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Impact of ETICS on corrosion propagation of concrete facade

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Abstract

The durability of reinforced concrete facades is an important field of research as the majority of dwellings in Northern and Eastern Europe were constructed 30–50 years ago. Recent condition assessments of the façades have indicated damage related to carbonation induced corrosion. Moreover, the problem might escalate since the future climate scenarios predict a significant increase of CO₂ in ambient air being a driving force for carbonation.

Assessment of residual service life of concrete facades is a complex phenomenon with a high level of uncertainty. A validated method used in this study combines dynamic hygrothermal simulation tool Delphin and existing corrosion models. Corrosion propagation consists of the time needed to concrete cover cracking and further expansion of a crack up to a width of 0.3 mm as a limit criterion. Additional exterior thermal insulation (mostly ETICS) is applied to existing dwellings as a renovation scenario in order to decrease the heat loss, improve thermal comfort and prevent the degradation mechanism e.g. carbonation induced corrosion. Hence, reinforcement corrosion before and after installing ETICS with mineral wool, EPS or PIR has to be evaluated. Impact of boundary conditions, e.g. wind-driven rain in addition to material properties, and built-in moisture was included.

The results indicate that corrosion propagation after carbonation has reached the reinforcement, is three to six years depending on the ratio of concrete cover depth against the reinforcement diameter. While applying ETICS, corrosion accelerates for a short period of time up to one year. Temperature inside the wall rises above +10 °C throughout the year, meaning no more freeze-thaw damage. Corrosion of reinforcement in carbonated concrete after applying ETICS is so slow, that no cracking will develop. Drying out moisture or vapour diffusion from indoor air is not able to propagate corrosion of reinforcement in carbonated concrete.

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Nomenclature

d_c	concrete cover depth, mm
d_{carb}	carbonation depth, mm
d	diameter of reinforcement, mm
F	Faraday's constant, $F=96487 \text{ A}\cdot\text{s/mol}$
I_{corr}	corrosion current, A/m^2
J_{WDR}	wind-driven rain intensity to the vertical facade, $\text{l}/(\text{m}^2\cdot\text{h})$
M_{loss}	mass of steel dissolved at the anode during the overall duration t , kg/m^2
M	molecular weight of corroding steel ($M=55.8 \text{ g/mol}$)
η	catch ratio of wind-driven rain, -
ρ	density of steel, g/cm^3
τ	corrosion duration, s
w_{crack}	crack width, mm
x_0	attack penetration or the radius loss of reinforcement, mm
z	valence of corroding metal, i.e. the number of electrons involved in the el.chemical reaction ($z=2$ for steel)

1. Introduction

The majority of dwellings in Northern and Eastern Europe were constructed in the 1960-s, 1970-s, and 1980-s during the industrialisation period. A significant amount of these dwellings in Estonia are constructed by reinforced concrete (RC) large-panels. Recent condition assessments of the façades have indicated the natural degradation mechanisms as carbonation induced corrosion and freeze-thaw damage [1]. In addition to degradation due to the time, problems appeared as a result of poor real estate maintenance and a lack of regular condition investigation leading to the growing need for renovation. Reliable renovation scenarios need to be developed to prolong the service life of RC façades.

In terms of the longer perspective and sustainability, tendencies of future climate scenarios should also be taken into account. For example the concentration of CO_2 in ambient air as a driving force for carbonation could rise up to 840 ppm by the year 2100 [2]. Future climate scenarios proposed for Southern Finland are also applicable for Estonia - rise in temperature, higher relative humidity (RH) and more precipitation, higher wind velocity and less solar radiation [3] are all worsening the situation in terms of corrosion. Also, extreme weather will be more likely.

Detecting a correlation between actual deterioration and climate loads is a highly complicated task because of many uncertainties, e.g. material properties (depending on moisture conditions), local climate loads at the building site and complexity of deterioration phenomenon. Regardless of this, durability properties of concrete and actual deterioration depending on climate loads has been studied in detail based on a field survey. Wind-driven rain (WDR) is involved in most of the main degradation mechanisms, like corrosion of reinforcement and freeze-thaw damage [4]. It has been estimated that the amount of WDR will increase by approx. 20% by 2100 in Southern Finland. At the same time the main wind directions remain from South-East to South-West [5].

