CREVICE CORROSION IN BOLTED LAP JOINTS MADE OF WEATHERING STEELS

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At bolted joints of certain design exposed to corrosive atmospheric environment, significant defects were found in the crevices which cause even deformations of the joints. These phenomena were quantified after dismantling and pickling. Recommendations were formulated to minimize these corrosion effects and also possibilities were considered of increasing the lifetime of structures already affected by crevice corrosion. Proposals for saving the crevice corrosion process consist from cleaning the open part of the crevice, application of polymeric cement (paste) and paint system over the crevice and surrounding area. Eleven different saving systems were tested on structural models by long-term cyclic accelerated laboratory tests and on atmospheric test site with higher corrosivity. Field inspections and testing consisted from two parts:

- periodical (1992, 2002) inspection of bolted masts exposed in aggressive North Bohemia region,
- field inspections on 20 masts of application of different saving systems in localities with differentiated corrosivity.

Weathering steel, transmission tower, crevice corrosion, recovery protective system, laboratory and field tests

Introduction

For certain types of steel structures the application of weathering steels is especially suitable. These are electrical transmission towers, masts, bridges and other structures used in outdoor atmosphere, where brown color is appreciated and low maintenance is necessary.

CEPS, Ltd. – Czech transmission system operator – maintains 14.000 steel structures on overhead lines and 400 fields of switchyards at voltage levels 400, 220 and 110 kV. The first steel structures (constructed in 50-s and 60-s of last century) were made of bare steel that was painted. Shortly after the year 1970 the material was changed to weathering steel Atmofix 52A (max. 0,12 % C; 0,30 - 0,80 % Mn; 0,25 - 0,70 % Si; 0,07 - 0,15 % P; max. 0,04 % S; 0,50 - 1,20 % Cr; 0,30 - 0,60 % Ni; 0,30 - 0,55 % Cu; min. 0,01 % Al) in former Czechoslovakia. There were installed about 4.000 steel structures on overhead lines and 130 fields at switchyards until 1990 on Czech transmission system.

Proposals for the use of weathering steels for various types of steel structures are based mainly on the results of field corrosion tests in which significantly higher corrosion resistance of weathering steels has been proved compared to plain carbon structural steel. The corrosion rate of free surfaces cannot be fully transferred to expected corrosion rate on surfaces of structural elements (1, 2). Significant defects which may even cause deformation of joints were found in crevices in bolted joints of certain design exposed to more corrosive environment (Figure 1) (3, 4, 5).

The worse corrosion condition in bolted joints are characterized by accumulation of water during condensation and rain periods. Water then penetrates into the joint together with corrosive components of the atmosphere. Drying is hindered as well as elution of corrosive rust components so that the periodic scaling of the upper rust layer does not take place.

Figure 1 - Typical crevice defect

SVUOM has been cooperating for a long period with CEZ (Czech Energetic Plants) and CEPS (Czech transmission system operator) on solving the problem of crevice corrosion on screw joints of electric transmission towers made of Atmofix weathering steel. Research and expertise of SVUOM involve:

- repeated inspections and evaluations of corrosion manifestations on outdoor tower crevices over the period of approx. 25 years,
- detailed laboratory evaluation of corrosion effects in crevices and their surrounding on samples taken from steel constructions,
- consultancy and opposition to projects for removing crevice corrosion effects on towers,
- systematic accelerated cyclic laboratory tests of coating and protective systems on models with a defined crevice,
- repeated field checks of protective systems on towers,
- station tests of effectiveness of protective systems on models with a crevice at the Atmospheric Corrosion Station of SVUOM in Kopisty.

1. Long-term evaluation of corrosion effects on transmission towers

Electrical transmission towers were the basic and most extensive application of weathering steels in various regions and also in specific microclimates. The extent is evident from the introduction of the paper. Therefore this area of application has been researched most thoroughly; special purpose short-term corrosion tests were carried out.

Corrosion attack on Atmofix 52A power transmission towers has been systematically evaluated for a long period with respect to:

- corrosivity of the location or area,
- microclimatic effects of the nearby surroundings,
- space orientation of the tower element above base height,
- corrosion of joining material,

- specific corrosion phenomenon, effects at important structural elements.

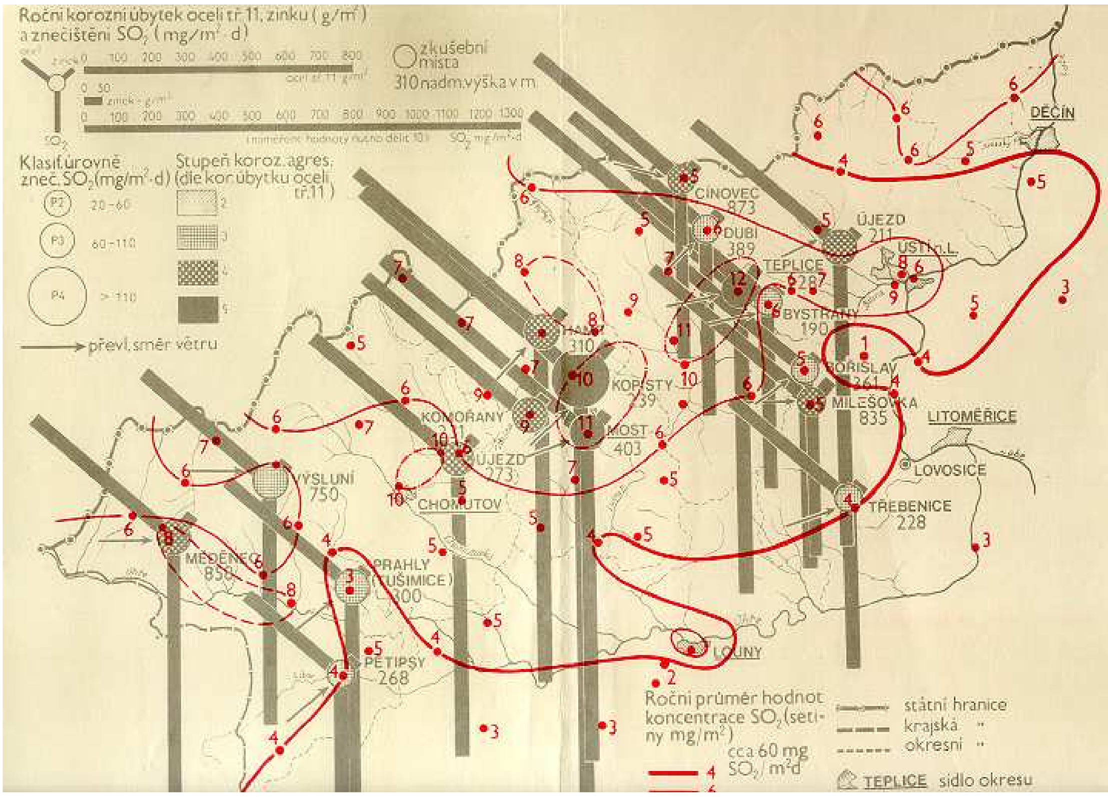
Corrosion behavior has been inspected repeatedly, most extensive checks being carried out between 1992 and 2000. While in 1976 there was no occurrence of crevice corrosion, in 1992 it was a problem which was subject to a broad research which was repeated after ten years with focus on the area of Northern Bohemia which was most effected by atmospheric corrosion. The same towers as before were evaluated. The aim was also to evaluate any possible positive impact of decreasing corrosivity on development of corrosion manifestations.

