# EVALUATION AND COMPARISON OF ANALYTICAL MODELS TO DETERMINE THE BOND CHARACTERISTICS OF STEEL FIBRE REINFORCED SELF-COMPACTING CONCRETE

**Farhad Aslani (1) and Shami Nejadi (2)**

(1) PhD candidate, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

(2) Senior Lecturer, School of Civil and Environmental Engineering, University of Technology Sydney, Australia

## Abstract

Steel fibre reinforced self-compacting concrete (SFRSCC) can be placed and compacted under its self weight with little or no mechanical vibration. It is at the same time cohesive enough to be casted without segregation or bleeding. Steel fibres improve many of the properties of self-compacting concrete (SCC) elements including tensile strength, ductility, toughness, energy absorption capacity, fracture toughness and cracking. Although the available research regarding the influence of steel fibres on the properties of SFRSCC is limited, this paper investigates the bond characteristics between steel fibre and SCC. This by comparison of the five analytical models including (i.e. Naaman et al. (1991a,b), Dubey (1999), Cunha (2007), Soranakom (2008) and Lee et al. (2010)) with the experimental results from the four recently conducted single fibre pull-out tests. The influence of the fibre end hook, embedded length, fibre orientation angle, on the bond characteristic between fibre and SCC are determined and discussed. The accuracy of each analytical model also has been examined.

## 1. INTRODUCTION

Steel fibre reinforced self-compacting concrete (SFRSCC) is a relatively new composite material which congregates the benefits of the self-compacting concrete technology with the profits derived from addition of the fibre to a brittle cementitious matrix. In the fresh state, SFRSCC homogeneously spreads due to its own weight, without any compaction energy. On the other hand, in the hardened state, the addition of fibres to brittle cementitious matrix mostly contributes to the improvement of the impact resistance and the energy absorption capacity [1], since the fibres that bridge the cracks will allow stress transfer between crack planes and retard the crack opening propagation. Fibre reinforced concrete (FRC) resists tensile forces through a composite action of the matrix and the fibres. A part of the tensile force is resisted by the matrix, while the other part is resisted by the fibres. Each of these resistances is determined by the stress transfer at the fibre–matrix interface, which is achieved by the bond defined as the shear stress acting at the interface. Before any cracking is taken place, elastic stress transfer is dominant. At more advanced stages of loading, debonding across the interface usually takes place, and frictional slip governs stress transfer at the interface. Therefore, the mechanical properties of SFRC, especially its tensile strength, toughness, and tensile stress–strain curve, are sensitively influenced by the bond characteristics at the fibre–matrix interface [2]. Hence, it is important to study the bond properties between the matrix and fibre prior to examining the various mechanical properties of this new composite material.

The bond characteristics depend on the several factors including the orientation of the fibres relative to the direction of the applied load, embedded length of the fibres, shape of the fibres, and strength of the matrix. Many researches concerning bond properties have been conducted to reveal the effects of parameters related to the fibre geometry or the strength of matrix and several models to predict the pullout behaviour of the fibres have been proposed. The inclination angle of a fibre in a cementitious matrix has a strong influence on the pullout resistance. Although several researchers have performed experiments to investigate the effect of fibre inclination angle, the focus was mostly on the peak pullout load, however its effect is still disputable. However, it is generally agreed that the effect of the fibre inclination angle on the pullout load and pullout energy is totally dependent on the fibre aspect ratio, the fibre shape (straight, hooked, corrugated etc.), and material properties such as yield strength, and whether the fibre is metallic or synthetic [2].

This study presents a comparison between five analytical models including (i.e. Naaman et al. [3-4], Dubey [5], Cunha [6], Soranakom [7] and Lee et al. [2]) with the experimental results from the four recently conducted single fibre pull-out tests. The influence of the fibre's end hook, embedded length, fibre orientation angle, on the bond characteristic between the fibre and SCC are determined and discussed. The accuracy of each analytical model also is examined.

