Long-term safety of hybrid reinforced concrete beams with rebar corrosion

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ABSTRACT

The present study investigated the durability and safety of hybrid reinforced concrete, i.e., fibre reinforced concrete combined with steel reinforcing bars. The effect of cracks on the corrosion pattern and influence of corrosion pits on the mechanical properties of rebars were experimentally investigated. It was found that flexural cracks induced pitting corrosion, and the most severe pit governed the tensile properties of rebars. Further, analytical modelling showed that the moment capacity of corroded hybrid reinforced beams was higher than conventional reinforced beams with the same level of rebar corrosion.

Key words: Cracking, Chlorides, Corrosion, Fibres, Durability.

1. INTRODUCTION

1.1 Hybrid reinforcement in concrete

Civil engineering structures like bridges and harbours have strict crack width limitation to reduce the risk of reinforcement corrosion caused by chlorides. For example, the allowable surface crack width according to AMA Anläggning 17 is less than 0.2 mm. This often results in very high reinforcement ratios in the structural design, and costly crack repairs during the service life of structures. As fibres can greatly improve the crack resistance of concrete, adding fibres in reinforced concrete is a very promising solution to meet the crack width requirement, using less amount of traditional reinforcing bars at the same time.

A hybrid reinforcement system is obtained when combining traditional rebars and discontinuous fibres in concrete. Compared to traditional reinforced concrete, hybrid reinforced concrete is beneficial to control the early-age restraint cracking and has superior structural performance under mechanical loading. However, more studies are necessary on the corrosion effects in hybrid reinforced concrete to appraise its long-term safety and durability in chloride environments.

1.2 Aim and scopes

The aim of this study was to provide research outcomes for an ultimate goal which will evaluate the life cycle cost of hybrid reinforced concrete elements, including the cost of materials, construction, and maintenance, repair/replacement, and environmental impact i.e., green-house gas emissions. The scope of this paper is to quantify the corrosion effects in hybrid reinforced concrete beams.

This work investigates the experimental results of a project initiated in 2013 where natural corrosion tests on hybrid reinforced beams with various types and amounts of fibres were carried out, cf. [1]. Previous studies by the authors showed that fibres can delay corrosion initiation [1] and corroded hybrid reinforced beams displayed higher residual capacity than corroded conventional reinforced beams [2]. To evaluate the overall benefits of hybrid reinforced concrete, this study focused on the following tasks:

- To examine the influence of cracks on the corrosion pattern of rebars.
- To analyse the mechanical behaviour of rebars with different levels of pitting corrosion.
- To develop a structural model for assessing the residual behaviour of hybrid reinforced beams with localised (pitting) rebar corrosion.

2 EXPERIMENTAL STUDY

2.1 Specimens and exposure condition

Beams with the dimension 1100 x 180 x 100 mm^3 and three Φ10 mm ribbed rebars at a clear cover of 30 mm were cast. Four mix series were included: conventional reinforced beams referred to as "plain" (PL) series, and three hybrid reinforced series with different types of fibres: steel fibres (ST), hybridized steel and PVA fibres (HY) and synthetic fibers (SY). The details about the mix proportions and specimens preparation can be found in [1]. Beams were pre-cracked under three-point bending until the maximum crack width reached a prescribed value. After the pre-loading, all the beams were subjected to wet-drying cyclic exposure of chloride solution for three years.

2.2 Crack pattern and corrosion pattern

The crack and pit locations, and crack widths were documented for finding their correlation. It was found that most rebars exhibited pitting corrosion at the flexural cracks; however, not all flexural cracks induced corrosion. In addition, longitudinal cracks caused by corrosion expansion were also observed. Figure 1 shows an example of the crack and corrosion pattern for one ST beam with 0.4 mm maximum flexural crack width under sustained loading during the exposure.