1.1. Pollution and corrosivity trends in Northern Bohemia

SVUOM has been observing the corrosivity development in Northern-Bohemian industrial region (NB) in a long term, detailed investigations are carried out at Atmospheric Corrosion Station of SVUOM in Kopisty. The highest corrosivity levels were reached in the 70's, i.e. the period of initial exposure of electrical transmission towers made of Atmofix weathering steel. Corrosivity spread in the period of building switching stations and transmission network (1972 – 1980) is demonstrated at a cartogram (Figure 2).

Long-term development of pollution levels and values of yearly corrosion loss of carbon steel for Kopisty station and Prague (for comparison) are presented in Table I. It is evident from the presented results that corrosivity decrease in the area was dramatic; however, the corrosion behavior of towers remains influenced by the initial adverse period.

Figure 2 - Corrosivity in North Bohemia region in 1978



Atmospheric tests carried out by SVUOM (Table I) show that there was a significant decrease of SO_2 concentration and yearly corrosion loss of carbon steel in the Czech Republic between 1990 and 1993. Reasons for the change were desulphurization of thermal power plants, decreased pollution levels in neighboring countries (Germany, Poland), change of main fuel types and restructuralization of industry.

Table I – Results of one-year atmospheric corrosion tests at SVUOM test stations

Year	1964	1970	1973	1978	1984	1987	1989	1993	1995	1997	2001
Prague Station											
Concentration of SO_2 ($\mu g/m^3$)	100	90	106	95	98	98	38	49	28	19	10
Corrosion loss of steel (g/m^2a)	396	264	431	520	387	490	418	271	241	232	134
Kopisty Station											
Concentration of SO_2 ($\mu g/m^3$)	-	100	110	153	111	98	79	59	45	36	17
Corrosion loss of steel (g/m^2a)	-	-	-	879	841	691	661	350	352	293	217

1.2. Corrosion tests on selected electrical transmission towers

This type of steel construction represents a typical product for which use of weathering steel is suitable if corrosivity of the atmosphere is not equal to strongly polluted industrial environment. The requirement for so called „outdoor“ exposure is met in maximum extent. Adverse corrosion effects may result from construction design.

A comparative testing program on weathering and carbon steel was set up on three selected towers of the transmission line Vyskov - Neznasov in 1973 (Table II). In 1976 an appearance evaluation was carried out and samples of steel were taken. The result of appearance evaluation was that the course of rust creation is favorable and the condition corresponds with approximately 3,5-year long exposure of steel surfaces exposed with scales. Corrosion appearance differences at construction joints did not signalize any adverse local corrosion manifestations. Similar condition was found also in 1976.

Taken samples were tested for corrosion loss and spread of sulfate nests. Appearance evaluation of taken samples suggested favorable course of corrosion while patina was not completely formed. However, there were significant differences between weathering and carbon steel.

While corrosion tests started in 1973 were carried out on small vertical frames placed directly on towers, further comparative tests of corrosion behavior of Atmofix 52A weathering steel and comparative steel which started in 1974 by the demand of the transmission network operator were carried out on small frames meeting requirements for standardized atmospheric corrosion tests (Table III). Typical locations involved in the above cartogram (Figure 2) were selected for the tests.

Table II – Corrosion loss of steel samples on observed towers (started in 1973)

Location	Exposure (days)	Type of atmosphere	Corrosion loss	
			carbon steel	Atmofix 52A
Brvany	1022	Medium pollution	768,8	583,5
Brozany	1022	Rural – medium pollution	737,5	484,0
Zelechovice	1022	Rural, fallout from Cizkovice	644,5	440,8

Table III – Course of corrosion at selected locations in Northern Bohemia (started in 1974)

Location	Corrosion characteristic				Exposure (days)	Corrosion loss ($g.m^{-2}$)	
	1	2	3	4		carbon steel	Atmofix 52A
Hamr	4	P_3	88,3	Increased humidity	180	322,0	318,2
					365	492,0	377,0
					796	802,4	522,2
Teplice	5	P_3	80,4	Combined influences	180	414,4	393,1
					365	714,7	436,6
					796	970,0	567,0
Prahly	3	P_3	62,2	-	180	280,0	241,5
					365	380,3	277,5
					796	549,9	476,8
Kopisty	5	P_4	137,3	-	180	288,2	208,8
					365	618,5	494,3
					796	-	-

Corrosion characteristics: 1 – corrosivity according to ISO 9223 standard
2 – SO_2 pollution level according to ISO 9225 standard
3 – average value of SO_2 ($mg.m^{-2}.d^{-1}$) for the period 1969-73
4 – other influences

More detailed results of station tests of various weathering steel types have been published individually (6, 7).

1.3. Evaluation of corrosion behavior of Atmofix 52A weathering steel on transmission system towers

Towers were made of Atmofix 52A weathering steel in the Czech Republic between 1972 and 1980, then only in a limited extent until 1994. There were no systematic inspections between 1976 and 1992, checks were focused rather on sporadic negative corrosion effects as was increased or layered corrosion at the base fixings in cases they were improperly or defectively designed or placed unsuitably (base under bulk where snow was accumulated and steel parts were exposed to long time of wetness).

Sporadic problems with crevice corrosion started to appear in the mid 80’s and in 1992 the first broad research was carried out (Table IV) (8). Little or medium developed crevice corrosion was found at majority of the territory on towers built between 1972 and 1980, in Northern Bohemia, where towers were exposed to corrosivity C4 – C5 for a long period, corrosion manifestations in crevices and their surroundings were significant, joints were deformed and strap plate edges were bended. Condition of rust on free surfaces of steel elements proved formation of protective rust - patina, in Northern Bohemia surfaces had higher portion of non-adherent particles and active sulfate nests.

General research was repeated in 2002 (8) covering only Northern Bohemia especially on towers that had been involved in the research in 1992 or even before (Table V). Crevice corrosion rate slowed down, certain regeneration of rust - patina was observed after a significant decrease of corrosivity of atmosphere in the area. Decrease of corrosion rate can also be derived from resistance induced by joint rigidity. The most endangered locations (base and web joint, bolt joints with strap plates) reached locally width of crevice (or thickness of rust layer in crevice) of 10 – 12 mm and of 7 mm in cases when thicker elements were used. Joints were deformed both between bolts and at strap plate corners. Use of distance washers had a positive effect. Pit corrosion attack was also observed on joint elements.

Four of observed towers (Kravare, Brozany, Rana, Brvany) had a red-and-brown, probably double layered coating (grey base) applied approximately eight years ago approx. 10 – 15 cm above the base and web joint. No more detailed information about application of the coating system is available. This measure was no longer effective at the time of evaluation. Examples of defects reported during the inspection are presented in the picture section (Annex A).