Hygrothermal conditions for corrosion in concrete depend heavily on WDR that must be considered in addition to the convection and diffusion of moisture [6] [7]. Impact of WDR can be divided into two large fields of research [8] – impinging WDR intensity (before raindrop impact) and response of a building wall (at and after raindrop impact). The first part must also consider averaging the technique and time step of WDR data. The second part analysed in the paper gives a solid overview of research conducted and progress related to the subject and points out the shortage – development, validation and implementation of WDR into hygrothermal models. In addition to experimental measurement in situ and in laboratories, (semi)-empirical, analytical and numerical methods also have a perspective to become a valuable tool in order to quantify WDR loads on building façade [6] [8]. A solid overview and comparison of two semi-empirical models and computational fluid dynamics (CFD) model is made by Choi [9] and extended by

Blocken and Carmeliet [10]. Variability of the wind velocity and horizontal rain intensity in time should be preserved where feasible, while applying WDR as boundary conditions for heat, air and moisture transfer modelling [11].

Hygrothermal simulation tools have a wide field of applications in modelling heat, air and moisture transfer in a building envelope. Main bottlenecks related to the use of hygrothermal simulation tools are the reliability of input data, calculation principles and simplifications. Even if reliable output data has been calculated, the application of this data in order to model the degradation phenomenon is limited as calibrated degradation models do not yet exist. Implementation of finite-element hygrothermal simulation in order to analyse the impact of cracking has been described by Rouchier [12]. This advanced research analysed the durability of porous material with and without cracking by taking WDR and hygrothermal conditions into account.

Computational simulations to assess the damage and service life of structures are already in use for corrosion [13], degradation of wood [14], and growth of mould [15], [16], [17].

The main aim of the paper was to evaluate the corrosion propagation in RC facades and answer the following questions:

- What is the time of corrosion propagation of RC façade in various boundary conditions?
- What is the critical moisture content for the exterior layer of RC before installing ETICS to prevent corrosion propagation and moisture damage during the latter drying out?

These questions are crucial to answer in order to evaluate the service life of RC facades after carbonation has reached the embedded steel.

2. Methods

2.1. Corrosion propagation model

Corrosion of RC can be divided into two main phases: initiation and the propagation [18], [19], [20], [21]. During initiation carbonation of concrete reaches the depth of embedded steel and breaks down the passive film surrounding the reinforcement. The propagation phase covers the actual deterioration of reinforcement and concrete cover. The main assumption in this paper is that in the beginning of the calculation, carbonation depth has just reached the reinforcement. The concrete is assumed to be solid, without cracks and not deformable at first. The corrosion process is assumed to be carbonation induced (i.e. content of chlorides < 0.03 wt% [4]).

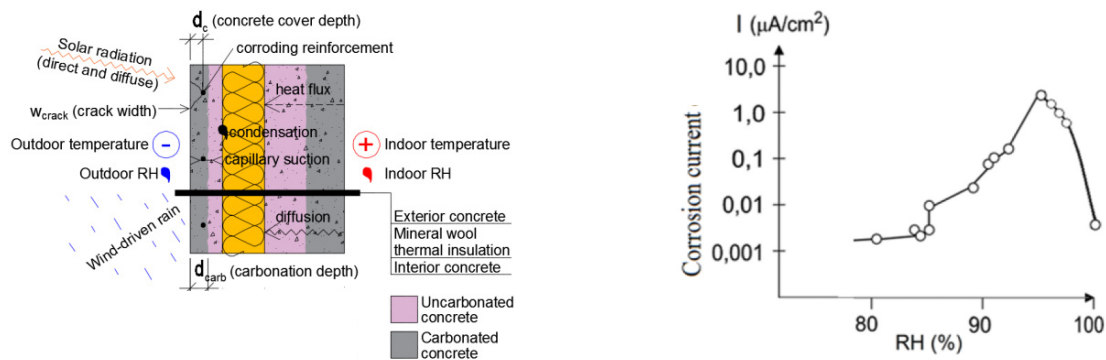


Fig. 1. Introduction of the research problem as a cross-section of a studied wall (left) and corrosion current depending on the RH of concrete (valid for a temperature of $+5^\circ C$), based on [18] (right).