## 2. DATABASE FOR BOND CHARACTERISTICS OF SFSCC EXPERIMENTAL TESTS

The included experimental results in the database are developed mainly from Grünewald [8], Holschemacher and Klug [9], Cunha [6] and Schumacher [10] references. The database includes the information regarding the composition of the mixtures, fresh properties of

SFSCC and testing methodology and conditions. It should be emphasized that this aspect has not been investigated as broadly as the other aspects of SFSCC, and the published experimental data is still not very extensive.

Using experimental data results from different sources can frequently be problematic for the following reasons: 1. there is often insufficient information regarding the exact composition of the concrete mixtures; 2. the size of the specimens, curing conditions, and testing methodology vary between the different investigations and, in some cases, this information is not fully indicated; 3. in many cases it is difficult to extract the relevant experimental values because the published results are incomplete or are presented in graphical form and the data values have to be extrapolated. Table1 presents a general summary of the fibre's shape (smooth or end hooked), fibre's length ($l_f$) and diameter ($d_f$), inclination angle, fibre type (Dramix), cement type, filler type and embedment length included in the database.

Table 1. Investigations included bond characteristics of SFSCC database

| | Reference | Smooth fibre | End hooked fibre | $l_f$(mm) | $d_f$(mm) | Inclination angle (°) | Fibre type | Cement type | Filler type | Embedment length (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Grünewald (2004) | no | yes | 30, 60 | 0.38, 0.75 | - | Dramix 80/60 BP and Dramix 80/30 BP | CEM III 42.5 N and CEM I 52.5 R | Fly ash | 10,30 |
| 2 | Holschemacher and Klug (2005) | yes | yes | 50 | 0.8, 1 | 30, 50 | - | CEM I 42.5R | Fly ash | 25, 17.5, 12.5 |
| 3 | Cunha (2007) | yes | yes | 60 | 0.75 | 0, 30, 60 | DRAMIX R° RC-80/60-BN | CEM I 42.5R | limestone | 10, 20, 30 |
| 4 | Schumacher (2008) | no | yes | 30 | 0.375, 0.666 | - | - | CEM I 52.5 R and CEM III/B 42.5 LH HS | Fly ash | - |

## 3. BOND CHARACTERISTICS OF SFSCC ANALYTICAL MODELS

One of the first pullout models which was proposed by Lawrence [11], relates the shear stress distribution along the fibre to the elastic properties of the matrix and fibre. In addition, the model was extended for the case of a partially debonded fibre, assuming constant frictional shear stress along the failed interface. Laws et al. [12] applied the analytical model developed by Lawrence [11] in the study of glass fibre reinforced cement composites failure [22].

Gopalaratnam and Shah [13], Lim et al. [14], Wang et al. [15], Stang et al. [16], Naaman et al. [4], Leung and Li [17]were developed for the fibre pullout problem based on the Lawrence [11] model. These models are one-dimensional, with many common features. They include a shear-lag model for the fibre embedded length in full bond conditions, gradual debonding, and frictional sliding for the fibre embedded length where debonding is occurring. In their study, Wang et al. [15] considered only frictional bond. Lim et al. [14] and Naaman et al. [4] deduced the force distributions in the fibre and matrix. Leung and Li [17] developed a two-way debonding theory, in which debonding can progress from both fibre ends. In other models, it is assumed that the interfacial shear bond stresses are elastic to start with, but gradually debonding takes place at the interface and the stress transfer is shifted to a frictional one [13]. To describe the debonding criterion, basically two different approaches can be used: a strength-based (or stress-based) criterion and a fracture-based criterion. In the strength based models, it is assumed that debonding initiates when the interfacial shear stress exceeds the shear strength. For the fracture-based models, on the other hand, the debonding zone is treated as an interfacial crack. The conditions for the debonding propagation are considered, in terms of fracture parameters of the interface based on an assumption that, to drive the debonded zone forward, adequate energy must be supplied (Stang et al. [16] and Li and Stang [18]). Nevertheless, the models for straight fibres are of limited use for end hooked fibres, since the behaviour of end hooked fibres is dominated by the mechanical anchorage [6].