1.4. Summary of results

- Corrosivity in Northern Bohemia was between category 4 and 5 at the time when towers were built, then it gradually decreased, current corrosivity of atmosphere in the Czech Republic (except few industrial areas) reaches category 3, although at the upper level of the classified category.
- Corrosion tests carried out at purpose-built stations of SVUOM around year 1975 proved that atmospheric corrosion rate of Atmofix 52A is significantly lower than corrosion rate of comparative steel and that rust - patina of prevailingly protective properties is likely to form. The same facts were proved by test on three electrical transmission towers in Brvany, Brozany and Zelechovice.
- Formation and development of crevice corrosion were evaluated in 1976, 1992 a 2002. In 1976 there was no crevice corrosion on towers built in 1972 and 1973, in 1992 there was a developed and strongly developed crevice corrosion found on these and other towers. Development over the next decade has not been so rapid.
- Effectiveness of recovery of crevices with a coating system with an undefined and rather limited removal of rust from crevices is very time-limited.
- The transmission system operator used the inspection data to have a project for crevice corrosion recovery worked out. Considered was a suitable impregnation of rust in crevices under the protective coating, joint disassembly, cleaning rust off joints, application of anti-corrosion protection into crevices before reassembling the joints and covering them with a coating system, then a recovery by removing rust from crevices without disassembling the joints, cementing the crevices and covering the crevices and their surrounding with a coating.
- While the SO_2 concentration in Northern Bohemia has significantly decreased, the current rust layers demonstrate protective properties in an increased extent. Development of rust layers in the location Hora sv. Sebestiana has not changed its original character, data for evaluation of the current corrosion rate are not available. Frequent occurrence of fog and frost probably increases the portion of locations with a more active course of corrosion. Rust at free surfaces of OK elements on other towers inspected in 2002 was evaluated as rust - patina with protective properties.

Table IV – Corrosion manifestations on towers – results of 1992 evaluation (examples)

Tower	Year of introduction to operation	Estimation of corrosivity at the time of introduction to operation	Corrosion manifestations	Note
195 Kravare	1972-73	C 4 -5	Rust corresponds with environment of higher corrosivity, partial protective effectiveness, developed crevice corrosion, deformed joints, layered corrosion above crevice, corrosion at base	Strongest corrosion manifestations
5 Brvany	1973-74	C 4	Rust corresponds with environment of higher corrosivity, partial protective effectiveness, developed crevice corrosion, deformed joints	Towers of this line have developed manifestations of crevice corrosion
6 Brvany	1973-74	C 4	Rust corresponds with environment of higher corrosivity, partial protective effectiveness, developed crevice corrosion	
26 Rana	1973-74	C 4	Favorable rust development, developed crevice corrosion, strong attack on joining material	
106 Brozany	1973-74	C 4	Rust corresponds with environment of higher corrosivity, partial protective effectiveness, developed crevice corrosion, deformed joints, strong attack on joining material, layered corrosion above crevice	
185 Hora. sv. Sebastiana	1976	C 4 - 5	Relatively favorable rust development, locally developed crevice corrosion, strong attack on joining material	Specific climatic influences - fogs, frosts
184 Hora. sv. Sebastiana	1976	C 4 - 5	Relatively favorable rust development, locally developed crevice corrosion	
2 Prunerov	1980	C 4 - 5	Rust corresponds with environment of higher corrosivity, locally developed crevice corrosion, deformed joints, attack on joining material	Aggressive microclimate, pollution, cooling towers closely neighboring

Table V – Corrosion manifestations on towers – results of 2002 evaluation (examples)

Tower	Year of introduction to operation	Current corrosivity	Corrosion manifestations		Note
			Part without coating	Part with coating	
195 Kravare	1972-73	C 3	Protective patina on bottom surfaces, layered rust in crevice, crevice of 10 – 12 mm at upper corner of base and web joint, rest of crevice of 5 – 7 mm width, bolt heads without pit corrosion	Coating on surfaces and bolt heads is fragile, without lustre, not corroded through; coating above crevice and on edges is completely fragile, falling off, strongly under-corroded, joint protection ineffective	Rust overlap above joint partially removed before coating application, friable rust formed above joint
5 - 6 Brvany	1973-74	C 3	Protective patina with slightly more developed pits, crevice condition as on tower 195 Kravaře	dtto	Marked corrosion pits on strap plate sheet (scaling)
26 Rana	1973-74	C 3	Protective patina, crevice at upper joint corner 10 mm on thinner sheet, 7 mm on thicker sheet	dtto Moderate degradation manifestations	-
106 Brozany	1973-74	C 3	Protective patina, crevice at upper joint corner 10 mm on thinner sheet, 7 mm on thicker sheet	dtto Marked degradation and corrosion manifestations	-
176 -77 Hora. sv. Sebastiana	1976	C 3 - 4	Patina with a prevailingly protective function, higher amount of pits, light-colored rust in pits, rust with pits on bolt heads, crevice of 4 – 5 mm, compact rust in crevice	Bottom parts without coating	Specific climatic influences – fogs, frosts
2 Prunerov	1980	C 3 - 4	Rust with prevailingly protective functions, less marked impact of high corrosivity, compact and friable rust in crevice, width of crevice 4 – 12 mm, pits on sheet with scaling, weld at welded mounting insert broken off	Bottom parts without coating	Pollution in the area decreased, influence of cooling towers continues

2. Quantification of crevice corrosion attack on joint

Selected dismantled elements of towers after different exposure periods (6 - 12 years) were evaluated and corrosion effects in crevices were quantified. Detailed results have been published individually (5).

2.1. Evaluation of corrosion attack

- photo documentation of elements, samples and contact surfaces before and after dismantling
- evaluation of rust inside the crevice by metallographic analysis of rust layer, phase analysis of rust and determination of corrosion stimulating components in rust
- measurement of residual thickness after rust removal by pickling in Clark´s solution
- corrosion attack of joining elements by visual evaluation, measurement of bolt shank diameter after removing rust in Clark´s solution and metallographic evaluation of local attack (pit depths)

2.2. Rust layer evaluation

Inside the crevice, the rust layer thickness and appearance is not uniform. Highest thicknesses are found near the edges where from layer can be distinguished. Towards the bolt whole, the rust layer thickness decreases. The rust in more coherent in close proximity of the bolts almost no rust is found. Lightest colours appear in direction to steel surface, the inside matter of rust shows a dark colour.

Qualitative phase analysis revealed α - and β - FeOOH, α - FeOOH, prevailing inside the layer. On its surface the amounts of both phases are almost equal. No specific phase features of rust in the crevice were found.

Results of the chemical analysis of rust inside and outside of joint including determination of sulphate and chloride contents and their soluble parts are shown in Table VI.

