On the influence of fibres on tensile laps of reinforcement loops

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Summary

In reinforced concrete structures, connections between members are often critical for the performance in the ultimate limit state. The most common approach to provide force transfer across the connection is to overlap reinforcement bars to form a lap splice. Here, looped reinforcement laps subjected to tension were studied using a three-dimensional nonlinear finite element approach. For the constitutive model of concrete, a damage-plasticity approach was used. In this model, the input for the tensile response is given in the form of a stress versus crack-opening curve, which, for the case of concrete with fibres, is adjusted to consider the bridging effect of fibres. The influence of lap length and fibres on the mechanical response was investigated. The numerical results show that fibres significantly increase the strength and ductility of lap splices.
Key Words: *reinforcement loops, lap splices, reinforced concrete, cracking*

Introduction

Force transfer between members of reinforced concrete structures is commonly provided by reinforcement lap splices. Understanding the failure process of these lap splices is important for being able to develop design approaches which can be used with confidence. In tensile lap splices made of reinforcement loops, the loop provides additional force transfer which reduces the overall lap length required. However, for these loop laps, complex failure processes involving spalling of the concrete cover have been reported in experiments [2].

For understanding the nonlinear response of reinforced concrete structures, the nonlinear finite element method provides a powerful tool. By modelling separately the nonlinear response of concrete, steel and bond between concrete and steel, it is possible to provide a better understanding of the processes which govern the often highly nonlinear composite response. This analysis strategy relies on robust numerical techniques, and constitutive models, which describe the material responses well.

In the present study, the nonlinear finite element method was used to study failure process of tensile laps made of reinforcement loops. The main aim is to investigate the influence of fibres in concrete on the response of the tensile laps of reinforcement loops. This work complements recent research in which the influence of fibres on straight tensile laps was studied [4].

Method

For the nonlinear finite element analysis of tensile lap splices of reinforcement loops, an explicit dynamic solution approach with an incremental displacement control was applied. For concrete, constant stress tetrahedral finite elements with the damage-plasticity constitutive model CDPM2 [5] were used. Reinforcement was modelled by frame elements which were positioned independently of the finite element mesh of concrete. The constitutive model for the reinforcement was chosen to be elasto-plastic without hardening. The interaction between concrete and reinforcement was modelled by linking the degrees of freedom of frame elements to those of the concrete elements [8], with a bond-slip law between reinforcement and concrete.

For the concrete constitutive model CDPM2, the stress evaluation is based on the concept of damage mechanics concept with nominal and effective stress. The nominal stress is evaluated by a combination of damage and plasticity, whereas the effective stress in the undamaged material is determined using plasticity only. For the nominal stress evaluation, tensile and compressive damage variables are applied to positive and negative components of the principal effective stress, respectively. The function for the tensile damage variable is derived from a bilinear stress-crack opening (σ-w_{c}) curve, so that the results of analyses of tensile failure in which strains localise in mesh-dependent regions are independent of the finite element mesh [1]. For fibre reinforced concrete, the parameters of the stress-crack opening curve were adjusted to consider the bridging stress of the fibres [6, 7]. Here, it was assumed that the steel fibres, which bridge cracks, are pulled out of the concrete, but do not yield. The presence of small steel fibre volume ratios considered in this study resulted in a small increase of the tensile strength, and a very large increase of the crack opening at which the stress becomes zero. This is also in agreement with meso-scale simulations carried out in [3].

Analyses and results

The tensile specimen consists of two pairs of symmetrically arranged overlapping reinforcement loops embedded in concrete (Figure 1).

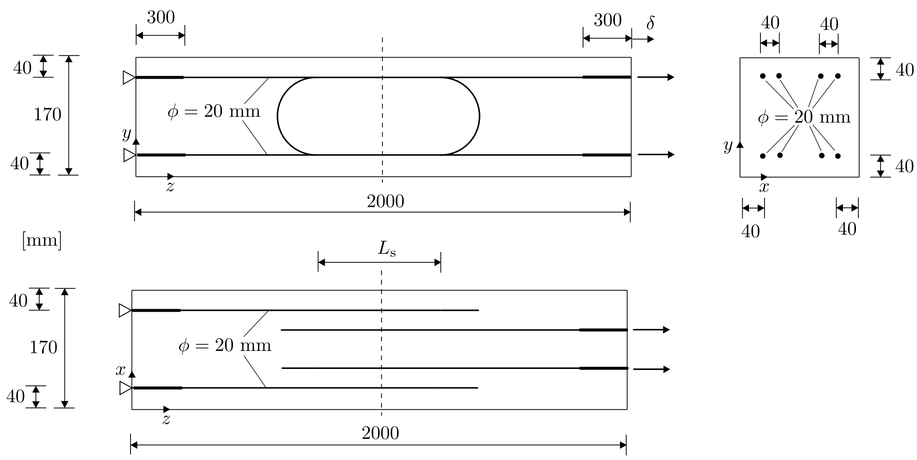

Figure 1: Geometry of splicing of reinforcement loops in direct tension.