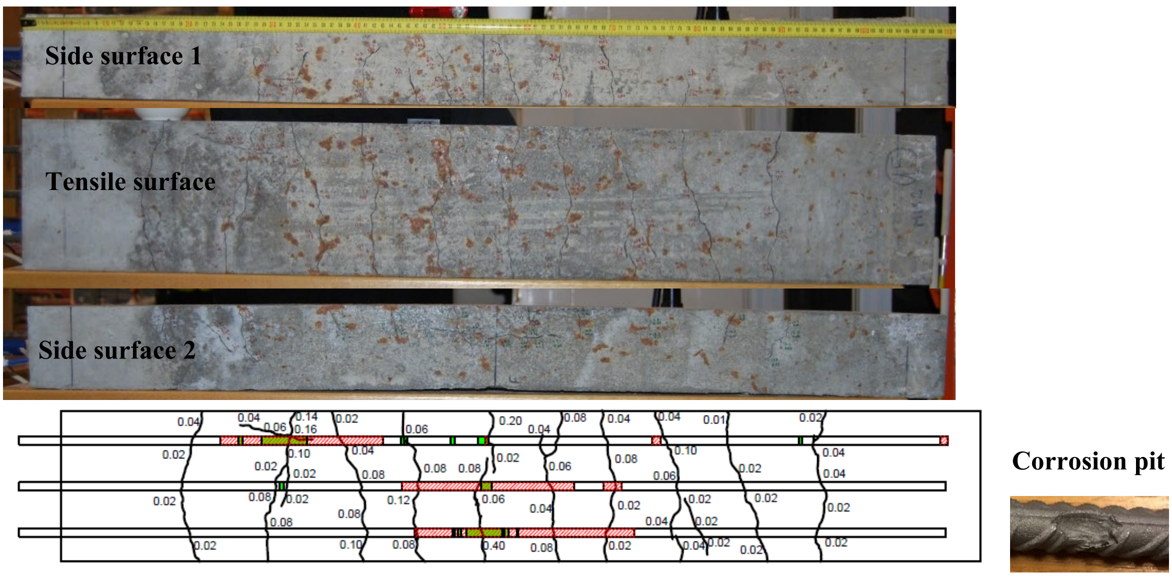

Figure 1 –Crack pattern and corrosion pattern on one ST beam. Red line hatch represents the general corrosion and solid fill represents corrosion pits where the colour indicates the severity.

2.3 Mechanical properties of corroded rebars

The mechanical properties of corroded rebars were studied from tensile testing. Digital Image Correlation (DIC) was used to study the effect of pit morphology on the yield strain development. The local strain distribution in Figure 2 revealed the strain localisation in the pit. With increasing maximum local corrosion level μ_{max} (i.e. maximum cross-sectional area loss measured by 3D-scanning), the strain outside the failure zone at ultimate (i.e. at the maximum force) decreased significantly, even to less than the yield strain of uncorroded rebar; while for the uncorroded rebar, the ultimate strain based on the gauge across and outside the failure zone was the same, as the strain localisation occurs at necking (after ultimate point).

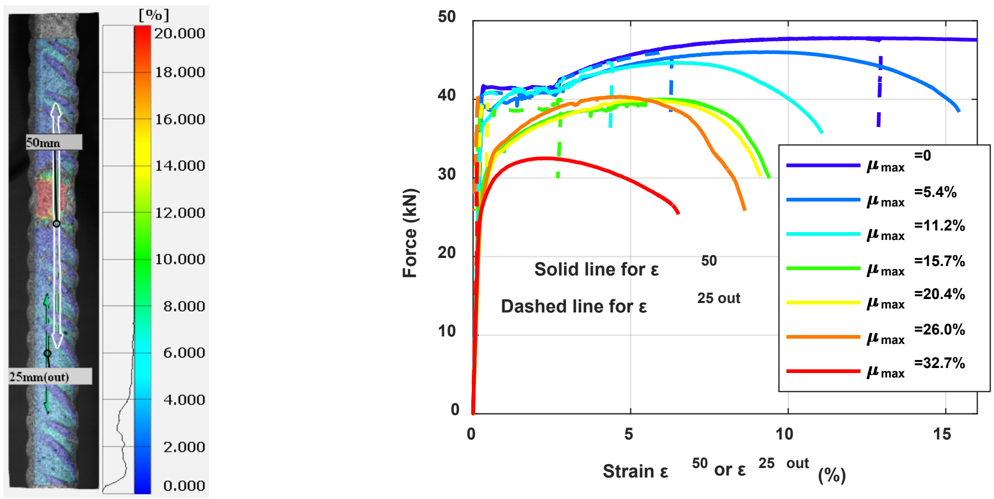

Figure 2 – Left: local strain distribution at ultimate for the bar with μ_{max}=15.7%. Right: force-strain curves, the two strain gauges l_g=50mm and 25mm(out) are shown in left.