Table VI - Content of corrosion stimulants in rust from crevice
(10 years of exposure)

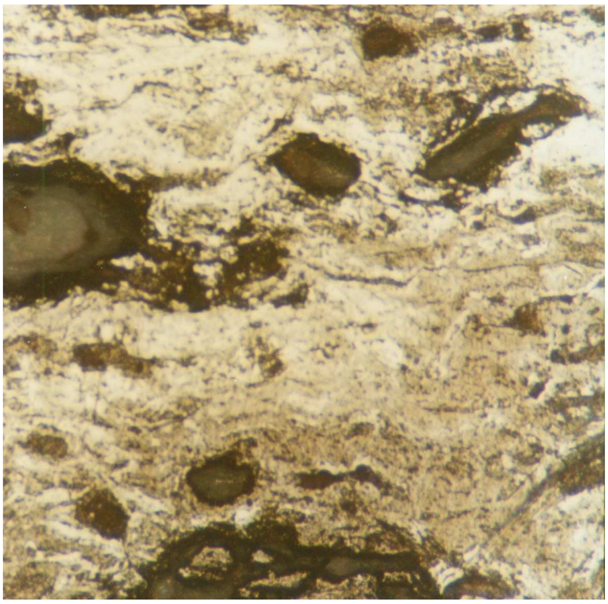
Layer	Content			
	Cl^-		SO_4^{2-}	
	total	soluble	total	soluble
outer	0,07	0,011	0,73	0,04
inner	0,06	0,007	0,45	0,07

The amounts of corrosion stimulating components are not very high. It can be concluded that stimulants do not get accumulated in the rust layer and that limited access of the outer environment lower than their content in the rust. The outer, light coloured layer shows a somehow higher content of stimulants, but even then this is lower than expected based on the appearance. The prevailing part of the stimulants is bonded in soluble form.

Metallographic analyses show a different type of rust inside the crevice that of the rust outside. Inside the crevice the rust seems more compact than outside on the open surface. The rust grows from the steel surface and later the rust layer becomes fused. The compactness and visual uniformity of rust inside the crevice gives evidence about the process stabilization and the limited effect of outside conditions (Figure 3).

Figure 3 - Rust layers from crevices


macro photo


cross section 200 x

3.3 Measurement of element residual thickness

Detailed areal thickness measurements and circumference measurements of the bolt holes were performed. The results were evaluated for selected areas, directions and lines on the joint surfaces. It is not possible to define the real corrosion losses as no initial thickness data are available. These corrosion losses should be understood as relative data covering losses of booth surfaces and relate to the nominal thickness of the elements. Example of results is presented in Table VII.

Table VII - Mean relative corrosion losses of elements after 10 years of exposure

Element	Measured area	Corrosion loss (μm)
A	free area	100 – 300
	1 cm from crevice edge	50 – 465
	in the bolt axis line	260 – 345
	circumference of bolt holes	215 – 30
	free corner of cover plate	435 – 503
B	free area	350 – 500
	1 cm from crevice edge	115 – 575
	in the bolt axis line	155 – 360
	circumference of bolt holes	10 – 260
	free corner of cover plate	175 – 260

3.4. Corrosion attack of joining elements

Joining elements always are the weak point of tower structures. Visual examination showed different severities and character of corrosion attack. Results of bolt evaluation for elements are shown in Table VIII and results of metallographic pit depth measurements on bolts and washers are shown in Table IX.

Table VIII - Visual evaluation of bolts

element	type of joint	heads and bolt	shank	thread
A	two bolts	rough, continuous rust layer, pits	discontinuos rough rust layer, one side deformation (depressions)	part covered by rust unsignificant attack, out of cover
B	one row joint M 16 bolts probably chromized	expressive local attack (pits)	different attack intensity - stems only slightly corroded, most of surface with no attack - stems with higher attack voluminess rust, pits, only small part of surface without attack - interne corrosion on stem, rough rust, local attack by pits	thread covered by nuts without significant only sligh attack, outside cover significant corrosion attack at some screws, partial thread partially leveled
C	two row joint M 24 bolts probably galvanized	medium, rough, uniform, adherent rust layer, some bolt ends without attack	nonuniform at some points incoherent, rough rust, some bolts with pits	by nut covered part of thread with white corrosion product and rust spots, thread outside cover near stem - heavy corrosion attack

Note: Element A was exposed for 6 years and elements B and C were exposed for 10 years.

Table IX - Metallographic evaluation of pitting attack of bolts (10 years of exposure)

corrosion attack	max. pit depth (μm)	
	bolt	washer
slight	135	140
middle	220	150
severe	335	215

2.5. Summary of results

The major location of corrosion failures of steel structures made from weathering are crevices at bolt joints. The degree of attack depends on the kind and quality of joint, corrosivity of environment, the position of the joint with respect to the tower, and, of course, on exposition time.

The nominal tolerances of the evaluated elements were, viewing their thickness, from ± 0,75 to ± 1,25 mm. The inside and outside mean relative corrosion losses expressed as difference between nominal thickness value and residual value were from about 0,01 to 0,80 mm.

The corrosion loss grows in the direction of the joint boundary line to the traverse axises between the line between two bolt holes. Highest corrosion attack is observed at points with both these characteristics. At such points some of corrosion losses exceed the minus tolerance values.

Minimum corrosion losses are found around the bolt´s hole circumferences, that is where at places where the joint is tightest. Corrosion losses at joints are in general higher than those of open surfaces, but not by range of order of magnitude.

Inside the crevice rust does not show protective properties. The rust layer thickness decreases from the joint boundary towards the bolt hole. The rust layers are compact and does not contain higher amounts of stimulants. The compactness of the layer distinctly grows in direction into the joint.

Roughness of surface and pits in the crevice are less if compared with fully exposed surface.

Corrosion attack of joining parts (bolts, nuts and washers) depends on the material, corrosivity conditions, and exposure time. No problems in the strength of the bolts have been indicated by the evaluation.

Elimination of crevice corrosion seems to be a complex problem with no simple or easy long-term solution. Viewing the volume of the rust in the crevice and its properties its hydrophobic treatment is practically impossible and can not be efficient. Barrier coatings will not easily penetrate the crevice, and their parts covering the crevice will decompose and lose protective capacity. Sanation of crevice corrosion attack should be used for selected structures with high corrosion attack.

New towers structures made of weathering steel should be designed with bolted joints that fully comply with the optimum recommended distances for bolt holes (9, 10), the necessary rigidity and planesess of the contact surfaces. The contact surfaces should be painted or otherwise coated but in complete accordance to actual standards and other recommendations. Another requirement is checking the bolt joints during and after assembly.

3. Accelerated laboratory tests of recovery systems for crevice corrosion on bolt joints on transmission system towers

Mechanical removal of most of rust from a crevice of an undisassembled joint, application of cement into a crevice and covering it and its surrounding with a protective coating was recommended as the best way of crevice corrosion recovery. Proposed method needed to be verified by accelerated laboratory corrosion tests at the first place.

Eleven recovery protective coating systems (RPCS) were recommended for testing. The design of the RPCS was proposed with following aims:

- primer in crevice intensify adhesion of cement to steel in crevice and shows a certain protective ability for steel with rests of rust,
- cement seal the crevice and shows a certain ability to resist to dynamic mechanical stress,
- paint system (PS) over cement in crevice and on surroundings steel element surface completes the total protective efficiency of the RPCS.

At selection of recovery protective coating systems it was intention to reach a relatively long-term protective efficiency at minimum number of layers with application of paint coats with thickness of the single layer over 60 μm.

The general specification of paints and cements is given in Table X. Paints were mostly of solvent type, only CS No 11 was of emulsion type (PVAc primer, styren-acrylate top coats).

