Chloride Corrosion in Danish Road-Bridge Columns

by Carsten F. Henriksen and E. Stoltzner

There are approximately 2000 bridges on the Danish highways, approximately 475 of them having columns along underpasses. In the past 10 years the Danish Road Directorate has found an increasing number of cases of chloride corrosion damage to the concrete bridges of the Danish highway network. The damage is found primarily on the bridge columns.

The extent of damage has been recorded during the Road Directorate's regular general inspections. In 1988 the Road Directorate carried out an overall evaluation of the number of bridges expected to have corrosion damage to the reinforcement. According to the evaluation, 102 bridges were by 1988 expected to have corrosion damage, corresponding to 22 percent of all bridges with columns.

The most interesting fact was that the frequency of damage was much higher in the Greater Copenhagen Area than in the rest of the country. In the Greater Copenhagen Area 50 percent of the bridges with columns are expected to have corrosion damage. In the counties outside the Greater Copenhagen Area the frequency of damage is 11 to 19 percent. In the period 1988 to 1990, the Road Directorate carried out around 90 special inspections of the bridges showing signs of corrosion damage at the general inspection. Most of the special inspections were carried out on bridges in the Greater Copenhagen Area. The special inspections indicated corrosion as the primary cause of damage. The most severe damage was found on bridges in the Greater Copenhagen Area.

As the bridges in all the areas mentioned are about the same age, the result was somewhat surprising.

Another important point is whether the corrosion damage is discovered at the earliest possible time at the general inspections carried out on the bridges. Is it for example possible for chloride corrosion to become critical without visible signs of damage to the concrete surface. If so, there is a risk of sudden collapse of the column.

In collaboration with Rambøll, Hannemann & Højlund A/S, the Danish Road Directorate started an investigation to evaluate if among the visibly undamaged columns there are columns with severe, concealed corrosion damage. Other objectives were to:

- Systematize the practical experience gained through special inspections of bridge columns with chloride corrosion.
- Evaluate the parameters expected to have an impact on the chloride load.
- Evaluate the usability of the usual models for chloride penetration, including the quantity of the critical chloride content initiating corrosion of the reinforcement.
- Evaluate the remaining service life of the columns,
- Evaluate possible repair strategies.

The investigation is described in the report "Kloridbetinget korrosion. Undersøgelse af kloridbelastning og korrosion på brosøjler. 1991 Vejdirektoratet, Broområdet" ("Chloride Corrosion. Investigation of Chloride Load and Corrosion on Bridge Columns. 1991, The Danish Road Directorate").

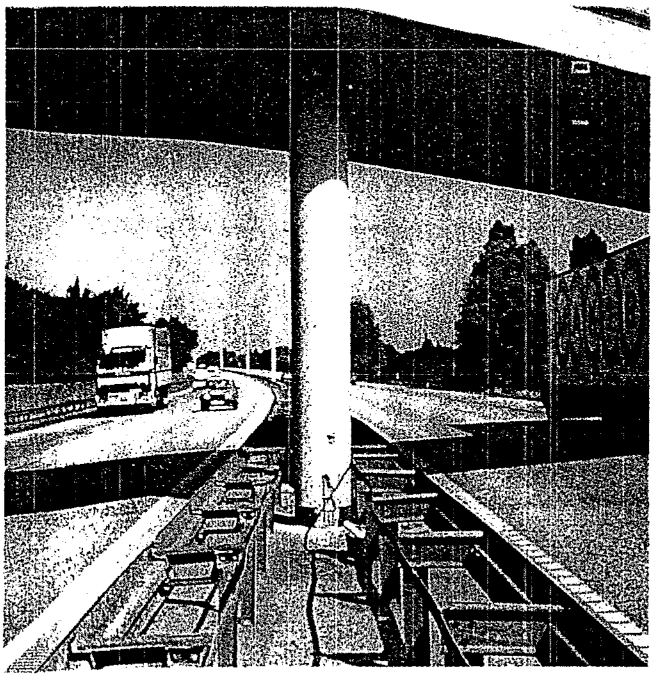
Following are the most important results and conclusions of the report.

