribution (arch-action) in the shear zone.
- The shear capacity is increased because the expansions lead to a prestressing of the reinforcement.

These hypotheses are to be investigated in connection with a ongoing research project. This project includes an analysis of the results from a fracture-mechanical point of view.

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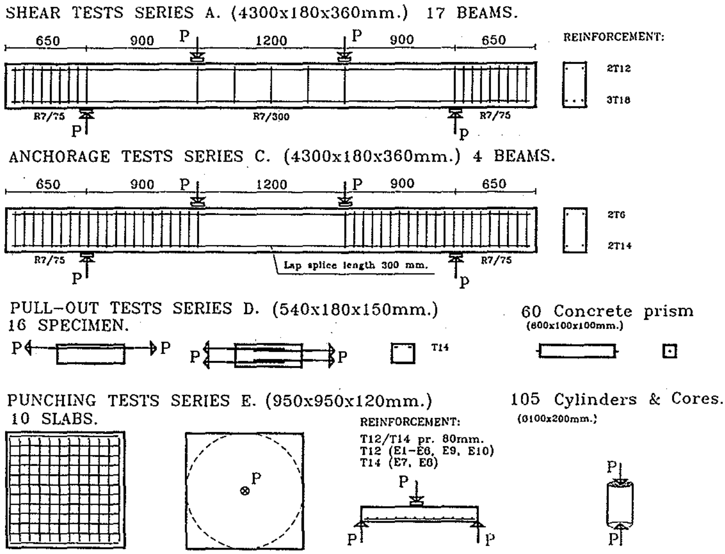


Figure 1 Test specimen, geometry, reinforcement, load and the principle of execution of tests are shown. All dimensions are in mm.

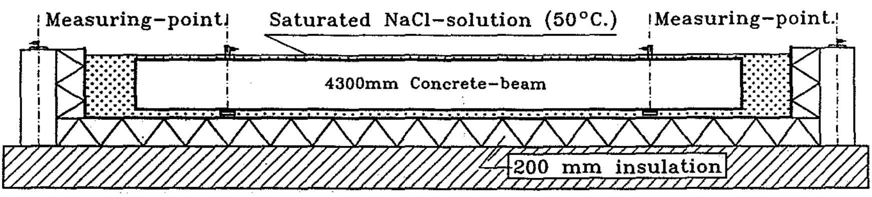


Figure 2 Storage tank (5000x1000x500 mm) for concrete specimen. Measuring points for longitudinal and transverse expansions are shown.

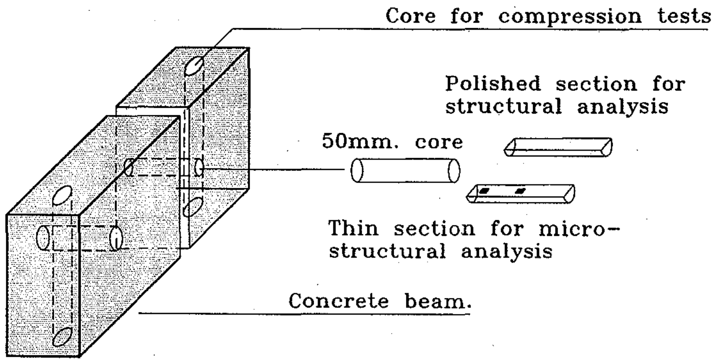
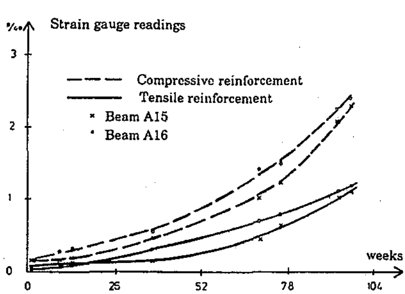


Figure 3 Drilling of cores for compression tests and cores for structural and micro-structural analysis.



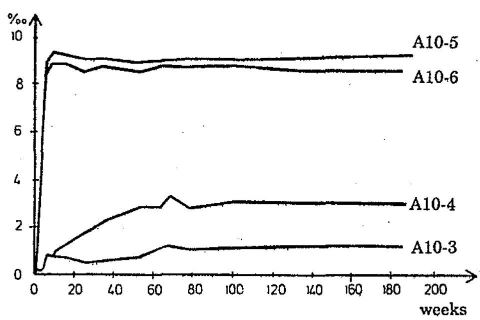


Figure 4 (left) Graph of the development of the strain in the longitudinal bars of beam A15 and A16 during the expansion.
Figure 4 (right) Longitudenal expansion of prisms of beam A10.

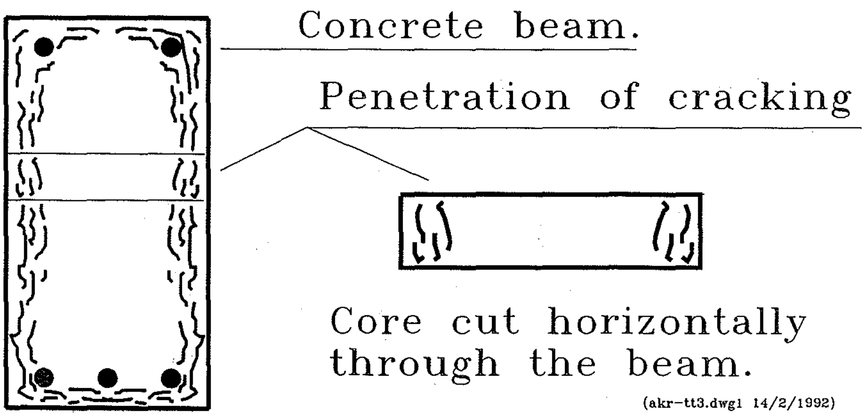


Figure 5 The crack system in beams moving inwards with increasing storage time in NaCl-solution.

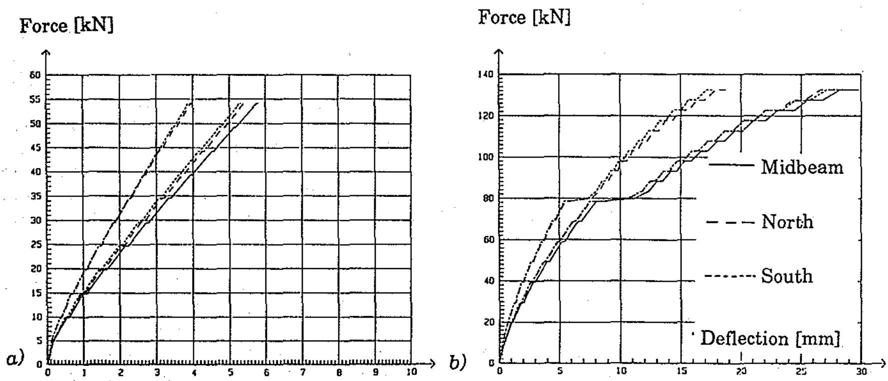


Figure 6 Deflection curves of beams. a) Reference beam (A0), b) Damaged beam (A12). Notice the different axis.