Alwan et al. [21] proposed an analytical model to predict the mechanical contribution of anchorage forces in the hooked end steel fibres. This model is based on the concept of frictional pulley along with two plastic hinges. The mechanical bond provided by the hook is considered as a function of the work needed to straighten the fibre during pullout. To predict the full pullout response a two-step process corresponding to the contribution of the two hinges, and then one hinge superposition of the frictional and mechanical components is needed. Regarding this two step process Sujivorakul et al. [22] developed an analytical model where both the frictional bond and mechanical anchorage components are combined in the solution. This model is an extension of the smooth fibre pullout model previously developed by Naaman et al. [4], where the adoption of a nonlinear spring component in the latter model intends to simulate the mechanical anchorage reinforcement mechanism.

Bentur and Mindess [23] pointed out the importance of proper evaluation of the pullout behaviour, which should not be based on the determination of a limited number of numerical parameters (e.g. maximum pull-out load, embedment length and fibre cross-sectional geometry). But rather, it should include analysis of the entire curves obtained during such tests. The problems of correctly interpreted fibre pull-out tests can explain the huge differences in the quoted values of the interfacial shear bond strength, which in the literature range from 0.5 up to 9 MPa, while the interfacial shear friction ranges from 0.5 to 5 MPa (see Beaumont and Aleska [24], Bartos [25], Bentur and Mindess [23], Gopalaratnam and Shah [13], Li and Stang [18], Groth [26] and Grünewald [8]) [6].

## 4. RESULTS AND DISCUSSION

Figures 1 to 4 show the comparisons of the pullout force versus end slip for SCC mixtures from experimental results of Holschemacher and Klug [9] and Cunha [6] with the predicted results from Naaman et al. [3-4], Dubey [5], Cunha [6], Soranakom [7] and Lee et al. [2] models.

Figure 1 shows the comparison of the pullout force versus end slip for smooth steel fibre from Holschemacher and Klug [9] experiments with the proposed theoretical models. It can be seen that the models have not good prediction. Figure 2 illustrates the comparison of the pullout force versus end slip for end hooked steel fibre from Holschemacher and Klug [9] experiments with the theoretical models. According to Figure 2, Cunha [6] and Lee et al. [2] models have more appropriate predictions.