Extent of investigation

The investigation included inspection of 20 bridges with visibly undamaged columns and review of the 90 special inspection reports already carried out. The 20 bridges were chosen at random, but in such a way that they were located in various places in the country on highway sections with various traffic loads and with an age composition as for the entire bridge stock (Table 1).

The bridges were investigated as follows:

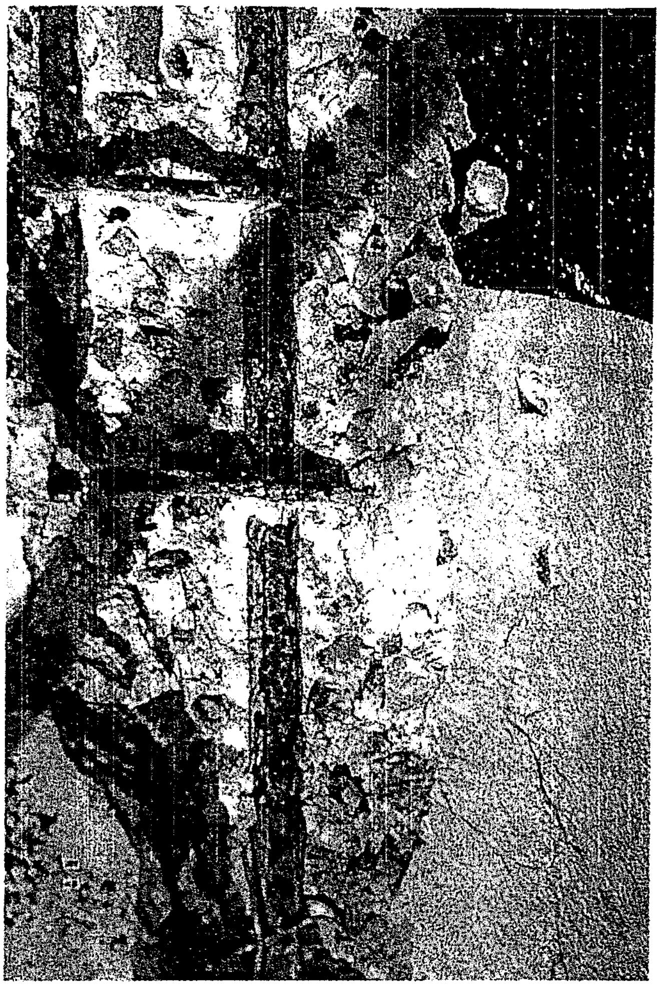
- Inspection of all columns.
- Chloride measuring on all columns.
- Electrochemical potential mapping on all columns.



Typical column placement.

Table 1 — Age distribution of column bridges outside Greater Copenhagen

Erection year	Percent of bridges	Bridges examined	
		Percentage	Percent of 20
1940—1955	~ 3	2	10%
1955—1965	~ 14	2	10%
1965—1970	~ 27	6	30%
1970—1975	~ 28	7	35%
1975—1980	~ 11	2	10%
1980—1985	~ 14	1	5%
1985—1990	~ 3	0	0%



Typical corrosion damage.

- Sample cutting to the reinforcement.
- Sample testing of the concrete quality through core sampling.

Overall evaluation

The main conclusions of the total investigation are:

- The concrete in all investigated columns is chloride-laden. Today, the chloride content for the visibly undamaged columns is so high that it must be expected that, within the next 10 years, more than 30 percent will reach a chloride level at the reinforcement that can initiate corrosion of the reinforcement.
- The primary cause of the problem results from inappropriate dewatering. Most columns are placed in the low points of the transverse profile of the road.
- Poor concrete quality or poor cover of the reinforcement are contributory causes of earlier development of the corrosion damage than expected (within 25 years after the construction).
- Chloride penetration is the parameter that may cause the worst damage in the form of corrosion of the reinforcement. Only a few cases of severe damage resulting from alkali-aggregate reactions and/or freeze-thaw have been found, and then only in combination with initial defects (shrinkage and thermocracks). However, both alkali-aggregate reactions and freeze-thaw actions are estimated to influence the development of damage. It is estimated that the alkali-aggregate reactions increase the porosity of the cover and thus allow for a quicker chloride penetration. It is estimated that freeze-thaw will accelerate the damage to concrete and reinforcement, once the corrosion has started. The interaction between the individual damage mechanisms is, however, unclear.
- In only 2 to 3 cases the Road Directorate's special inspection indicates corrosion to an extent that could involve a safety risk.
- As a principal rule, chloride corrosion on columns will cause visible damage to the surface before the damage becomes critical.
- Correctly cast columns — low water/cement ratio, adequate cover, located off the road and sufficiently vibrated — will limit the chloride penetration radically and postpone the time of development of corrosion. The investigation shows that most of the visibly undamaged columns fulfil these conditions and reach a service life of more than 50 years.
- The corrosion damage occurs at ground level, especially on surfaces facing the traffic.
- Investigations show that electrochemical potential mapping can be used to describe the corrosion condi-

