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Published in:
Proceedings of the fib Symposium: Concrete Structures for Sustainable Community

Publication date:
2012

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ABSTRACT
A mechanical model has been used to evaluate the rebar-concrete debonding length and Crack Mouth Opening Displacement (CMOD) in reinforced concrete. The modelling is based on the theory of the fictitious crack. It is shown that there is a non-trival relationship between the debonding length and the CMOD, indicating that if the debonding length has a significant influence on the risk of corrosion initiation and propagation (as indicated in the literature), then CMOD cannot be used alone as corrosion risk indicator. A limited parametric study has been performed and it has been shown that the shear strength of the interface has a significant influence on the debonding length. The cover layer – on the other hand – has relatively little influence on the debonding lengths.

Key words: Theory of the fictitious crack, debonding length, CMOD, finite element modelling, reinforced concrete, three-point bending.

1. INTRODUCTION

Durability of structures in the infrastructure is of great importance in the society and the longest possible service life is required combined with as little financial and environmental costs as possible. A number of different deterioration mechanisms are governing the service life of reinforced concrete structures among which reinforcement corrosion is by far the most important, see e.g. (Rendell et al., 2002). Concrete cracks have a major influence on the risk of reinforcement corrosion, however in spite of a significant number of detailed research studies with the purpose of quantifying the influence of structural defects on corrosion, including defects on the reinforcement and cracks in the concrete, no consensus has been established in the area.

The lack of consensus could very well be due to the fact that in standard approaches to service life design, the risks of reinforcement corrosion initiation and propagation are related to the surface crack width alone, in spite of the fact that a number of other conditions seem to be equally or more important as suggested in the literature. Tammo (2009) suggested that the crack width close to the reinforcement is a more appropriate measure for the risk of corrosion initiation. Experimental results published in (Pease, 2011) indicate that the risk of corrosion may be closely linked to damage at the rebar/concrete interface and further that formation of concrete cracks is (always) associated with such damage (Pease 2006). Thus, there are indications that the damage along the reinforcement/concrete interface could be a fundamental indication of the risk of corrosion to be considered together with the crack opening at the concrete surface – the Crack Mouth Opening Displacement (CMOD). Thus appropriate models should be set up and investigation of these parameters (CMOD, the debonding length and their relation and the influence on such relations from geometrical and mechanical parameters) should be performed in order to give a better guidance regarding risk of corrosion initiation and propagation and thereby the service life of a given structure. In this work a mechanical model developed in (Thybo and Rasmussen, 2011) is applied for this investigation. In the following the modelling approach is presented and parametric studies performed.

2. MODELLING APPROACH

The model is based on the Fracture Band Model (Christensen 2003) which is based on the theory of the fictitious crack (Hillerborg et al. 1976).

2.1 Basic equations

The basic equations regarding the deformations are derived on the basis of the Fracture Band Model (FBM). Overall, the curvature of the fracture band element can be considered given. The end sections of the fracture band element remains plane (to be compatible with adjacent beam elements). The (average) strain distribution is linked purely geometrically to the curvature and the stress is linked to the strain through the stress-strain relationship shown in Fig. 1 a). The stress-strain relation of the fracture band is linked to the two constitutive pre- and post-peak constitutive relationships shown in Fig. 1 b) and c). In Fig. 1 f_{ct} is the tensile strength, E_c is the elastic modulus of concrete, σ is the stress, ε is the strain and δ is the crack width.