Table X - The general specification of paints and cements

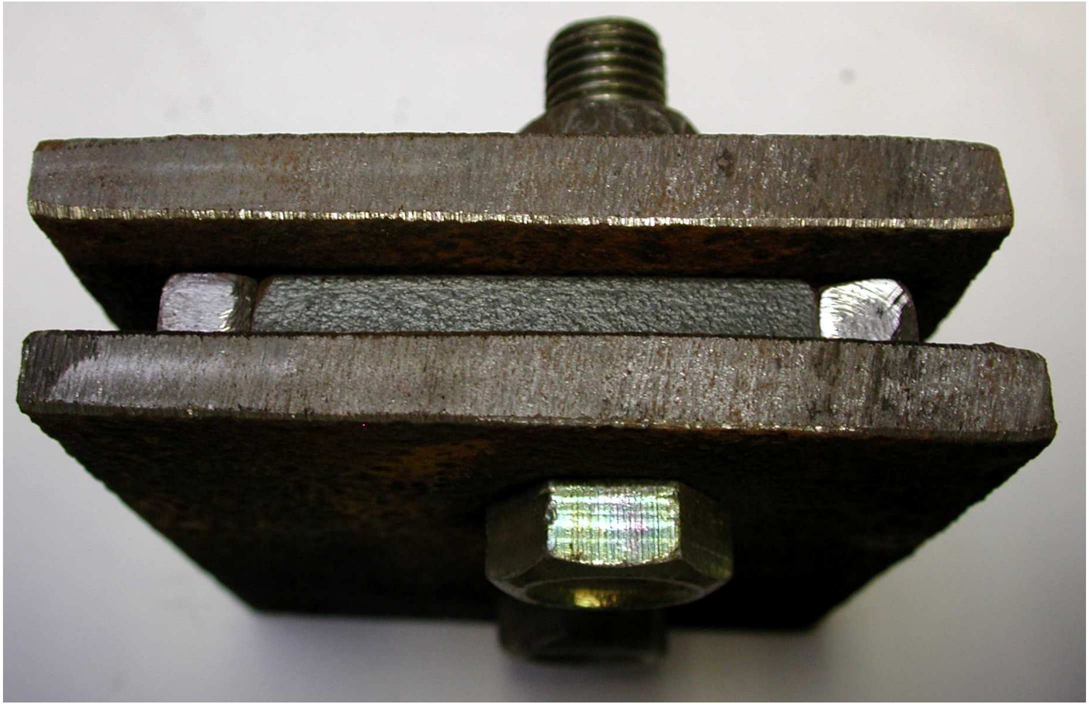
RPCS	number of layers	layer	binder of paint	recommended thickness of PS (µm)	binder of cement	application of cement in RPCS
1	3	PC	alkyde	200	polyurethane	after PC
		IC	alkyde			
		TC	alkyde			
2	3	PC	epoxy ester	180	polyurethane	after IC
		IC	epoxy ester			
		TC	alkyde - acrylate			
3	3	PC	penetrating synthetic resin	160	styren-acrylate	after PC
		IC	synthetic resin			
		TC	synthetic resin			
4	3	PC	oil - alkyd	160	polyurethane	after IC
		IC	oil - alkyd			
		TC	oil - alkyd			
5	3	PC	acrylate	200	polyurethane	after IC
		IC	alkyd-urethane			
		TC	alkyd-urethane			
6	3	PC	alkyde	200	polyurethane	after IC
		IC	alkyde			
		TC	alkyde			
7	2	PC	polyurethane	160	polyurethane	after PC
		TC	polyurethane			
8	2	PC	PVC - acrylate	160	polyurethane	after PC
		TC	alkyd - acrylate			
9	2	PC	polyurethane	120	ISR polymer	after PC
		TC	alkyde			
10	2	PC	vinylalkyde	140	tar	after PC
		TC	vinylalkyde			
11 *	3	PC	polyvinylacetate	165	styren-acrylate	after PC
		IC	styren -acrylate			
		TC	styren -acrylate			

Note: PC priming coat, IC intermediate coat, TC topcoat
* waterborne coating

3.1. Test sample specification - preparation

Samples were made of two steel plates (Atmofix steel supplied by the project assignee) of approx. 95 x 120 mm dimensions and 8 mm thickness. Material for samples was taken from corroded strap plates removed from tower constructions. Artificially formed crevice on samples was of 10 mm width (sample design is shown in Figure 4).

Figure 4 - Sample with model of crevice



Mechanical cleaning to grade 3 according to ISO 8501 – 1 was done manually with a steel brush.

Before applying the recovery protective system thickness of adhesive corrosion products was measured non-destructively by an electromagnetic method according ISO 2808 using Fischer Deltascop MP3 gauge. Measurement was done at seven places according to a stencil and total average value was derived.

Tests were carried out on eleven recovery protective coating systems (RPCS) selected by CEPS Ltd. Five samples were tested from each system – three with a use of cement in crevice, one with a protective coating only and one with a protective coating and a layer of cement on outer side. Coating systems (PS) were applied on test samples with a brush. Cements were applied with a gun or a blade.

3.2. Evaluation criteria for laboratory tests of recovery protective systems

Evaluation of physical and chemical properties of PS and RPCS before tests and exposure of samples in a cyclic test was done five weeks after they had been prepared.

Criteria corresponding with national and international standard were proposed in the maximum possible extent as evaluation criteria for preparation of samples and evaluation of changes during and after accelerated tests. Recovery protective coating systems and samples in general are not typical, therefore also atypical criteria had to be set for partial evaluations (crevice, mechanical test, inner surfaces) (Table XI).

Table XI – Evaluation methodology

Evaluation	Procedure	Results
1 Appearance evaluation (individually on PS and outer crevice surface)		
- Defect generally	ISO 4628-1	Description
- Blisters	DIN 53 209 (ISO 4628-2, ASTM D 714)	Quantity, size, degree
- Corroding-through	ISO 4628-3	Degree, surface
- Cracks	ISO 4628-4	Quantity, size
- Peeling off	ISO 4628-5	Surface, dimensions, shape
1.1. Evaluation on PS		
1.2. Evaluation on RPCS – outer crevice surface		
2 PS adhesivity	ISO 2809	Degrees 0 – 5
3 Physical and mechanical properties of RPCS - adhesivity	ASTM D 3359	Degree 5A – 0A
4 Mechanical properties of joints	Tearing machine test	Graph – elongation before joint failure
5 Mechanical test failure	Verbal description	Elasticity, cohesion-adhesion failure
6 Evaluation of mating surfaces after mechanical test	Verbal description	Crevice coverage, environment penetration and other effects
Mechanical properties of joints were evaluated by testing cemented samples with a tearing machine at elongation speed of 2.5 – 3.0 mm/min. and temperature of 23 ± 2^{0}C. Induced force was transferred to electric signal (voltage) by tensometric pressure sensor which was measured with KEITHLEY multi-meter, recorded every second and registered by computer creating a graph of induced force vs. time function simultaneously.		

Properties of cements used can be derived from evaluation of graphs documenting the course of mechanical tests and comparison of surfaces of torn-away samples. Comparison of the maximum value of induced force necessary to tear away individual samples or value of induced force at which first visible cracks appear on surfaces of sample joints with time necessary for reaching the maximum force and comparison of graph curves shapes (total time necessary for tearing away samples and time course of the force give a statement of strength, adhesivity and plasticity of cements used) can be used to decide about suitability of use of individual cements in given cases (with respect to other behavior of cements). Selected criteria (curing, cracks on PS, sticky surfaces) allow for evaluation of coating and cement compatibility.