Corrosion model used in the study is the same as that which is described thoroughly and compared with field measurements in [22]. The research problem itself is introduced in Fig. 1, left. In the propagation phase, carbonation induced corrosion current primarily depends on RH as shown in Fig. 1, right and secondly on the temperature inside the concrete.

Electrical resistivity is related to RH in concrete, since resistivity/conductivity depends on the amount of water molecules in the pores. There is a thicker layer of water molecules on pore walls at high RH causing smaller electrical resistivity. Appearance of a first crack and its expansion up to a limit criterion is shown in Fig. 2.

Higher temperatures accelerate corrosion as there are more intensive electrochemical (anodic and cathodic) reactions caused by electrons that are moving faster. In [22] and in this study as well, a change of corrosion current 5-10 times with a 10°C temperature based on [24], is used.

Corrosion propagation was calculated according to the following steps:

- Hourly values for temperature and RH were calculated inside the exterior concrete at different depths of the reinforcement ($d_c=10-15$ mm, $d_c=15-20$ mm and $d_c=20-25$ mm, see Fig. 1, left) by using a dynamic hygrothermal simulation tool (a description of the buildings and a simulation tool follows in a later chapter);
- Hourly values for corrosion current I_{cor} were calculated from the RH according to [18] in Fig. 2, right (MS Excel post-processing);
- Hourly values for corrosion current I_{cor} were corrected with the temperature (by 7.5 times with a 10 °C temperature change reference to a 5 °C baseline);
- A cross-section loss of the reinforcement was calculated according to Faraday's Law (Eq. 1), from [25].
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$$M_{loss} = \frac{M \cdot I_{cor} \cdot \tau}{z \cdot F} \quad (1)$$

where M_{loss} is the mass of steel dissolved at the anode during the overall time τ , kg/m²; M is the molecular weight of corroding steel ($M = 55.8$ g/mol); I_{cor} is the corrosion current, A/m²; τ is the corrosion duration, s; z is the valence of corroding metal, i.e. the number of electrons involved in the electrochemical reaction ($z = 2$ for steel); F is Faraday's constant, $F = 96487$ A·s/mol;

- A cross-section loss x_0 that relates to the first visible crack ($w=0.05$ mm) depends on the cover depth c , mm and diameter of the reinforcement d , mm being calculated (see Fig. 2, left): $x_0=7.53+9.32 \cdot d_c/d$. The uniform corrosion of a cylinder-shaped reinforcement and the density of the steel $\rho=7.85$ g/cm³ is assumed.

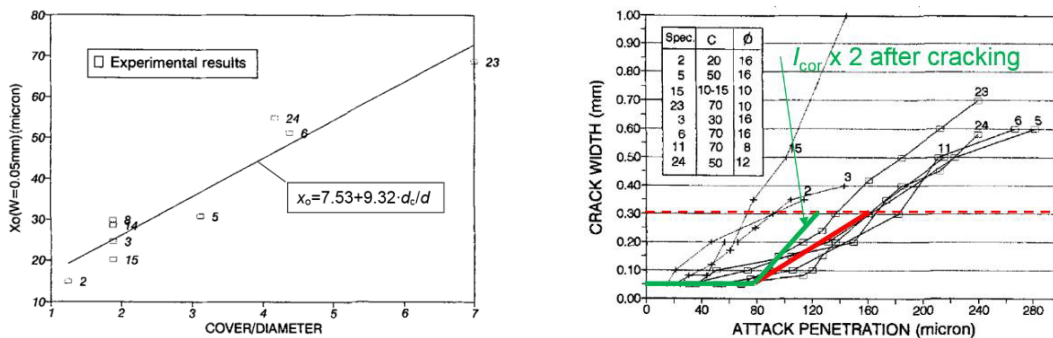


Fig. 2. In the left, the ratio of the reinforcement's cover depth against diameter causing the first crack (crack width at the y axis $w=0.05$ mm) and further crack evolution ($w=0.3$ mm, right) [23].

