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# Possibilities to validate design models for corrosion in carbonated concrete using condition assessment data

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ABSTRACT

This study analyses the actual observed corrosion damage and active corrosion in concrete facades in Nordic outdoor climate and compares this data with the DuraCrete design model for carbonation initiated corrosion propagation phase. Active corrosion was examined in this study by calculating backwards the age of the building and the initiation time by carbonation from a large condition assessment data from concrete facades and balconies using statistical simulation methods. The earliest visible corrosion damage on concrete facades was observed in condition assessments already after 8–15 years from construction. In a large group of buildings the damage occurrence was found to reasonably well follow a normal distribution. The design model was found in the case of concrete facades and balconies in Finnish climate conditions to overestimate considerably the propagation phase predictions in all of the studied structure types compared to the statistical analysis. The overestimation in the model is due to the high influence of concrete resistivity and the definition of corrosion penetration needed for the initiation of a crack.


## 1. Introduction

Starting from the 1960s, concrete structures have become prevalent in Finnish construction. This is a result mainly from urbanization and domestic housing policy in Finland which triggered the production of prefabricated concrete buildings. Corrosion is responsible for approximately 11–40% of the repair costs of prefabricated concrete facades in Finland depending on the surface finishing [1], and along with insufficient frost resistance, carbonation induced corrosion is the most significant degradation mechanism of concrete buildings in Finnish environment. The damage caused by the both mechanisms accounts for € 3.5 billion in repair need and is increasing [1]. It alone makes 1.8% of yearly GDP of Finland [2]. This is an issue that cannot be solved instantly, but requires a rehabilitation plan over several years.

There must be a subjective methodology to compare different repair options technically as well as economically including instant and life cycle costs. Large amount of information on the durability properties of single buildings and their repair possibilities can be gathered in condition assessments but to estimate the residual service life of a concrete structure it is necessary to utilize predictive models.

Degradation models can be divided into empirical, numerical and analytical ones depending on how they have been developed [3]. Empirical models such as [4] are based on assumed direct relationship between corrosion rate and influencing parameters such as experimentally determined coefficients or material properties. Also the use of Delphic oracle method [5] falls under the category of empirical models. Numerical models such as [6,7] are mathematical models that provide approximate solutions using boundary conditions and differential equations inside a medium divided in element matrix (e.g. FEM). Analytical models such as [8,9] are based on closed-form solutions of mathematical equations.

This study analyses the actual observed corrosion damage and active corrosion in concrete facades in Nordic outdoor climate and compares this data with the DuraCrete design model [4] for carbonation initiated corrosion propagation phase. The statistical analysis is based on condition assessment data gathered from the assessment reports of 443 concrete facades and 331 concrete balconies built in 1965–1995. Lollini et al. [10] have conducted a similar study on the initiation phase by carbonation using the fib initiation model [5] and a case study on eight reinforced concrete buildings. This study aims at finding out what is the correspon-

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dence of the design model to actual observed corrosion damage on concrete facades in Finnish outdoor climate conditions.

## 2. Background

### 2.1. Effects of reinforcement corrosion in concrete

The effects of reinforcement corrosion have resulted in high maintenance costs in concrete infrastructure around the world in varying climates but also in climates similar to Finland [11–13]. Regarding concrete facades, corrosion of reinforcement is usually initiated by carbonation. In Finnish outdoor climate in particular there are scarce environmental sources for external chlorides [14].

Corrosion of reinforcement affects concrete structures basically either by cracking of concrete cover caused by corrosion products or by reduction of effective steel cross-section. Cracking occurs in structures where the reinforcement is placed quite near the concrete surface. Cracking accelerates the penetration of harmful agents to concrete and causes visual defects in concrete facades. The performance requirements for structures are many and the suitability of each depends on the type of structure. Therefore the occurrence of cracks is not the ultimate limit for the life of the structure, but rather a limit based on the appearance or serviceability of the structure. There exists an undefined period of residual life after cracking, where the structure will still continue to function adequately until the final limit state were it structural failure, rehabilitation or deconstruction.

### 2.2. Concrete facades and balconies in Finland

The concrete structures of this building stock that are subject to degradation are facades and balconies, commonly built of prefabricated sandwich facade panels and balcony slab, frame and parapet elements. Building even today is based on an open concrete element system (BES) developed in 1969 that standardizes building units and their details of joints. Table 1 shows a collection of key properties of these structures in regard of durability.