3.3. Carrying out accelerated laboratory tests

Laboratory tests were carried out as cyclic with the following regime:

Initiation period:	8 hours in a clean condensation chamber according to CSN 03 8131
Cyclic test:	16 hours at -20^{o} C
	8 hours in clean condensation chamber
	16 hours at + 60 ^{o} C
	8 hours in clean condensation chamber
Time of one cycle:	168 hours (l week)
Time of test:	3, 5, and 10 cycles

Evaluation was done in several stages involving preparation of samples, accelerated cyclic tests, mechanical tests, additional evaluation and summarizing evaluation.

Tests were carried out on samples before exposure (after five weeks after preparation) and on samples after finished exposure (after three days of acclimatization in laboratory conditions).

All observed properties of coating systems and recovery protective systems were evaluated with respect to relevant international standards. Acquired values were transferred into point evaluation, this evaluation was done as weighted, i.e. importance of individual criteria was taken into account.

3.4. Test result summary

Comparisons of accelerated cyclic corrosion and mechanical test of eleven recovery protective systems were offered to the project assignee within the market research frame.

Laboratory cyclic tests involved exposure of model samples with PS and RPCS in conditions of humidity condensation, heat (60^{0}C) and frost impact (-20^{0}C). Mechanical influences present during real exposure were not involved in the tests. Results of accelerated tests were evaluated for paints on steel surface and for sealed crevice separately. Defects on paint surfaces were rare (loss of gloss). Defects on surfaces of treated crevice (complex RPCS) were more developed, situated to the edge with steel or on cement surface covered by paint. On these surfaces as an important criterion, the compatibility of paint and cement was evaluated. Alkyd paints or modified alkyd paints on polyurethane cement show longer time of curing (1 – 2 weeks after application), surfaces are still sticky after some weeks of accelerated testing, soiling effects are higher.

Defects in the surface of sealed crevice:

- RPCS 1 - fine cracks on cement surface and at edge with steel
- RPCS 2 - cracks at edge with steel, deepening of cement, sticky paint on cement
- RPCS 3 - without defects, high deepening of cement
- RPCS 4 - random cracks on cement surface
- RPCS 5 - cracks at edge with steel, loss of gloss of paint on cement
- RPCS 6 - without defect, sticky paint on cement
- RPCS 7 - cracks at edge with steel, deepening of cement
- RPCS 8 - without defects
- RPCS 9 - fine cracks on cement surface and at edge with steel
- RPCS 10 - wide cracks (3mm) in paint and cement, high deeping of cement
- RPCS 11 - cracks (1mm) in paint and cement, deeping of cement

Corrosion manifestations that would result from penetration of the environment into crevices were not found on any of RPCS in the crevice area of model samples after mechanical tests. Removal of samples protected with a coating system only was not involved in the presented evaluation system. Condition of coating systems in the crevice area shows the protective effectiveness of coating systems in this area.

Individual recovery systems were differentiated especially by the tendency to form cracks, injured adhesion at the steel edge or the influence of cement on the coating covering it. Basic manifestations of recovery protective systems degradation after accelerated laboratory test are documented in the picture section (Annex B).

4. Model samples test at atmospheric test site in Kopisty

The testing methodology is exceptional in the way that samples that had been previously exposed to the environment within accelerated ten-week cyclic test were exposed which is a new and original way to obtain technically exploitable results effectively. Results of the following two-year station tests proved the above presupposition to be right.

Samples were exposed during spring 2002 (Figure 5) and were evaluated during the course after 6, 12 and 24 months of exposure. Appearance was evaluated, photos were taken. The final evaluation including evaluation of the character of destruction was done after two years of exposure. Overview of environmental parameters at Kopisty test site for the given exposure period is outlined in Table XII.

Table XII - Environmental characteristics at Kopisty test site

Year	T [°C]	R V [%]	Precipitation [mm]	SO_2 [μg.m^{-3}]	NO_x [μg.m^{-3}]	Precipitation pH
2000	10,1	76	509,8	16,0	28,0	4,8
2001	9,2	80	509,3	17,4	24,8	4,4
2002	9,4	78	692,8	11,2	24,7	4,8
2003	8,9	73	284,2	10,7	24,5	6,3

Figure 5 - Exposure of samples with model crevice at atmospheric test site

The intention to expose samples at atmospheric testing station after accelerated tests proved to be right. Complex influence of climatic factors including pollution affecting materials in cycles corresponding with natural conditions give rise to processes that cannot be modeled in an accelerated test.

Corrosion tests on specially prepared models made of materials corroded for long periods that had coating systems and recovery protective systems applied later were carried out for the first time. It was also the first time when systematic evaluation involved mechanical tests of joints carried out on matured models before environmental impact tests, on models after accelerated laboratory tests and on models which were later exposed for two years at atmospheric test site in Kopisty. This original and complex way of preparing samples, exposing them to the environment and evaluating their condition periodically proved to be working very well.

Brand new knowledge was brought by the evaluation of recovery protective systems in the crevice area. This involved both appearance evaluation around the crevice and in the crevice after opening it and periodical evaluation of mechanical properties of RPCS during mechanical stress tests on a tearing machine. Comparable information cannot be provided even by evaluations of RPCS on towers.

Results of the mechanical test of joints involved appearance evaluation during the test and after separating the plates and graphs showing the course of the mechanical test. Table XIII allows for comparison of conditions for initial phase of main fracture of cement on models after mechanical test for condition before station exposure (i.e. after accelerated laboratory test) and after two-year exposure at a station. Differences between individual RPCS are documented by selected curve examples showing the course of tearing machine test. Examples of the course of mechanical test and manifestations visible after opening crevices are presented in the picture section (Annex C).

Table XIII – Mechanical properties of cements – evaluation of tearing machine curves

RPCS No.	After ten-week accelerated test			After two-year station exposure		
	Main fracture			Main fracture		
	Force (kN)	Time (sec)	Elongation (%)	Force (kN)	Time (sec)	Elongation (%)
1	0,99	310	129	0,80	180	72,1
2	1,60	323	135	0,87	64	26,2
3	0,69	42	18	1,13	29	11,7
4	1,43	43	18	1,11	94	38,8
5	0,44	43	18	0,12	25	10,0
6	2,09	83	40	2,22	49	20,0
7	3,66	123	51	3,06	276	68,8
8	3,01	34	14	0,39	284	109,6
9	3,23	631	160	2,76	48	19,6
10	0,90	21	8	0,80	182	62,0
11	1,02	113	47	0,30	48	19,2

5. Evaluation of behavior of recovery protective systems on towers (field tests)

The transmission network operator asked selected suppliers of recovery protective systems to apply these systems directly on towers to allow for evaluation of technical and technological suitability in the operation conditions and evaluation of gained protective effectiveness by repeated checks. Evaluation methodology was based on methodology used for evaluating laboratory tests results and is presented in Table XI. During evaluations in the field the methodology was generally adhered to or modified according to actual conditions.

Observation of physical and mechanical properties of PS was carried out on tower webs and cross beams in the height of 1 – 2 m. Evaluation of RPCS as a whole was limited, because only base part and web joint and partly joint at first splice and single-bolt joints on lower cross beams were accessible. Appearance evaluation (rust character, crevice condition, deformation, cementing carefulness) was carried out both at lower parts of towers and higher using a telescope.