Table 2 — Details of bridges and calculated values for C_S and D

Bridge	Distance to lane, m		Traffic intensity x 1000	Quantity of salt consumed		C_s, percent		D, mm²/yr	
	Side	Middle		Total/year, kg/m²	Average, g/m²	Ground level	+ 1 m	Ground level	+ 1 m
70-0146	>4	2.5	21	1.0	13	0.08	0.03	19	18
70-0182	>4	3.5	22	1.0	13	0.07	—	110	—
70-0186		3.5	11	1.0	13	0.13	0.04	36	36
70-0036	3.5	2.5	9	1.1	14	0.07	0.08 to 0.10	21 to 79	2 to 48
70-0047	4.5	2.5	11	1.1	14	0.06	0.03	16	16
60-0017	3.5		14	1.1	14	0.05	0.05	5	5
40-0004	2.5	0.5	9	0.9	19	0.06 to 0.25	0.11	11	8
40-0040	3.5		15	0.9	19	0.07	0.04	7	7
40-0054	>4	2.5	20	0.9	19	0.06	0.06	24	24
40-0070	>4	3.5	20	0.9	19	0.04 to 0.16	0.04 to 0.08	19 to 61	25 to 49
30-0119	2.5	1.5	5	0.6	16	0.09	0.05	11	11
30-0132	2.5	1.5	5	0.6	16	0.09	0.04	23	11
30-0016	3.5	2.5	17	0.6	16	0.07	0.07	117	76
30-0023	3.5	>4	17	0.6	16	0.05	0.05	135	135
30-0026	3.5	>4	17	0.6	16	0.02	0.02	40	40
10-0085	>4	2.5	32	1.1	17	0.08 to 0.13	0.17	29 to 41	28
10-0050	>4	3.5	46	1.1	17	0.24	0.14	51	12
10-0031	>4	2.5	46	1.1	17	0.10 to 0.12	0.17	16 to 30	12
20-0085	>4	2.5	10	0.8	20	0.08	0.05	87	63
20-0020	>4	>4	15	1.1	19	0.05	0.05	3	3
Average						0.08 - 0.10	0.07	39 - 46	28 - 32

tion, but the measurements should be calibrated by sample cutting to the reinforcement.

- Fick's second rule contains a suitable method — though uncertain — for prognostication of the future chloride penetration and thus for evaluation of the remaining service life. Calculations of the remaining service life should always be followed up by a risk analysis.
- The investigation shows that 0.05 percent chloride of dry concrete weight is the minimum for initiation of corrosion of the reinforcement.

The report concludes that the economically optimal strategy of management is a strategy aiming at repair as soon as possible after discovery of visible damage at the general inspections. As an overall conclusion none of the corrosion damage is "hidden" or surprising. The damage results from errors in execution, in particular, but also from errors in design.

Of course, it is easy to be wise after the event, but had the requirements known today for concrete quality, reinforcement layout, cover and dewatering been known 20 to 25 years ago, the corrosion damage to the reinforcement would not have reached the current extent.

The following sections stress a few conclusions from the report so as to focus on some of the concrete world's problems and uncertainties.

Calculation of service life

Theoretical know-how level

The present know-how level about initiation and development of damage to concrete structures is both high and low. It is high because of the know-how about the individual parameters determining the initiation and the development of damage. It is low because we have not yet succeeded in using this know-how as a basis for calculation of the service life, which is the main reason for carrying out investigations.