Further attack penetration for the crack's opening, from 0.05 mm up to 0.3 mm ($\Delta 0.25$ mm crack width corresponds to $\Delta 80$ μm attack penetration) is independent of the cover/diameter ratio from Fig. 2, right. Corrosion current is assumed to double ($\Delta 0.25$ mm crack width corresponds to $\Delta 40$ μm attack penetration) after the formation of the first crack caused by increased WDR penetration as well as the dependence of the crack opening on the corrosion current as stated in [23]. Cracks wider than 0.3 mm lead to escalating degradation as well as aesthetic problems.

2.2. Calculations

The studied wall of a typical five story apartment building composing of two layers of RC and thermal insulation in between is shown in Fig. 3. Dynamic hygrothermal simulation tool Delphin was applied for calculation conformity in two earlier studies, in which the hygrothermal simulation model was developed and validated [26], and validation of a corrosion propagation model [22].

Indoor hygrothermal loads based on measured data in Estonia by [27] was used. Indoor air temperature level was stable at $+22$ $^{\circ}\text{C}$ during the heating season. Two moisture excess levels $\Delta v=3$ g/m^3 as a typical average and 5 g/m^3 being a critical value representative for the occupancy level ~ 25 m^2/person was used.

Outdoor climate conditions with an hourly resolution shown in Fig. 1, left, was measured by the Estonian Weather Service during 2006–2012 (and 1970–1976 for the comparison). Direct solar radiation was ignored since the wall might shaded by the neighbouring buildings or trees. The vertical wall was chosen to have South-West orientation having the most severe WDR loads [28]. Rainfall to the vertical façade was calculated by the user according to the standard rain model of Delphin, considering rain intensity, wind direction, and wind velocity. This approach with an average catch ratio $\eta \sim 0.2$ represents a typical load for the centre of a façade in an urban environment and is well consistent with $\eta \sim 0.5$ at wind velocity 10 m/s given in [10]. A critical WDR level at the centre of the unobstructed façade was achieved via the corrections according to [29], ending up with a catch ratio $\eta \sim 0.43$. A critical WDR level at the top edge of a low rise building was doubled ($\eta \sim 0.86$), as proposed in [10]. One percent of WDR load [30] was assumed to penetrate through the ETICS on the exterior surface of the original RC façade.

Several calculation cases were set in order to cover the variability of factors affecting the wall's performance (base case is marked in **bold**):

- Calculation period (climate): 1970-1976/**2006-2012**
- Initial moisture content of exterior layer of RC: $w_0=90/110$ kg/m^3
- Wind-driven rain load: $\eta \sim \mathbf{0.43/0.86}$
- Indoor moisture excess: $\Delta v=3/5$ g/m^3
- Water vapour diffusion resistance of exterior RC: $\mu=19/41$
- Three different materials for additional thermal insulation: **EPS**, mineral wool, polyisocyanurate (PIR)

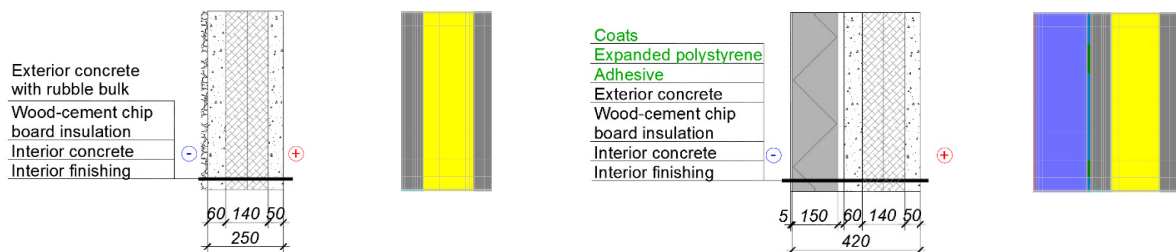


Fig. 3. Cross-section of original RC wall (left) and its simulation model from the software Delphin (2nd from the left). Cross-section of the wall with the installed ETICS (2nd from the right) and the same as a Delphin model (right).

Table 1. Material properties used in calculations.