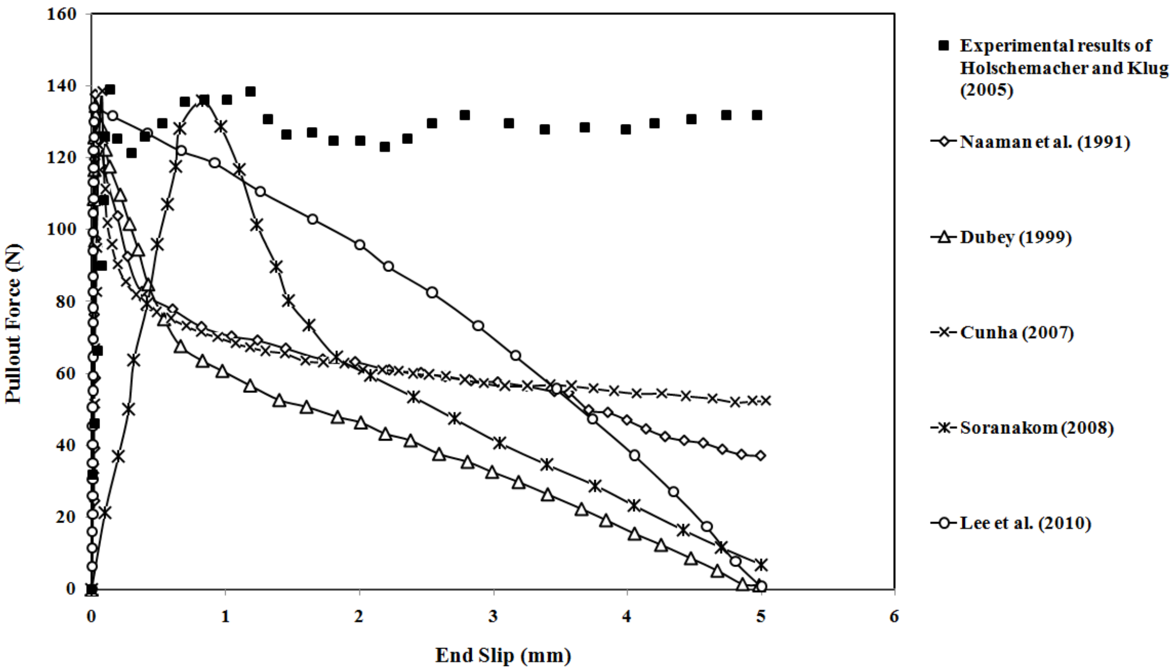

Figure 1: Comparison of the pullout force versus end slip for smooth steel fibre from Holschemacher and Klug [9] experimental results with theoretical models

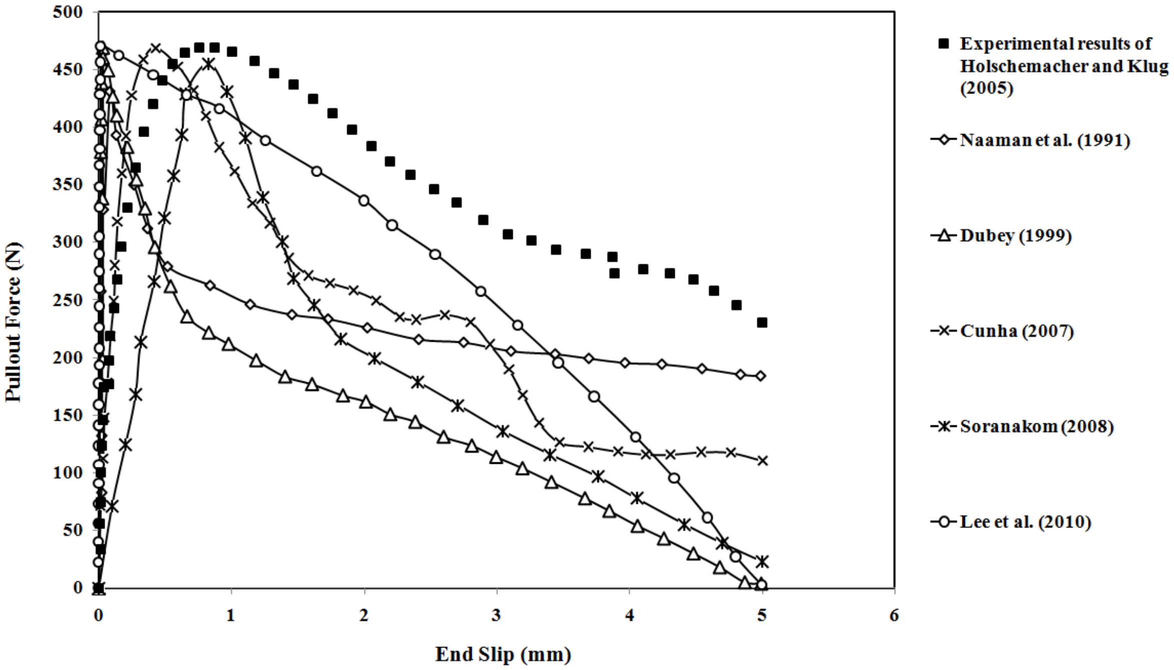

Figure 2: Comparison of the pullout force versus end slip for end hooked steel fibre from Holschemacher and Klug [9] experimental results with theoretical models