In the report, chloride-initiated corrosion is expected to be the damage parameter that leads to the worst damage to the yet undamaged columns. Chloride penetration can be described by Fick's second rule:

$$C_x = C_s - (C_s - C_i)\,\mathrm{erf}\,(X/2\sqrt{t \cdot D})$$

where:

C_x = Chloride content at depth x measured in percent of dry concrete weight.

C_s = Maximum chloride content in the concrete surface measured in percent of dry concrete weight.

C_i = Initial chloride content of the concrete measured in percent of dry concrete weight.

erf = Error function (the function is tabulated in mathematical reference books).

Table 3 — Future distribution of damage cases resulting from corrosion

Time interval	Expected bridges with initiated corrosion*		Expected bridges with initiated corrosion	
	Ground level, C_{cr} = 0.05 percent	Ground level, C_{cr} = 0.06 percent	At + 1 m, C_{cr} = 0.05 percent	At + 1 m, C_{cr} = 0.06 percent
1990—1995	97	32	48	16
1995—2000	0	32	0	0
2000—2005	48	0	16	0
2005—2010	0	16	0	16
2010—2020	16	16	0	16
2020—2050	32	16	0	16
2050—	128	209	257	257

*It is expected that corrosion will have created a need for repair of columns and cover 10 to 15 years later than the time stated. The need for thorough repairs, including main reinforcement, is expected after 20 to 25 years.

Table 4 — Economic calculation for C_{cr} = 0.05 percent for maintenance and repair strategies

Year	Strategy					
	I	II	III	IV	V	VI
1990	6.1			4.4	4.4	3.2
1995						
2000	6.1			1.8	1.8	
2005	15.5	15.5		15.5		15.5
2010	4.3			1.8	1.8	
2015		7.7	31.0		31.0	2.6
2020	4.3			1.8	1.8	
2025		1.3	15.4			
2030	4.3	1.3		1.8	1.8	
2035		1.7	2.6			
2040	4.3		2.6	1.8	1.8	
2045		1.7	3.4			
2050	4.3			4.3	4.3	
Present value*	16.9	7.4	7.5	11.8	11.8	9.3

*Prices in millions of Danish kroners at discount rate of 7 percent.

x = Penetration depth of C_x (in mm)
t = Concrete age (in years)
D = Diffusion coefficient (in mm^2/year)

By means of the formula the parameters C_s and D can be calculated from a measured chloride profile. On this basis it can be calculated when the critical chloride content reaches the reinforcement. The formula applies only to diffusion and not in cases where the penetration is by capillary rise. However, a chloride profile caused by capillary rise has the same shape as a chloride profile caused by diffusion. As the cause of the profile can seldom be determined, the use of the formula for calculation of service life involves great uncertainty. The formula is, however, presently the only possibility of calculating the service life.

In principle, the use of uncertain or approximate know-how is not wrong as long as the technical and economic consequences are evaluated at the same time.

Calculation of service life

Based on the measured chloride profiles, C_s and D are calculated for the investigated bridges (Table 2). It appears that the average of C_s is 0.08 to 0.10 percent of dry concrete weight at ground level. The average of the diffusion coefficient is 44 mm^2/year, but varies much. This indicates varying concrete qualities from bridge to bridge.

From these data forecasts of the service life of 321 visibly undamaged bridges have been made, depending upon the size of the critical chloride content (Table 3). As can be expected, it appears that the size of the chloride content is of great importance to the distribution of the future cases of damage. It also appears that the conditions at ground level determine when the column will develop corrosion damage.

Repair philosophy

There are many ways to repair columns with chloride corrosion damage. Which method to choose depends upon the total costs involved in a specific strategy over a given period — in this case up to year 2050.

In the report the following strategies are calculated from costs of contracts:

Strategy I: Surface treatment of all columns within the near future.

Strategy II: Cover repair after the first discovery of damage.

Strategy III: Thorough repair after development of damage but before the critical point.

Strategy IV: Preliminary investigation of bridge stock and repair according to Strategies I and II.

Strategy V: Preliminary investigation of bridge stock and repair according to Strategies I and III.

Strategy VI: Construction of berm around column roots in the near future and repair according to Strategy II.