3 ANALYTICAL MODELING OF BEAMS UNDER THREE-POINT BENDING

To calculate the structural behaviour of conventional and hybrid reinforced beams with rebar corrosion, a simple analytical model based on section analysis was developed. In the modelling, corrosion-induced cracking in the cover was not considered to affect concrete properties, as the cracking degree was limited, and no spalling occurred (see Figure 1). The bond properties were not modelled, as no beams failed due to bond failure [2]. The stress-strain relationship of plain concrete in compression was modelled by Thorenfeldt model [3]; in tension, a linear stress-strain relation before the strength and zero residual strength were assumed. For fibre reinforced concrete in compression, the modified parabola proposed in [4] was adopted, and a bilinear softening stress-strain relation based on an inverse analysis from materials test results in [2] was used. For the corroded rebars, the strength was considered constant as the load loss ratio was close to the maximum cross-sectional area loss ratio; a bilinear constitutive law was used, and the maximum area loss was considered. Since the strain distribution of corroded rebars is not uniform, a length equal to the average crack spacing was chosen to calculate the ultimate strain.

Figure 3 shows the relation of yield moment (M_y), ultimate moment and curvature (M_u and κ_u) with the maximum local corrosion level for PL and ST series beams. Yield and ultimate moments decreased almost linearly with the corrosion level, and the moment capacity at yielding and ultimate of hybrid reinforcement was greater than that of conventional reinforcement. The ultimate curvature with conventional reinforcement was greater than with hybrid reinforcement for low corrosion levels. This is because the contribution of the residual tensile stress of fibre reinforced concrete caused the maximum moment to occur at a smaller curvature compared to conventionally reinforced concrete, in which the bars were more stressed at failure. However, the curvature of hybrid reinforced elements at failure was higher than that of conventional reinforced beam for higher corrosion levels. The ultimate curvature for both types of reinforcement increased with increasing corrosion level up to a certain corrosion level, after which started decreasing. This is due to an initial unloading of the concrete in compression preventing crushing, followed by a decrease of ultimate curvature caused by failure due to the rupture of steel bars.

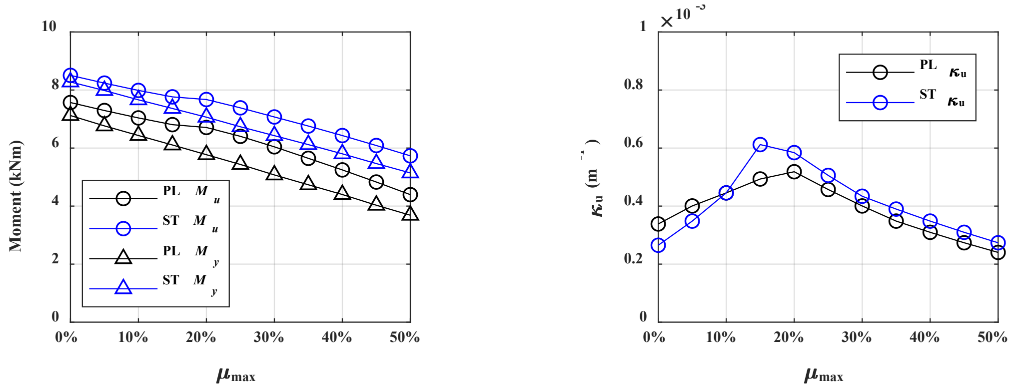

Figure 3 –Influence of maximum local corrosion level. Left: M_u versus μ_{max}. Right: κ_u versus μ_{max}.

4 CONCLUSIONS

This study investigated the long-term safety of hybrid reinforced concrete beams. From the experiments, the relation between the cracks and corrosion pits was examined, and the mechanical properties of corroded rebars were obtained. From the sectional analysis, the residual capacity in terms of moment and curvature of conventional and hybrid reinforced beams under three-point bending were calculated by considering rebar corrosion. The main conclusions from this study were:

- Flexural cracks caused localised pitting corrosion, but not all cracks promoted corrosion.
- DIC technique enabled observing the strain localisation in the corrosion pit. It is crucial to correctly evaluate the ultimate strain of corroded rebars in order to accurately predict the residual deformation capacity of corroded elements.
- The yield and ultimate moment of hybrid reinforced beams were greater than those of conventionally reinforced beams under the same corrosion level. The ultimate curvature of beams in this study was found to increase at smaller corrosion levels but decrease later.

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