In this short paper, selected results for one short lap length $L_{\mathrm{s}} = 300$ mm with and without fibres are shown in the form of normalised load-displacement curves (Figure 2) and maximum principal strain contour plots representing cracks (Figure 3) for stages marked in Figure 2. The load and displacement are normalised by the force and displacement of four continuous reinforcement bars at yielding, respectively.

For concrete without fibres, the peak load is reached before the reinforcement bars yield, which indicates that the strength of the lap limits the overall strength of the specimen. The post-peak response is characterised by a reduction of load with increasing displacements. The crack patterns for the loop splices without fibres show the formation of longitudinal (in the direction of loading) splitting cracks within the lap length (Figure 3a). These cracks represent spalling planes which were experimentally reported in [2]. Outside the lap zone, tensile cracks perpendicular to the load direction are visible.

For concrete with fibres, the peak load exceeds the yield load of the reinforcement. In the post-peak regime, the load remains constant. This response indicates that yielding of the reinforcement limits the strength of the specimen. The maximum load is greater than the yield load of the steel bars, since the bridging stress of steel fibres across cracks contribute to the load transfer. Outside the lap zone, the tensile cracks perpendicular to the load direction have a smaller spacing than for plain concrete. Inside the lap region, almost no longitudinal cracks are visible.

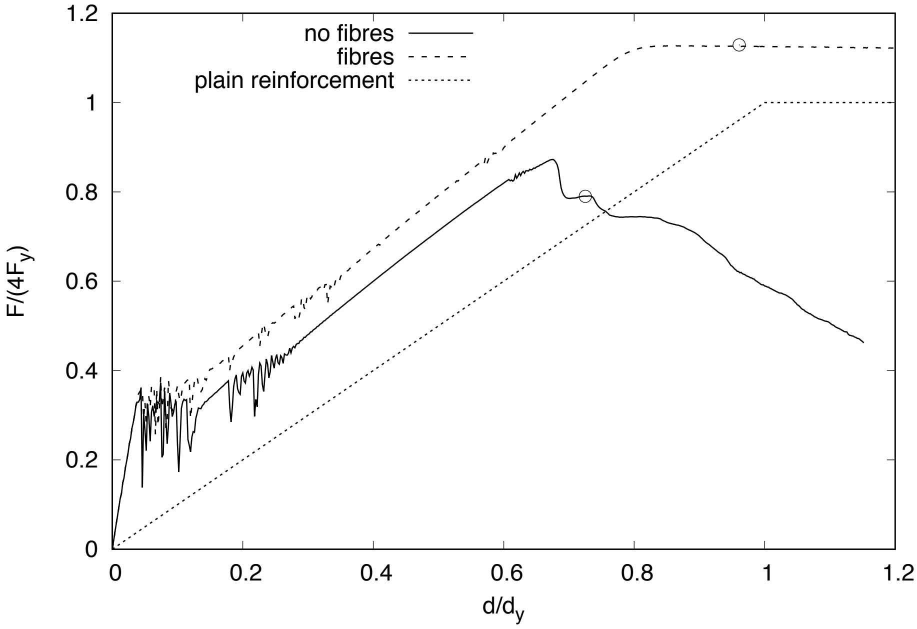

Figure 2: Load-displacement curves for lap splices of reinforcement loops in concrete with a lap length of $L_\mathrm{s} = 300$ mm with and without fibres obtained from nonlinear finite element analyses with the concrete damage plasticity model CDPM2.

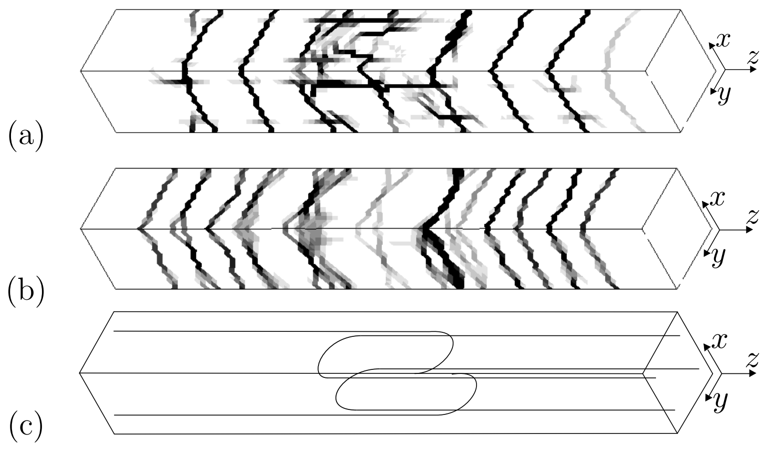

Figure 3: Contour plots of the maximum principal strain for lab splices (a) without fibres and (b) with fibres. Black indicates strains which correspond to crack openings greater than 0.3 mm. The geometry of the loops is shown in (c).