Strategies I, II and III are chosen because they are currently the cheapest solutions within the three main strategies of preventive maintenance, cover repair and thorough repair. Table 4 shows the total costs of the six strategies, expressed by present value. Strategies II and III are the cheapest solutions. It appears that strategies involving preventive maintenance or previous investigations are uneconomic given the expected volume of damage and the present price level.

The optimum solution is to await the first visible damage before repair. This conclusion is surprising and contrary to the opinion of the last 10 years — viz. that concrete shall be maintained. The conclusion of the report should not be considered as a conclusion valid for all structures. From a technical aspect, maintenance is still — as a starting point — to be regarded as recommendable.

However, the conclusion is that special attention should be given to uncritical use of the maintenance idea — it can be too dearly bought. Normally, this will be the case for structures of such good quality or for structures exposed to such limited environmental impact that the initiation of damage is very slow. Or in cases of damage at hand so that — with the current know-how — it cannot be guaranteed that preventive maintenance will succeed.

This is the situation for the Danish bridge columns. Hence the surprising conclusion that it does not pay to start maintenance at the present moment. However, it is mentioned that the costs of the maintenance strategy — construction of a berm — will be close to the chosen repair strategy. It is also to be expected that methods of preventive maintenance (surface treatment, cathodic protection etc.) will be further developed in the future, so the meth-

Table 5 — Incidence of visible corrosion damage to reinforcement at various chloride contents*

	Chloride content at reinforcement at ground level, percent						
	≤0.04	0.05	0.06	0.07	0.08	0.09	0.10
Number of corrosion cases†	0% (21)	40% (8)	100% (2)	33% (3)	67% (3)	0% (0)	92% (11)

*Includes chloride measurements on the 20 undamaged bridges.
†Figures in parentheses indicate the number of cuttings in the specific period.

Table 6 —Incidence of visible corrosion damage to reinforcement at various potential values*

	Potential at ground level, VS Ag/AgCl, mV			
	> → -100	-100 → -200	-200 → -300	< -300
Number of corrosion cases†	0% (16)	14% (7)	10% (10)	82% (17)

*Includes chloride measurements on the 20 undamaged bridges.
†Figures in parentheses indicate the number of cuttings in the specific period.

Table 7 — *D* values and time from construction to corrosion for visible damaged and undamaged columns

Calculated values for *D*, mm^2/yr	Number of bridges, percent		Time to start of corrosion, years*
	Damaged columns	Undamaged columns	
0 to 10	10	15	100
10 to 20	19	20	40 to 100
25 to 50	28	30	20 to 40
50 to 100	28	20	10 to 20
100 to 150	5	15	7 to 10
150 to 200	5	0	5 to 7
200	5	0	5

*Calculations made with $C_s = 0.1$ percent and $C_{cr} = 0.05$ percent of dry concrete weight.

ods may prove profitable compared to the repair strategies. Thus it will under all circumstances be advantageous in this situation to hold back maintenance.

The use of preventive maintenance should always be evaluated carefully —both technically and economically.

Uncertainty of service life calculations

As mentioned earlier, the calculations of service life are uncertain. The uncertain items are:

- The size of the critical chloride content, including the importance of part of the chloride binding in the cement.
- The measured and calculated values of C_s and *D*.
- The penetration mechanism.
- The deterioration rate.
- The importance of porous aggregate in the concrete.

The investigation has shown that the discovery and measurement of a representative chloride profile is very uncertain, and the penetration mechanism has a large influence. This makes the calculation of C_s and *D* values very uncertain — especially on structures with a moderate (0.1 percent) chloride content in the surface and consequently a long remaining service life.

Another important uncertainty is the future chloride load. In general, the most certain prognoses lie within a limited service life horizon (maximum 25 to 50 years). The uncertainty involved in an overestimate of the remaining service life is in this case estimated at 4 to 13 years. The uncertainty of an underestimate of the remaining service life can be much larger. But this situation is not critical for the management of the structures.

Also the possible content of porous aggregate in the concrete and its importance to the density of the concrete to chloride penetration is uncertain. The porous aggregate will react and lead to microcracks in the concrete (this also applies to concrete with the usually accepted content of porous aggregate of maximum 2 percent). This may lead to an increased porosity of the concrete, thereby reducing the time before corrosion begins.

