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Pull-out behaviour of spiral-shaped steel fibres from normal-strength concrete matrix

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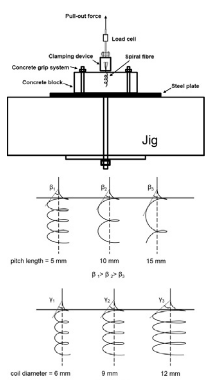
HIGHLIGHTS

- Pull-out behaviour of spiral steel fibres from normal-strength concrete was studied.
- Effects of embedment depth, loading rate and 3D geometrical variations were studied.
- Hybrid steel fibre reinforcement for normal-strength concrete was proposed.
- Significant improvement by the synergistic effect of hybrid fibres was demonstrated.

GRAPHICAL ABSTRACT



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ABSTRACT

Reinforcing concrete with steel fibres has been proven being able to improve the properties of concrete such as strain capacity, impact resistance, energy absorption and tensile strength because the discrete steel fibres act as dispersed reinforcement in mitigating crack propagation. A number of laboratory tests in recent years have indicated the superiority of spiral geometry of steel fibres as compared to other fibre types in terms of ductility, crack controllability, dynamic strengths and energy absorption. Understanding fibres' pull-out behaviour is essential to evaluate the properties of steel fibre reinforced concrete (SFRC). The pull-out behaviour of straight, hooked-end and twisted steel fibres have been investigated by many researchers. However, there has been no study that focuses on pull-out behaviour of spiral fibres in the literature yet. The pull-out behaviour of steel fibre with spiral geometry from concrete matrix is experimentally investigated in the present study. In addition, steel fibres with hooked ends were also prepared and tested for comparison. The spiral fibres with various geometric characteristics such as pitch length, embedment length and coil diameter were pulled out from concrete matrix at different rates. Test results showed several peak loads before reaching a final maximum pull-out force. Based on the experimental results, the influences of embedment length, pull-out rate, coil diameter and pitch length were investigated. Through analysing the testing results, combining hooked-end fibres and spiral fibres was proposed as a hybrid steel fibre reinforcement technique in order to further improve the performance of SFRC materials and structures. Laboratory tests in this study proved the effectiveness of this technique in enhancing the capacity of the reinforced concrete structure.

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1. Introduction

Concrete can be considered as one of the most important and widely used building materials around the world. It has been used in construction for centuries due to the affordability and availability of materials in a vast number of applications. The main weakness of concrete is its brittleness, owing to very low tensile strength and resistance to cracking. The addition of short fibres to concrete mixtures contributes to control crack opening and propagation. The most important type of fibres for structural concrete are steel fibres which can be made in different shapes and sizes to improve the fibre-matrix bonding. Steel fibre reinforced concrete (SFRC) has had many practical applications in improved construction of structural elements, including long span bridges, highways, airfields and high rise buildings.

Failures of fibre reinforced concrete material are caused mainly by either fibre rupture or fibre debonding. For steel fibres, fibre debonding from concrete matrix is a critical problem that impedes reaching the full strength capacity of fibres before structural failure. Different geometries and shapes of steel fibres have been heavily researched to understand and increase the bonding strength of steel fibres in concrete matrix. These include straight, crimped, hooked-end, cold-rolled and undulated to compare the effects these different fibres have on the overall mechanical properties of the reinforced concrete. Spiral-shaped steel fibres were recently proposed to increase the bonding strength of fibres with the concrete matrix. Laboratory tests have indicated the positive aspects of using spiral shaped steel fibres to reinforce concrete materials [15,16,17,27,28]. The efficiency of crack control in SFRC using spiral fibres was demonstrated in a number of previous studies because of the strong bonding to the matrix and high frictional resistance to pull-out. For example, the post-cracking resistance of SFRC specimens with spiral fibres was found higher than those with hooked-end fibres under static splitting tension [17]; under repeated impact loads, spiral SFRC beam specimens were able to substantially absorb more amount of energy compared to those reinforced with hooked-end fibres [17]; in dynamic splitting tensile tests the spiral fibres were even found to be able to partially recover the crack by pulling back the split halves of the tested specimens [16]. The mechanical properties of SFRC heavily depend on the interacting mechanism between the fibre and the matrix. To further understand the performance of spiral fibre reinforced concrete material, it is essential to study the mechanism of single fibre being pulled out from the matrix for fundamental understanding of SFRC material properties.