	Concrete	Wood-cement chip-board	Adhesive mortar	EPS	MW	PIR	Exterior rendering
Bulk density ρ , kg/m ³	2320	500	700	35	75	35	1270
Porosity θ , m ³ /m ³	0.14	0.93	0.73	0.94	0.92	0.91	0.50
Specific heat capacity c , J/(kg·K)	850	1470	945	1500	840	1500	960
Thermal conductivity λ , W/(m·K)	1.5	0.12	0.19	0.035	0.038	0.027	1.0
Vapour diffusion resistance factor μ , -	19/41	3.8	15	15	2	225	10
Liquid water conductivity k , kg/(m·s·Pa)	$4.4 \cdot 10^{-11}$	$16 \cdot 10^{-9}$	$3.2 \cdot 10^{-9}$	0	0	$8 \cdot 10^{-6}$	$0.27 \cdot 10^{-6}$
Air permeability K_g , s	$1 \cdot 10^{-6}$	$7 \cdot 10^{-3}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-2}$	0	$1 \cdot 10^{-6}$
Initial moisture w_0 , kg/m ³ / RH, %	90-110/98.2-99.8	27 / 60	200 / 100	0.6 / 60	3.1 / 60	~0 / 60	300

Material properties used in the calculation are given in Table 1. Material properties originate from the software's database and were corrected in the case of concrete according to data measured in Tampere University of Technology in Finland. In addition to the latter fixed values, Delphin's default functions of material properties depending on the hygric environment, was included.

3. Results

Presentation of the results is derived from the research questions set up in the introduction. Hence, the temperature, RH, and corrosion current in the exterior layer of RC during the propagation period is presented, see Fig. 4. As expected, the temperature inside the RC after applying ETICS is relatively stable and does not drop below +10 °C even in winter. Hence, no more freeze-thaw cycles in RC will appear.

A notable delay of approximately ten days between the WDR hitting the façade and an increase of RH/corrosion current at 20–25 mm (as a typical cover depth) from the concrete's surface was observed. RH in the beginning of the calculation inside the exterior RC is close to 100% for the original wall as well as for the ETICS wall, see Fig. 4, left. In the case of the original, uncovered wall, RH drops in spring within each year but rises up to close to 100% due to WDR in summer and autumn. In the case of ETICS, the majority of the initial moisture in RC dries out during the first year and the rest during the second year. Fig. 4, right, indicates that summer periods characteristic of severe WDR cause the majority of the corrosion propagation.

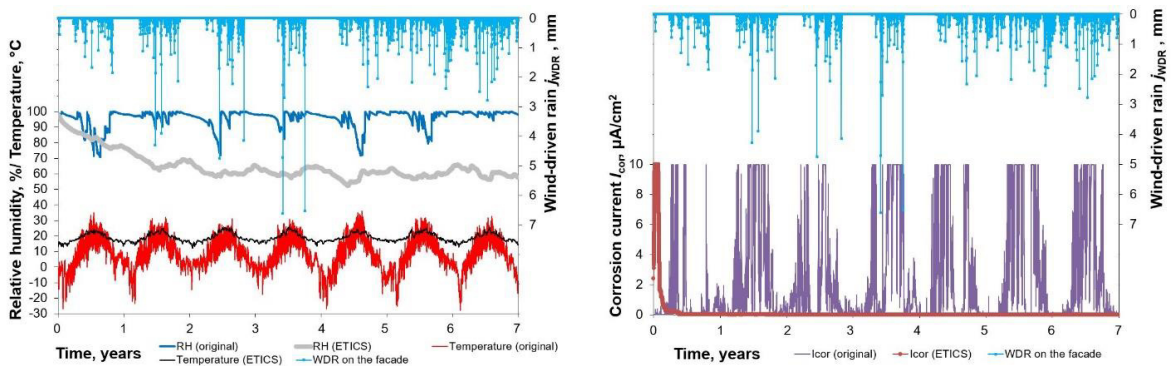


Fig. 4. Temperature and RH inside the exterior layer of RC (left) at a depth of 20–25 mm from the façade surface. Corrosion current of an original wall against after applying ETICS (right).

Corrosion current (shown in Fig. 4, right) was summarised for the total corrosion current, see Fig. 5 and Fig. 6. This enables us to evaluate whether the total corrosion propagation causes cracking of RC or not.