The Finnish building stock, concrete blocks of flats in particular, is highly homogenous by structural solutions. These structures and their construction techniques have remained comparatively uniform for many decades. Finishing, thermal insulation and dimensions of units have changed over time with building regulations but the basic structural idea remains. The concrete panels used in exterior walls of multi-storey residential buildings have been chiefly prefabricated sandwich-type panels with thermal insulation placed between two concrete layers. The surface finishing in 1965–1995 has typically been either exposed aggregate surface or brushed concrete surface that has been painted with a more or less permeable paint. The most common balcony type in Finland from the late 1960s until today consists of a floor slab, side panels and a parapet panel of precast concrete. These stacked balconies have their own foundations and are braced to the building frame horizontally. Balcony slabs are typically cast upside down to form the necessary slope and chutes for the runoff water. The soffit surface of a balcony slab is thereby most commonly floated and painted with a permeable paint.

The requirements given for reinforcement in national concrete code are shown in Table 2. In addition, a common requirement for the cover of auxiliary reinforcement (manufacturing reinforcement, lifting straps) has been 15 mm. Basically, the requirement for concrete cover has remained the same from 1978 to this date (concerning facade concrete). However, in current code the minimum requirement is set, according to climate exposure class, to 10–40 mm. For carbonation induced corrosion, minimum requirements of 10 mm (dry or constantly wet structures) to 25 mm (e.g. facades and balconies) are nowadays used [15]. Nevertheless large scatter is associated with the cover depths of existing concrete facade panels [14] as is later illustrated in Fig. 9. The same was also observed in [10] in the case of reinforced concrete nuclear power plant buildings.

### 2.3. Climate exposure conditions

Lahdensivu [14] has shown that the most crucial climatic factor for durability of concrete facades are prevailing wind directions during rain and amount of freeze–thaw cycles after liquid precipitation. The most common wind directions during liquid precipitation in Finland are concentrated on south and west direction. Thus, the distribution of rainfall is concentrated on southern and western facades and that can be seen also on cases of observed deterioration caused by carbonation induced corrosion and frost damage. On coastal area annual precipitation is on average mildly higher than in inland. Typically facades and balconies fall into the exposure classes XC3 and XC4 in European standards [17].

Finnish climate is much milder than its location on mid-latitude predicts, mostly due to the warm and steady Atlantic Ocean. Also Scandinavian Peninsula prevents Finland for the most extreme conditions of e.g. coastal areas of Norway. In the Köppen Climate

**Table 2**
Requirements for the minimum concrete cover of working reinforcement and concrete grade in Finnish concrete codes from 1965 to 1995 [16].

| Year | Required minimum concrete cover of reinforcement (mm) | Required concrete grade/ cube strength (MPa) |
|---|---|---|
| 1965–1977 | 20 | C20/25 |
| 1978–1988 | 25 | C20/25 |
| 1989–1992 | 25 | C25/30 |
| 1993–1995 | 25 | C32/40[a] |

[a] Converted from cube strength to concrete grade.

**Table 1**
Typical dimensions and reinforcement properties of Finnish prefabricated facades and balconies.

| Structure/unit | Dimensions | Reinforcement | Comments |
|---|---|---|---|
| Facade sandwich panel | Outer layer 40–70 mm, inner layer 80 mm (non-bearing) or 150 mm (load bearing) | Outer layer: mesh 3–4 mm with 150 mm spacing, edge rebars 6–8 mm, trusses connecting outer and inner layer spacing 600 mm, aux. reinforcement/lifting straps | Thickness of thermal insulation varies with regulations, elastic element joints (polymer sealants), usually no ventilation gap = dries slowly |
| Balcony slab | Thickness 140–200 mm (sloped upper surface) | Bearing reinforcement: 10–12 mm spacing 100–150 mm in the lower section of the slab upper section: tie rods, aux. reinforcement, lifting straps | Water drainage system varies: drain pipe, spout pipe through the parapet, gap between slab and parapet. No waterproofing |
| Balcony side panel | Thickness 150–180 mm | Edge rebars 10–12 mm, aux. reinforcement/lifting straps | Height of no more than 8 floors allows the use of non-reinforced concrete panels |
| Balcony parapet | Thickness 70–85 mm | Heavy reinforcement near both surfaces, rebars 6–8 mm spacing 150 | Often cast as one unit with the slab |