In the past four decades several researchers have investigated and developed models for predicting the pull-out behaviour of steel fibres with various geometries in SFRC [8,9]. Various attempts have been made to improve the bond-slip characteristics of steel fibres, with the most effective method utilising mechanical deformation [11]. Numerous attempts have been made to better understand the effects of fibre geometry on the mechanical behaviour subjected to pull-out in SFRC [2,23]. Research on the bond-slip behaviour of inclined straight and hooked end fibres has been performed mostly on an experimental basis. On top of debonding and interfacial friction, additional mechanisms governing the pull-out response of inclined fibres are introduced including fibre bending, matrix spalling and local friction effects [26]. Several papers have investigated the influence of inclination angle [22,26,25,4,21] and embedded length [18,22,26,25], through setting boundary conditions and analysing pull-out results. The majority of these papers compare hooked-end and straight fibres. The influence of the hooked-end geometry on bonding strength was quantified in a number of papers by making comparisons with the pull-out response of straight fibres [23,30]. This proves an effective way to quantify the performance, however these outcomes are valid only for the limited cases because they depend on the experimental boundary conditions, fibre properties and matrix properties. Nonetheless, it is generally observed that when fibres with more complex geometries are examined, the introduction of more complex pull-out behaviours results in difficulties in measuring the effects of fibre geometry and embedment length on bonding strength.

Additionally, the effect of concrete strength [25] and pull-out rate [20,1,19,13] on pull-out behaviour have been explored in numerous papers. Certain papers have chosen to use different concrete mixtures, some of which have elected to use mortar or cement mixtures as a boundary condition to eliminate any inconsistencies the concrete aggregates may have on pull-out behaviour. However, this does not accurately represent the realistic pull-out behaviour, as SFRC in practice will always involve a concrete mixture. Depending on the size and location of a fibre spanning a crack in SFRC, each fibre may be subject to a different pull-out rate. These pull-out rates have been assessed through various boundary conditions and fibre geometries. Results of these studies indicate that for complex geometries, increasing the pull-out rate increased the total energy required to pull-out the fibre. Thus, investigation into the effects of pull-out rate on the complex spiral geometry is needed for better understanding the pull-out behaviour.

Apart from experimental observations, a few models have been developed with consideration of mechanical deformation [30]. However the mechanisms associated with pull-out behaviour of deformed fibres are still not well understood. The first successful attempts to model the pull-out behaviour of hooked-end steel fibres were made by Alwan et al. [3] and Chanvillard [10]. Alwan et al. [3] proposed an alternative approach, modelling the hook as two plastic hinges and presenting the pull-out curve as a chain of different parabolas. Chanvillard [10] developed a model using the principal of energy conservation, dividing the hook into distinct curved and straight segments. More recently, Laranjeira et al. [22] and Ghoddousi et al. [12] have developed models based on the same approach proposed by Alwan et al. [3], however the model proposed by Laranjeira et al. [22] takes into account the different orientation of fibres within the concrete by introducing a steel fibre inclination angle. No model has been able to fully explain the fibre-matrix interactions at the critical cracked section due to limitations on the ability to effectively understand all of these pull-out mechanisms [24]. Since pull-out behaviour is the major mechanism contributing to the toughness of SFRC, further research into the effect of alternate geometries, embedment lengths, and pull-out rates on their pull-out behaviour is the key to the technological advancement in this field.

The use of spiral shaped fibres in SRFC is a new technology that requires further research. Despite the valuable understanding gained from the experimental and analytical studies, there have been only a few investigations into spiral shaped steel fibres in SFRC and no attempt to understand the pull-out behaviour of a spiral fibre. Since very little is known about spiral fibres, complications arise with the number of different geometries a spiral can have, such as the pitch length and coil diameter that lead to the optimum toughness while maintaining a viable steel concrete ratio. Therefore, to understand the mechanism, especially with the consideration of the 3D geometrical variations, of spiral fibres in SFRC, more researches into their pull-out behaviour are required. This paper presents a series of laboratory tests on pull-out behaviour of spiral steel fibres from concrete matrix. Variations in geometry, embedment length, and pull-out rate were taken into consideration in the tests for comprehensive understanding of the pull-out behaviour of spiral fibre from concrete matrix. From the testing data, it was observed that spiral fibre has better deforma-