One of the main results of the paper is the residual service life for an original RC wall of three to six years (see Fig. 5) if using a failure criterion crack width $w=0.3$ mm, as in the paper where the method was validated in. Latter residual service life is valid for a façade, where carbonation depth has just reached the reinforcement and a building facing the South-West is not sheltered from WDR. Variations between the corrosion current at a different depth from the surface (10–15 mm; 15–20 mm; 20–25 mm) are rather small whereas a higher and more stable RH level deeper inside the concrete leads to faster corrosion. The key factor to define the residual service life is the ratio of concrete cover depth d_c against reinforcement diameter d that the initiation of the crack depends on. In the case of a small cover depth, say 10 mm, or thick reinforcement, say Ø8 mm, cover depth d_c diameter d ratio is only 2–3, meaning a residual service life of 3–4 years.

Installation of ETICS (another, lower group of results in Fig. 5 and Fig. 6) increases the corrosion propagation during a short period of time while the moisture dries out. Corrosion at the start of drying out is most intensive with a material having the highest vapour diffusion resistance (PIR, $\mu=225$). In this case, the total corrosion current increases linearly for about half a year, followed by slower growth for about a year. Levels of total corrosion have similar behaviour in the case of high initial moisture content of concrete ($w_0=110$ kg/m³), reaching much higher levels compared to the ETICS base case (defined in the last section of methods). From the criterion of corrosion propagation (crack width $w=0.3$ mm), all three thermal insulation materials used for ETICS are fair. Still, the durability of ETICS, especially in the case of mineral wool, has to be further analysed in terms of large moisture flux originating from the concrete while drying out. If one would use ETICS with PUR insulation or initial moisture content $w=110$ kg/m³, it would cause failure in the case of cover depth/diameter ratio $d_c/d < 4$ and taking the crack initiation ($w=0.05$ mm) as the criterion. Since only one parameter was changed at the time to study its effect, using PIR insulation in combination with high initial moisture content might lead to failure and therefore, should be avoided.

Small deviation of the results concerning different climatic years, WDR load, material properties, and indoor moisture excess in Fig. 6 increase the reliability of the calculated residual service lives. An increase of WDR load ($\eta=0.86$) indicates a somewhat surprising result – the total corrosion current during certain periods (e.g. fourth year) decreases. The reason for such phenomenon can be derived from Fig. 1, right, and Fig. 4, left, where the dependency of corrosion current on RH, and RH of concrete, respectively, is presented. An increase of WDR causes too high levels of RH in terms of corrosion current, being $\approx 97\%$. Climatic years chosen (1970–1976 vs 2006–2013) have a detectable impact on the results. In any case, the statement for the residual service life being three to six years is evident. An increase of moisture excess ($\Delta v=5$ g/m³) accelerates the corrosion a little as expected.

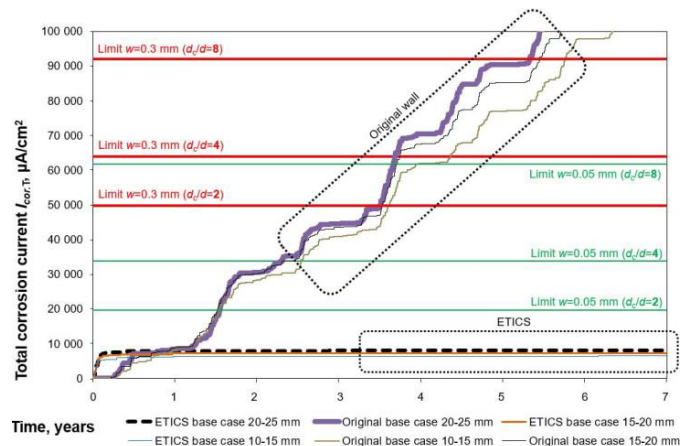


Fig. 5. Total corrosion current at different depths from the surface without ETICS (original wall) and after applying ETICS. Horizontal lines stand for the limit criteria for different ratios of concrete cover depth d_c against reinforcement diameter d .