The main points of RPCS evaluation applied in the filed conditions were:

- total thicknesses of coating systems
- PS adherence to cleaned surface
- cement applicability evaluation
- cement and coating compatibility evaluation

Total thickness of applied coating systems was measured to be equal to or higher than recommended thickness on more than a half of evaluated towers. On the rest of towers total thicknesses were significantly lower by as much as 56 % than recommended values.

Adhesivity of coating systems to surface metals measured by grid test was out of limit in case of five coating systems. Other systems measured had satisfactory or acceptable values, in one case results oscillated (satisfactory vs. out of limit). The method of evaluation by cross cut is more tolerant and all measured values were satisfactory except one. In case of tearing adhesivity test all results were satisfactory except one, although in three cases the measured values were at the lower limit of acceptability.

Appearance evaluation of cemented crevice at the first splice proved that in many cases the crevice in the splice lower corner had not been cemented carefully. The degree of removal of rust from crevices cannot be evaluated. Width of recovered crevices varied according to position and thickness of joined material; in most cases it was not over 10 mm which corresponds with corrosivity of the environment and tower age. Defects (through-corroding at more than 1 % of surface) after one-year and three-year exposure were found only scarcely.

Carried-out field evaluation of coating systems and recovery protective systems effectively complements results of accelerated laboratory tests carried out before. A definite conclusion can be derived from the carried-out evaluations that effective recovery of crevice corrosion is conditioned by partial steps being taken which involve removal of layered rust from crevices and careful application of cement. The problem cannot be solved by applying a coating system only.

Results of research carried out between 2002 and 2004 prove that certain defects on individual systems, both on coating and recovery system in the crevice, begin to appear after four years of exposure in field conditions.

Corroding-through and cracks in coatings as well as formation of blisters occurred rather sporadically, more often in case of water-diluted and two-layer coating systems. More defects were found on recovery systems in the crevice area (cracks in cement, injured adhesion of cement to steel, rust penetration). Coating on some cements does not dry well and gets dirty. Elasticity or stiffness of cements changes too. Technical applicability of cements can be well evaluated when applying cements on real joints. Some of the systems evaluated had a good level of elasticity and high level of compatibility of cements with coatings.

Correspondence of manifestations (defects) found on recovery systems during accelerated laboratory tests and during field evaluations was almost perfect which proves the evaluation methods to be chosen well. Examples of defects on sealed crevices on transmission tower are presented in picture section (Annex D).

Conclusion

Because of developed manifestations of crevice corrosion on some bolt joints the transmission system operator had to find a manner of recovery. The method based on application of cement and coating system in the crevice and surrounding area after removal of layered rust was tested in cooperation of CEPS and SVUOM.

Carried-out field evaluations and station tests and evaluations of these tests produced a lot of information on formation of crevice corrosion on bolt joints of tower constructions made of Atmofix weathering steel. Former published recommendations (2, 3, 9, 10) were considered.

Protective effectiveness of surface finish of PS in relation to formation of corrosion in crevices or preservation of crevices from corrosion cannot be derived in the link to standard provisions. However, the protective effectiveness will be lower at open space because aged coating will probably not resist to dynamic mechanical stress in a sufficient manner. When coherence of PS is injured, other influences as e.g. freezing of penetrated water will come into effect.

An outline of facts that influence the length of service life is presented in the chapter on RPCS service life estimates. Combined accelerated and station test carried out on models involved lot of these facts. The following field research deepened the knowledge of recovery system properties.

The following facts are especially important for achieving a long-term protective effectiveness of RPCS in crevices:

- degree of removal of loose or partly loosened rust fractions from the crevice,
- portion of soluble aggressive components in remaining rust,
- adhesivity of coating in the crevice to steel and cement,
- compatibility of coating and cement in the crevice area,
- ageing of RPCS in the crevice under the impact of environmental factors,
- changes of mechanical properties of cements,
- resistance of RPCS to dynamic mechanical stress.

Therefore it is difficult to give a qualified estimation of service life or rather time of effective protective operation of recovery protective system in a crevice. First it would be necessary to define a set of properties which outline the required protective effectiveness. Definitions and procedures according to EN ISO 12944 cannot be taken over. However, based on results of accelerated cyclic tests and following station tests it may be supposed that the time of effective protection against formation and development of corrosion will be long, exceeding 15 years in case of very positively evaluated recovery protective systems. In case of positively evaluated systems the service life estimation is approx. 10 years. If the transmission network operator requires protective effectiveness to last for decades, it can be supposed that the recovery protective system will have to be periodically maintained. Renewing the recovery protective system as a whole is not possible. Evaluation of achieving required protective effectiveness in relation to the service life of steel constructions must be more complex and should involve also time of service life of steel construction left after the penetration of the environment into the crevice is re-established.

The results in confirm with CEPS policy were to treat all the steel structures as soon as possible and some of the steel structures which are in the worst condition to replace for new ones. Concerning the overhead lines CEPS have started the sealing of the joints in 1999. About 25% of total number of steel structures has been recovered until 2004. The plan is to finish sealing of all the steel structures by 2010. Other reasons are ongoing projects (esp. renewal of the system 220 kV) that limit the possibility of shutdowns of other lines. Concerning the switchyards treatment, it is connected with total reconstruction of switchyards. There has been repaired about 40% of switchyards made of weathering steel and the plan is to finish their repairs by 2012.

Acknowledgement
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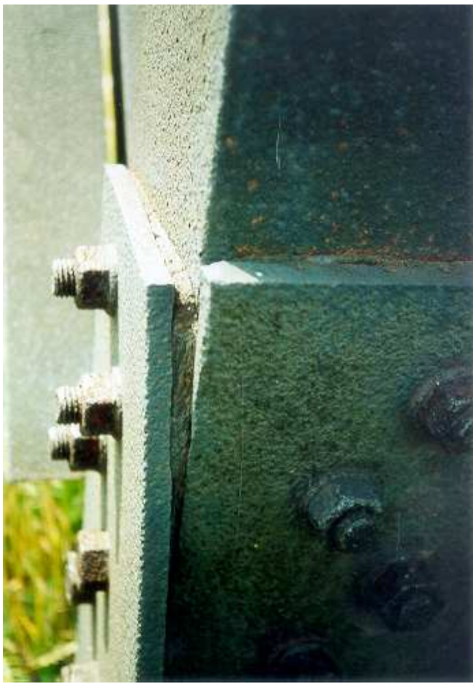
Annex A1
Examples of defects on inspected transmission towers