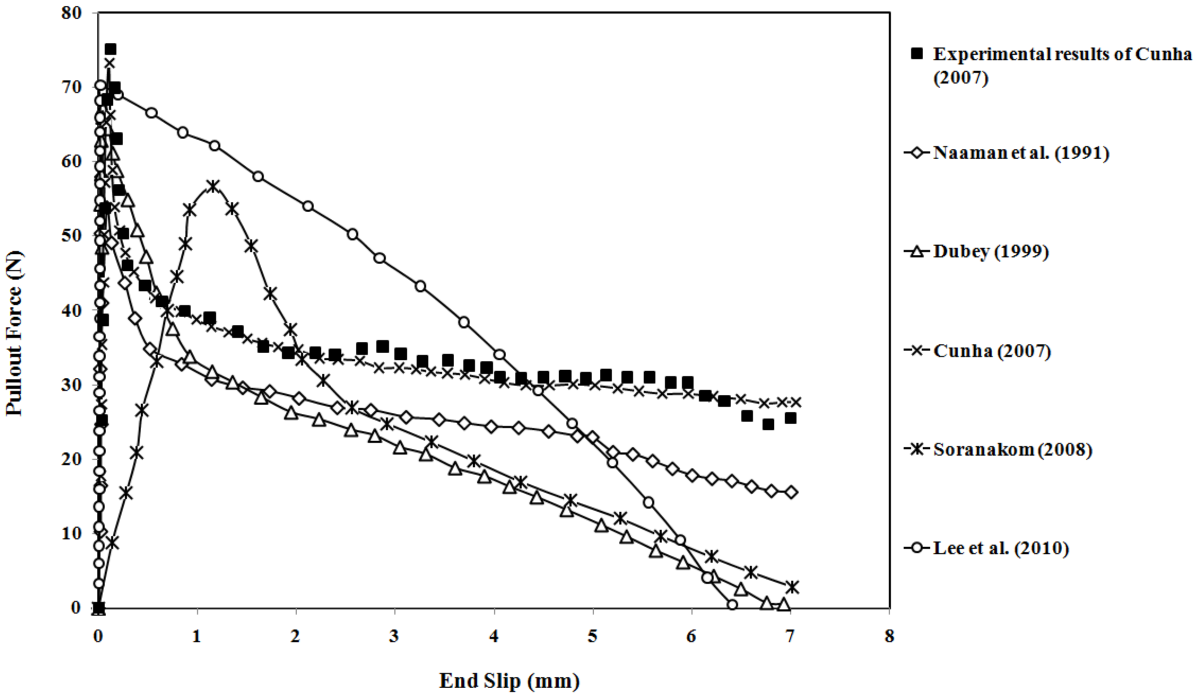

Figure 3: Comparison of the pullout force versus end slip for smooth steel fibre from Cunha [6] experimental results with theoretical models