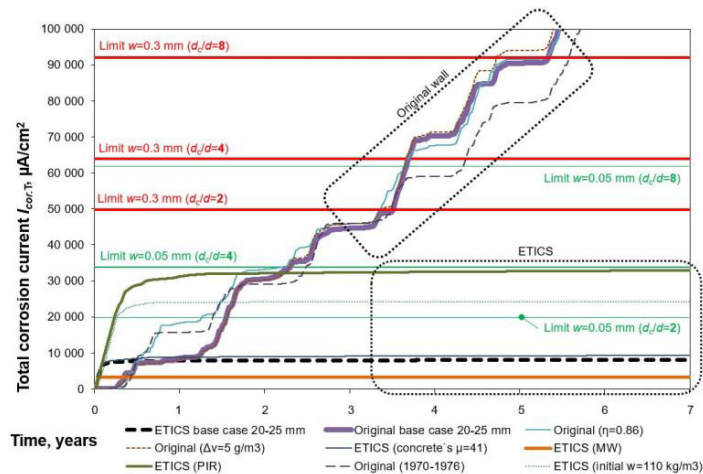


Fig. 6. Total corrosion current of different calculation cases against the limit criteria and the impact of applying ETICS at a 20–25 mm cover depth. Each calculation case represents one deviation from the base case – changed parameter named in the parentheses.

4. Discussion

According to the studies carried out, the propagation time of reinforcement corrosion after the carbonation depth has reached the reinforcement takes only three to six years for the crack to appear. Three years stand for a small cover depth/diameter ratio (e.g. $d_c/d < 2$) while six years stand for a typical cover depth in combination with a thin, say $\varnothing 3$ mm reinforcement ($d_c/d > 8$). A limit criterion for the crack width $w=0.3$ mm was used for defining the residual service life conformity with the study in which the method was validated in [22]. Other criterion can be discussed but an increase of corrosion propagation after the appearance of the first crack $w=0.05$ mm is evident. This is to say that the initiation period, i.e. time until CO_2 penetrates into RC and the carbonation front reaches the reinforcement, is crucial for the service life of RC façades. Studies [1] have shown that the average measured carbonation depth of Estonian RC façades is typically 10–40 mm and up to 40–70 mm in maximum cases. Since the carbonation depth could exceed concrete cover depth, RC façades should be protected against future corrosion.

Different climate periods (1970–1976 vs 2006–2012) were studied in order to determine the impact on the results. In the long term, the earlier period (1970–1976) ends up with lower levels of corrosion, although, it has more intense rainfall (537 vs 506 mm as annual average). The explanation for this is larger WDR loads leading to RH being too high (initial moisture content of concrete is high already). Another reason is the time resolution of climate data that is automatically saved with an hourly interval since 2006. In earlier times, data was collected manually with a three or six hour interval. For the hourly resolution used in our study, data had to be converted first. As stated in [31], as short resolution as possible (maximum an hour or ten minutes, if available) should be used, since averaging the data might cause significant inaccuracy. Evenly distributed WDR penetrates into the façade much more as saturated water film and run-off emerges later.

5. Conclusions

Corrosion propagation time of unprotected concrete facade exposed to WDR loads is approximately three to six years after the carbonation depth has reached the reinforcement. The exact duration depends mostly on the outdoor climate, hygrothermal properties of concrete, but also on the ratio of concrete cover depth against the reinforcement diameter. The most intense time of the year in terms of corrosion for the original RC facade is summer, characterised by a high level of rainfall and outdoor temperature.

The results also show that the ETICS with all the studied thermal insulation materials do not increase the reinforcement corrosion in long term. Corrosion of reinforcement in carbonated concrete after applying ETICS rises for less than a year but becomes low later on, and therefore, no cracking will occur. Therefore, ETICS as a renovation scenario is acceptable in terms of corrosion propagation. Drying out moisture or vapour diffusion from indoor air is not able to propagate the corrosion of reinforcement in carbonated concrete if it has not started yet before installing ETICS. Temperature of exterior layer of old concrete facade after applying ETICS remains above +10 °C throughout the year, meaning no more freeze-thaw damage. High initial moisture content of concrete ($w_0 > 90 \text{ kg/m}^3$) in combination with high water vapour resistance of the additional exterior thermal insulation (e.g. $\mu=225$) might cause corrosion induced cracking and is therefore advised to avoid.

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