Annex A2
Examples of defects on inspected transmission towers

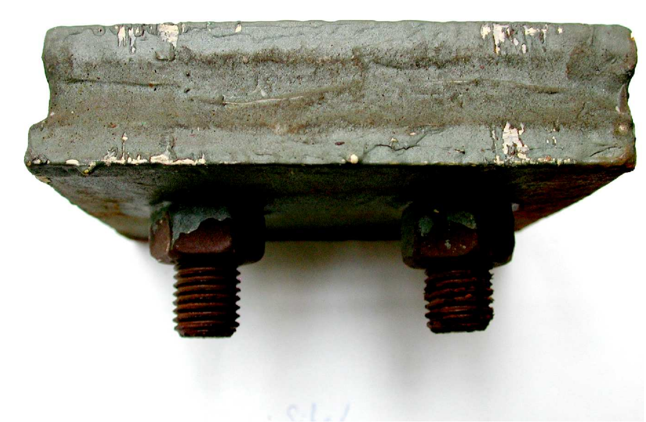
Rust layer on carbon steel

Protective patina on weathering steel

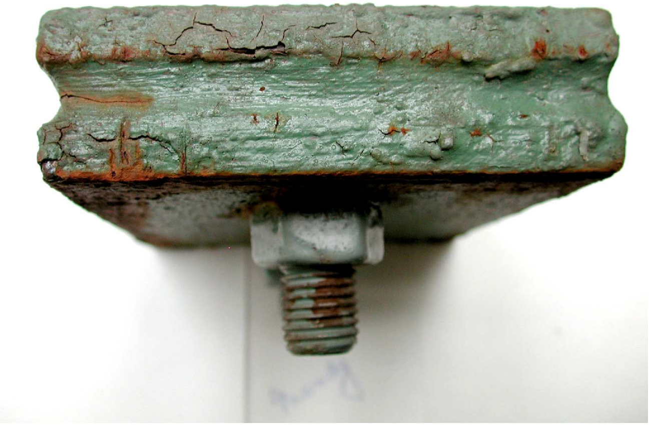
Less protective patina on weathering steel

Annex B
Examples of defects on model samples after accelerated testing


RPCS 1 - cracks in paint


RPCS 6 - sticky surface


RPCS 10 - cracks in paint and cement


RPCS 11 - total deterioration of system

Annex C1

Examples of the cement ageing and degradation manifestations after accelerated and atmospheric site testing

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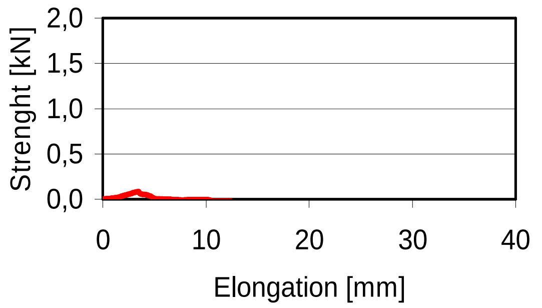
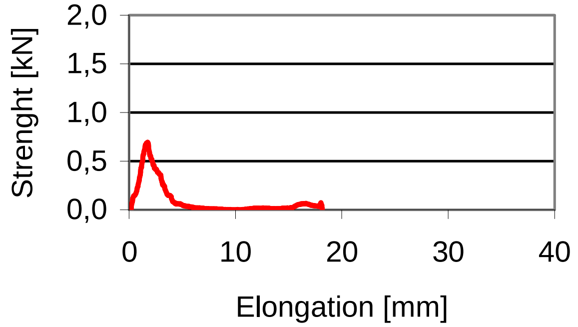
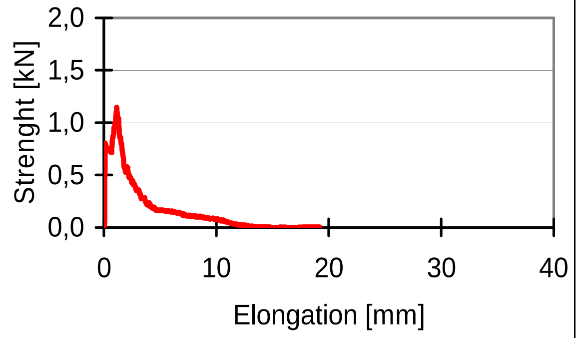
<tr><td colspan="3">RPCS 3 - Better mechanical properties after environmental exposure, cement is getting stiff</td></tr>
<tr><td>
</td><td>
</td><td>
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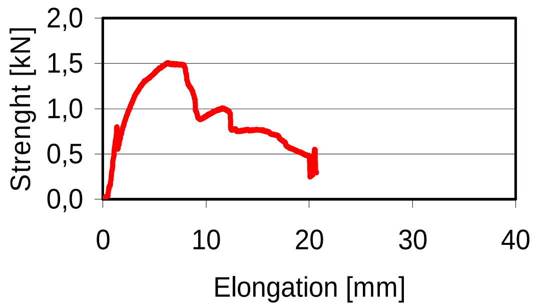
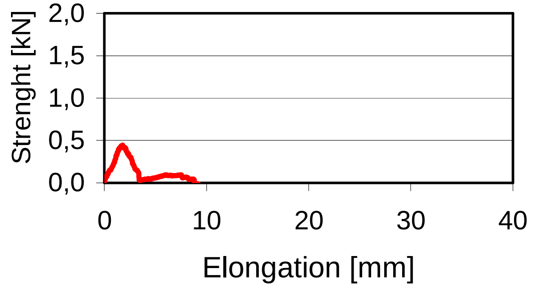
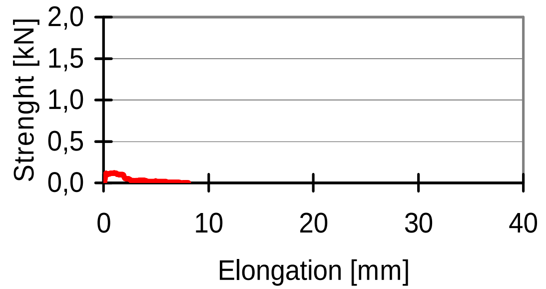
<tr><td colspan="3">RPCS 5 - High drop of mechanical properties after environmental exposure</td></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>before exposure</td><td>after 10 cycles of laboratory exposure</td><td>After two years of atmospheric exposure</td></tr>
</table>

Annex C2

Examples of the cement ageing and degradation manifestations after accelerated and atmospheric site testing

RPCS 6 - Acceptable performance

RPCS 8 - Rusting of interface of cement and steel

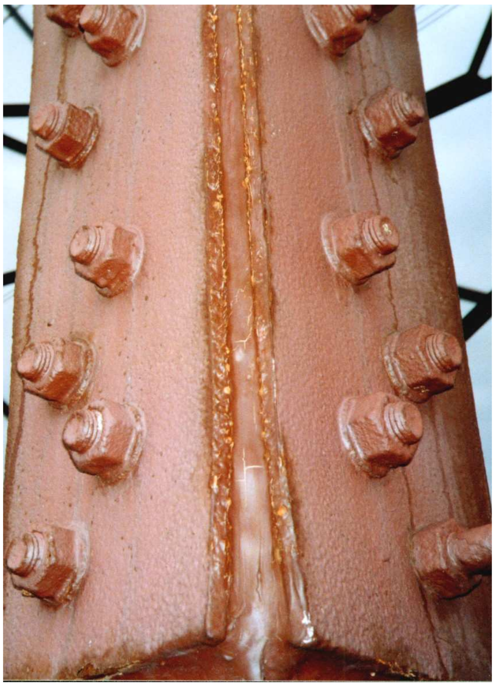
RPCS 11 - Total deterioration of system

Annex D
Examples of defects on sealed crevices on transmission towers (after 4 years of exposure)


RPCS 10 - total degradation of system


RPCS 10 - big blister in paint and cement


RPCS 10 - cracks in paint and cement


RPCS 8 - cracks in paint and cement