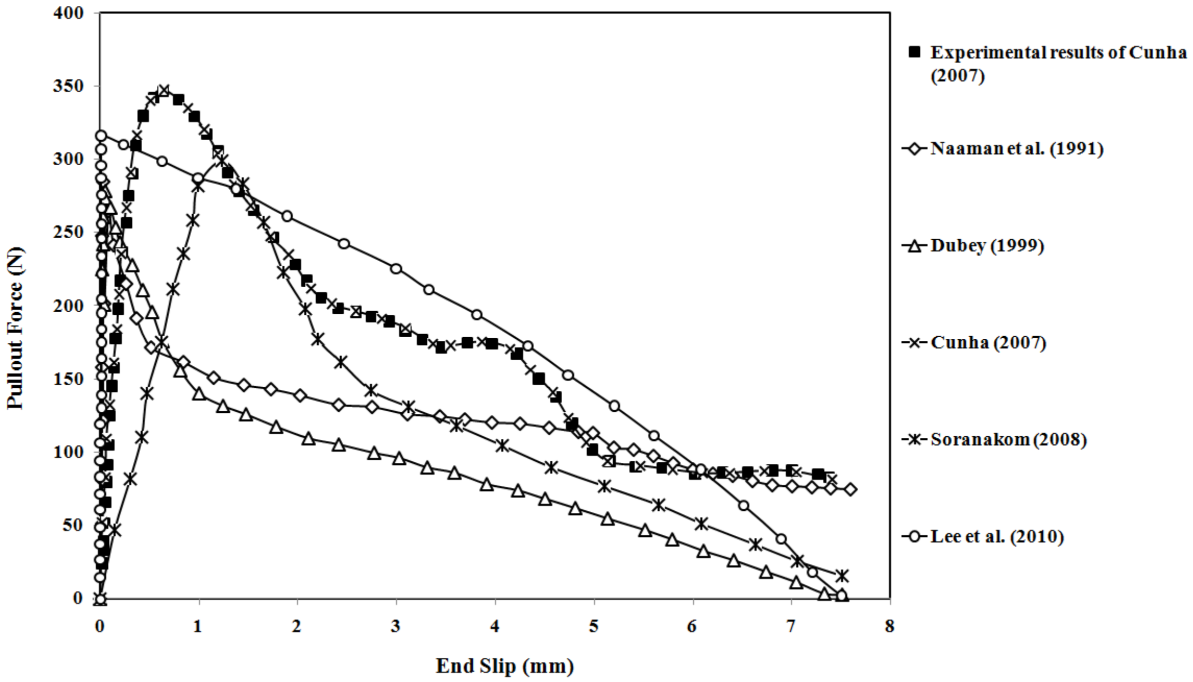

Figure 4: Comparison of the pullout force versus end slip for end hooked steel fibre from Cunha [6] experimental results with theoretical models

Figure 3 indicates the comparison of the pullout force versus end slip for smooth steel fibre from Cunha [6] experimental results with the proposed theoretical models. Based on the presented results the Cunha model [6] has the best prediction and the Naaman et al. model [3-4] has appropriate prediction.

Figure 4 shows the comparison of the pullout force versus end slip for end hooked steel fibre from Cunha [6] experimental results with the proposed theoretical models. It can be seen that the Cunha model [6] has very good prediction and Soranakom model [7] has suitable estimation.

## 5. CONCLUSIONS

Based on the presented results, the following conclusions can be made:

- The Cunha’s model [6] has appropriate prediction based on the available experimental results in the literature although this model has not accurate prediction for smooth steel fibre experimental results conducted by Holschemacher and Klug [9] and has complicated model.
- The Naaman et al. [3-4] has slight good prediction model to some extent for the pullout response of smooth steel fibre results.
- The Lee et al. [2] has sensible prediction but this model consider uniform behaviour in ascending and descending pullout response.
- Dubey’s model [5] underestimates the predicted results in comparison with the experimental results.

## REFERENCES

[1] ACI Committee 544, 'State-of-the-Art Report on Fiber Reinforced Concrete - ACI 544.1R-96 (Reapproved 2002)', ACI Manual of Concrete Practice, Part 6, 2008, pp. ACI544.1R-7 - ACI544.1R-24, 2008.

[2] Lee, Y., Kang, S-T., and Kim, J-K., 'Pullout behavior of inclined steel fiber in an ultra-high strength cementitious matrix', *Construction and Building Materials*, **24** (2010) 2030–2041.

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

[4] Naaman, A.E., Namur, G.G., Alwan, J.M., Najm, H.S., Fiber pullout and bond slip II: experimental validation, Journal of Structural Engineering, Vol.117 (9), p.2791–2800, 1991.

[5] Dubey, A., 'Fiber reinforced concrete: characterization of flexural toughness & some studies on fiber-matrix bond-slip interaction', PhD Thesis, University of British Columbia, (1999).

[6] Cunha, V., 'Pullout behaviour of end hooked steel fibres in self-compacting concrete', Report 07-DEC/E06, University of Minho, (2007).