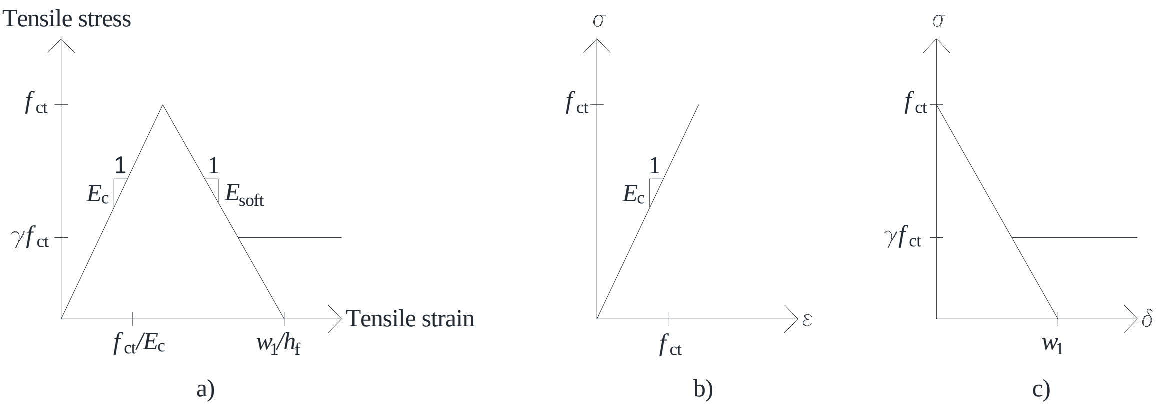


Figure 1 – a) Stress-strain relation in fracture band. b) and c) Constitutive models.

The modulus of elasticity of softening, E_{soft}, is linked to the stress-crack width relationship (Fig. 1 c)) and the width of the crack band element, h_f. In the figure w_1 is the crack width at which the stress transfer is equal to zero. The stress-crack opening relationship applied allows taking possible fibre reinforcement into account through the term γf_{ct} taking the stress relating to fibre bridging into account.

2.2 Computing the crack formation

Crack formation is analyzed in different steps reflecting the various characteristic stages including cover cracking, cracking across the rebar and finally combined crack propagation, crack opening and associated debonding along the concrete-rebar interface. The debonding length is calculated assuming a constant shear stress along the debonded concrete-rebar interface. The analysis allows determination of the relationship between crack width at the rebar, at the bottom face of the element (the so-called Crack Mouth Opening Displacement, CMOD) and the debonding length.

3. RESULTS AND DISCUSSION

The model in Thybo and Rasmussen 2011 was used to simulate the interrelation between the debonding and the CMOD during crack propagation and values as show in Table 1 was applied.

Table 1 – Values used in the simulations unless else stated.

b = 180 mm	f_y = 550 MPa	f_c = 40 MPa
h = 350 mm	E_s = 210000 MPa	E_c = 20000 MPa
d = 318 mm	f_u = 660 MPa	f_{ct} = 3.5 MPa
γ = 0.0	No. reinforcement bars = 3	Gf = 0.15 N/mm
$\varepsilon 1$ = 0.01	Radius of reinforcement = 7 mm	εu = 0.025
τ = 4 MPa		