The differences in the crack patterns are further elucidated in Figure 4 by showing plots of only those elements with a maximum principal strain corresponding to a crack opening greater than 0.2 mm for stages marked in Figure 2. For concrete without fibres, the crack plane along the edge of specimen within the lap length is clearly visible, which indicates the onset of spalling.

For the low volume fraction of steel fibres ($V_\mathrm{f} = 1\%$) used, the peak stress in tension is not significantly increased ($f_\mathrm{t} = 3.22$ MPa for fibre reinforced concrete versus $f_\mathrm{t} = 3$ MPa for plain concrete). Still, the bridging stress after cracking is sufficient to prevent spalling and to change considerably the crack pattern.

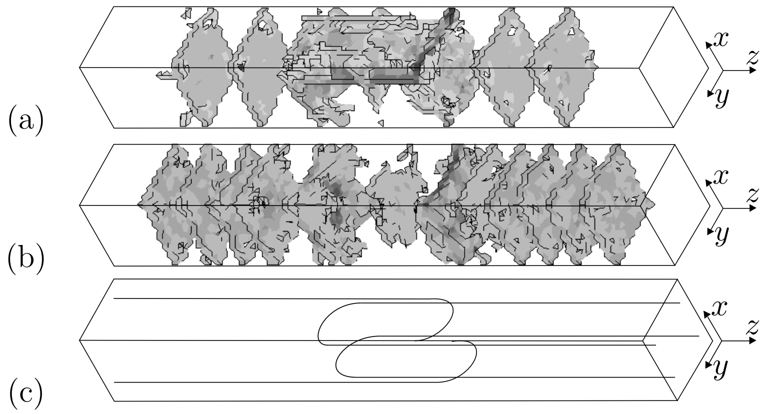

Figure 4: Finite elements with a maximum principal strain corresponding to a crack opening greater than 0.2 mm for lab splices (a) without fibres and (b) with fibres. The geometry of the loops is shown in (c).

Conclusions

The present nonlinear finite element analyses of a short lap splice of reinforcement loop in both plain and steel fibre reinforced concrete showed that 1 % of volume fraction of steel fibres has a strong influence on the mechanical response. For plain concrete, spalling cracks resulted in an abrupt drop of the load before yield load of the reinforcement could be reached. On the other hand, for steel fibre reinforced concrete, spalling was prevented so that yielding of the reinforcement occurred.

References

[1] Bažant, Z. P. and Oh, B.-H. Crack band theory for fracture of concrete. *Materials and Structures*, 16:155–177, 1983.

[2] Grassl, P. Splicing of reinforcement loops in beams: Experiments and non-linear finite element analyses. MSc thesis, Chalmers University of Technology, Göteborg, Sweden, 1999.

[3] Grassl, P. and Antonelli, A. 3D network modelling of fracture processes in fibre-reinforced geomaterials. *International Journal of Solids and Structures*, 156-157:234–242, 2019.

[4] Grassl, P. and Middlemiss, J. Finite element modelling of tensile reinforcement laps in steel fibre reinforced concrete. In *SEMC 2019: The seventh international conference on structural engineering, mechanics and computation*, 2019.

[5] Grassl, P.; Xenos, D.; Nyström, U.; Rempling, R., and Gylltoft, K. CDPM2: A damage-plasticity approach to modelling the failure of concrete. *International Journal of Solids and Structures*, 50 (24):3805–3816, 2013.

[6] Naaman, A. E. High performance fibre reinforced cement composites. *IABSE reports*, 55:371–376, 1987.

[7] Naaman, A. E.; Namur, G. G.; Alwan, J. M., and Najm, H. S. Fiber pullout and bond slip. I: Analytical study. *Journal of Structural Engineering*, 117(9):2769–2790, 1991.

[8] Phillips, D. V. and Zienkiewicz, O. C. Finite element non-linear analysis of concrete structures. In *Institution of Civil Engineers, Proceedings*, volume 61, 1976.