[7] Soranakom, C., 'Multi-scale modeling of fiber and fabric reinforced cement based composites', PhD Thesis, Arizona State University, (2008).

[8] Grünewald, S., 'Performance-based design of self-compacting fibre reinforced concrete', PhD Thesis, Delft University of technology, (2004).

[9] Holschemacher, K., Klug, Y., 'Pull-out behaviour of steel fibres in self-compacting concrete', First International Symposium on Design, Performance and Use of Self-Consolidating Concrete, China, (2005).

[10] Schumacher, P., 'Rotation Capacity of Self-Compacting Steel Fiber Reinforced Concrete', PhD Thesis, Delft University of technology, (2008).

[11] Lawrence, P., 'Some theoretical considerations of fibre pull-out from an elastic matrix', *Journal of Materials Science*, **7**(1) (1972) 1-7.

[12] Laws, V., Lawrence, P. and Nurse, R., 'Reinforcement of britle matrices by glass fibers,' *Journal of Physics*: D Applied Physics, **6** (1972) 523-537.

[13] Gopalaratnam, V. and Shah, S. P., 'Failure mechanisms and fracture of fiber reinforced concrete', In A. SP-105 (editor), 'Fiber Reinforced Concrete Properties and Applications,' 1-25. Oslo, Norway (1987).

[14] Lim, T., Paramasivam, P. and Lee, S. 'Analytical model for tensile behavior of steel-fibre concrete,' *ACI Materials Journal*, **84**(4) (1987) 286-298.

[15] Wang, Y., Li, V. and Backer, S., 'Modelling fiber pullout from a cement matrix,' *International Journal of Cement Composites and Lightweight Concrete*, **10**(3) (1988) 143-149.

[16] Stang, H., Li, Z. and Shah, S. P., 'Pullout problem: Stress versus fracture mechanical approach,' *Journal of Engineering Mechanics*, **116**(10) (1990) 2136-2150.

[17] Leung, C. K. Y. and Geng, Y., 'Effect of lateral stresses on fiber debonding pull-out,' *J. Compos. Eng.*, **5**(10-11) (1995)1331-1348.

[18] Li, V. C. and Stang, H., 'Interface property characterisation and strengthening mechanisms in fibre reinforced cement based composites,' *Advanced Cement Based Composites*, **6**(1997) 1-20.

[19] Naaman, A. E. and Najm, H., 'Bond-slip mechanisms of steel fibers in concrete,’ *ACI Materials Journal*, **88**(2): (1991) 135-145.

[20] Robins, P., Austin, S. and Jones, P., 'Pull-out behaviour of hooked steel fibres,' *RILEM Journal of Engineering Mechanics*, **35**(251) (2002) 434-442.

[21] Alwan, J. M., Naaman, A. E. and Guerrero, P., 'Effect of mechanical clamping on the pull-out response of hooked steel fibers embedded in cementicious matrices,' *Concrete Science and Engineering RILEM*, **1**(1) (1999) 15-25.

[22] Sujivorakul, C., Waas, A. M. and Naaman, A., 'Pullout response of a smooth fiber with an end anchorage,' *Journal of Engineering Mechanics*, **126**(9) (2000) 986-993.

[23] Bentur, A. and Mindess, S., 'Fibre reinforced cementitious composites,' Elsevier Applied Science, London (1990).

[24] Beaumont, P. W. R. and Aleska, J. C., 'Cracking and toughning of concrete and polymer concrete dispersed with short steel wires,' *Journal of Materials Science*, **13**(8) (1978) 1749-1760.

[25] Bartos, P. J. M., 'Bond in fibre reinforced cement and concretes,' *The International Journal of Cement Composites*, **3**(3) (1981) 159-177.

[26] Groth, P., 'Fibre reinforced concrete - Fracture mechanics methods applied on self-compacting concrete and energetically modified binders,' Ph.D. thesis, Department of Civil and Mining Engineering, Lulea University of Technology, Sweden (2000).