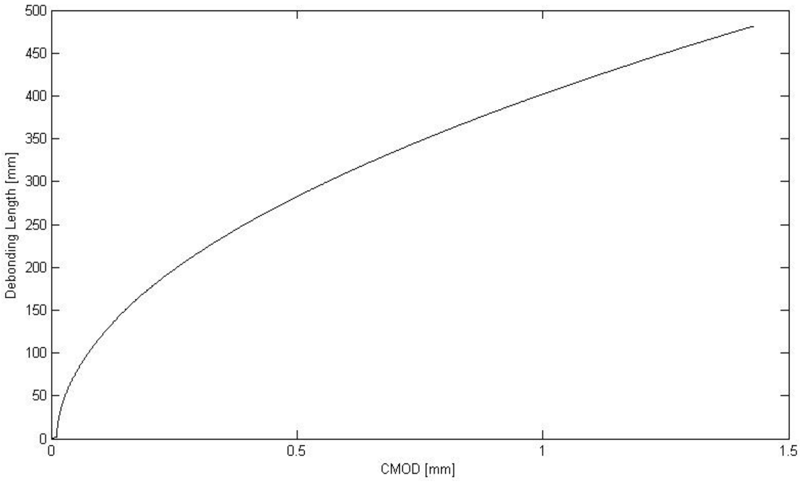
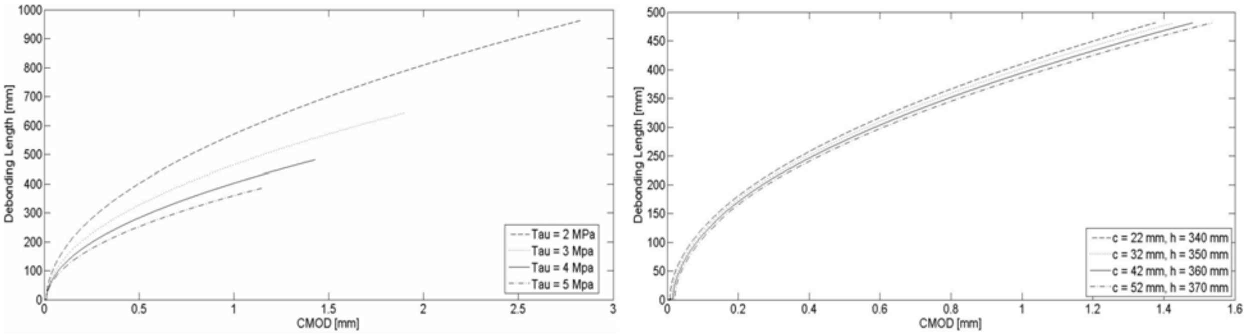


Figure 2 – Illustration of relation between debonding length and CMOD.

In Table 1 b designates the width of the beam, d the effective height, $\varepsilon 1$ the maximum strain during yielding, τ the shear strength of the interface, f_y the yield strength of the re-bar, E_s the modulus of elasticity of steel, f_u the tensile strength of the re-bar, f_c the compressive strength of the concrete, Gf the fracture energy and εu designates the ultimate compressive strain in the concrete. In Fig. 2 the relation between the two parameters is illustrated. From the figure it is seen that the debonding length increases fast for small values of CMOD – typically less than 0.1 mm where a debonding length of approx. 100 mm has been obtained. For increasing values of the CMOD the curve becomes flatter and gets almost linear for CMOD larger than 0.3 mm.

The influence of two parameters, the shear stress at the debonded interface and the cover layer is illustrated in Fig. 3 a) and b) respectively. As seen in Fig. 3 a) the shear stress on the debonded interface (or the shear strength of the interface) has a significant influence on the debonding length – a reduction of the shear strength resulting in significantly larger debonding lengths. Due to the steepness of the curves for small CMODs this effect is particularly important for larger CMODs. The cover layer – on the other hand – has relatively little influence on the debonding lengths. Given the hypothesis that the risk of corrosion initiation is closely related to the debonding length the consequences of these studies are that if the concrete cracks, the influence of CMOD is significant – though even small cracks (0.1 mm or smaller) also give rise to significant corrosion risk and increasing CMOD from 0.1 mm to 0.3 mm only doubles the debonding length. The influence of cover thickness is negligible over the influence of CMOD, but the strength of the interface can easily overrule the influence of CMOD.



a) b)

Figure 3 – Parametric study of a) the shear strength of the interface, τ*, and b) the cover layer, c.*

3. CONCLUSION

An analytical model is presented and applied for the evaluation of the debonding length and the crack mouth opening displacement (CMOD). It is shown that there is a non-trival relationship between the debonding length and the CMOD indicating that if the debonding length has a significant influence on the risk of corrosion initiation and propagation (as indicated in the literature), then CMOD cannot be used alone as corrosion risk indicator - as typically assumed in normative prescriptions.

A limited parametric study has been performed and it has been shown that the shear strength of the interface has a significant influence on the debonding length – a reduction of the shear strength resulting in significantly larger debonding lengths and that this effect is particularly important for larger CMODs. The cover layer – on the other hand – has relatively little influence on the debonding lengths.

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