The effect of these uncertainties concerning the choice of repair strategy is limited. Irrespective of the repairs occurring sooner or later than expected, the choice of strategy will be changed only if the extent of damage is much greater or more developed than expected. But the economic planning will be affected when the need for repair is not as expected — in particular when the damage occurs sooner or to a greater extent than expected.

In the specific case, the economic uncertainty is estimated to be a factor of 2.

Therefore, the final choice of repair strategy should be evaluated on the basis of both the expected costs of the specific strategy and the economic risk involved.

Critical chloride content

Critical chloride content is uncertain and difficult to define. Each structure has its own limit. For Danish bridge columns at ground level, the lower critical limit seems to be around 0.05 percent of dry concrete weight. It also appears from Table 5 that at much higher chloride content (0.1 percent) a few cases did not show ongoing corrosion.

Electrochemical potential mapping

The only method of non-destructive evaluation of corrosion is electrochemical potential mapping. The mapping values depend on a series of parameters connected to the local conditions of each structure (e.g. oxygen supply, moisture content). It is not possible to establish general criteria for the relation between the measured electrochemical potential mapping value and the extent of corrosion on the reinforcement. Therefore, electrochemical potential mapping should always be supplemented by cutting to the reinforcement.

The investigation has shown that the values in Table 6 may be used as a starting point for the evaluation and the choice of cutting areas on columns at ground level.

Evaluation of the cause of increased intensity of damage in the greater copenhagen area

As the average age of the bridges in the Greater Copenhagen Area and the rest of the country is more or less the same, difference in age cannot account for the difference in damage frequency. The report points out that increased intensity of damage depends on one or more of the causes mentioned below:

- In the Greater Copenhagen Area, 30 percent more deicing salt is used on the roads than the average in the rest of the country.
- Differences in the size of the cover. The cover is too small (20 to 30 mm) on the columns with visible damage.
- Higher traffic intensity.
- Shorter column distances to the traffic lane.
- Differences in geometry and construction of reinforcement.

Primarily, the columns in the Greater Copenhagen Area are round and slim with a small diameter. The distances between the reinforcement bars at ground level where the reinforcement is often lapped will be short with consequent casting and vibration technical problems. This means that the cover may become more porous.

The columns in the rest of the country have large, quadrangular cross sections with better possibilities of casting and vibration. Moreover, the control of the reinforcement net and the size of the cover is easier in a large timbering than in the steel spirals normally used for casting of the round columns.

But the concrete quality is hardly the primary cause of the difference. Based on the measured *D* values and thin sections the basic quality of the concrete has been the same for damaged and undamaged columns (Table 7). The large variation in *D* values indicate, however, that the quality obtained on the bridges varies much — despite an apparently similar basis. Therefore, the concrete quality actually obtained is as important for the service life of a column as for example the depth of cover.

Design and execution of bridge columns in future

On the basis of the investigations carried out on 20 bridges with undamaged columns and special inspections of bridges with damaged columns, the following obvious measures shall form the basis of design and execution of bridge columns in the future:

- The cover of the reinforcement shall be at least 30 to 40 mm.
- The water-cement ratio of the concrete shall be 0.40 as a maximum, and fulfil the requirements for maximum content of porous aggregate and chloride.
- The columns shall not be situated at low points or shall be protected at the column base, e.g. with a berm, especially in areas with heavy traffic, or if the columns are situated close to the traffic lane.
- Appropriate reinforcement at ground level. The reinforcement shall be placed with sufficient spacing, irrespective of lapping. The columns shall not be too slim.
- The columns shall not be situated too close to the traffic lane, especially in areas with heavy traffic.
- Correct vibration of the concrete.

Preventive measures such as surface treatment or cathodic protection of new, correctly executed columns are normally unnecessary and expensive if the above measures are carried out. However, the requirements for future bridge columns and the concrete contained in these columns should be based on a clearly formulated service life criterion verified by a calculation of service life. It should be recognized that today's know-how of methods for calculation of service life for chloride loaded structures is uncertain. Also the know-how of the important parameters in each calculation of service life — critical chloride content, size of outer environmental impact and the density of the cast concrete — is limited.

The report shows some sizes for all three parameters that may be used as guidelines until the necessary development is implemented to improve our decision basis — for the benefit of the individual engineer and society in general.

Selected for reader interest by the editors.

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