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An efficient method to derive statistical mechanical properties of concrete reinforced with spiral-shaped steel fibres in dynamic tension

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HIGHLIGHTS

- Multivariable kernel regression developed to derive predication models of materials.
- Kernel density estimation used to estimate the distributions of material property.
- Kernel regression method used to obtain statistical model for SFRC with limited data.
- 2D meso-scale model developed to simulate SFRC with randomly distributed fibres.

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ABSTRACT

Steel-fibre-reinforced concrete (SFRC) has been recognised as an effective solution to resist impact loading on structures. The reliable application and efficient design of SFRC structures depends on the knowledge of its mechanical properties. Since many important factors, including the locations and orientations of fibres and aggregates in concrete and the material properties of concrete matrix, are intrinsically random, the mechanical properties of SFRC present a high level of randomness. To accurately quantify them, effective statistical techniques are indispensable. Using traditional statistical techniques, a large quantity of data, from either experiments or numerical simulations, are needed to derive the correlation between the mechanical properties and the random factors. However, both ways are time-consuming and costly. Therefore, very little information regarding the statistical mechanical properties of SFRC can be found in the current literature. In this study, a kernel-based nonparametric statistical method is proposed to derive the statistical mechanical properties of SFRC with limited number of data. The behaviours of SFRC with randomly distributed spiral-shaped fibres and aggregates under impact loading are simulated using commercial software LS-DYNA. The simulation accuracy is validated by the experimental results. The influences of various volume fractions of fibres on dynamic increase factor (DIF) of the tensile strength of SFRC specimens under dynamic loadings at different strain rates are quantified through a prediction model obtained from kernel regression. The results demonstrate that the proposed method is able to estimate the DIF value of SFRC based on the tensile strength and strain rate, and to derive the statistical mechanical properties of SFRC.

1. Introduction

Extreme loadings, including blast, hurricane, and earthquake, can lead to catastrophic results on the traditional reinforced concrete structures. Since concrete is intrinsically a brittle material with low tensile strength and strain capacities, increasing its tensile capacity can enhance the concrete structure safety. Adding fibres into concrete has been studied as an effective measure for decades. Fibres of different materials and various shapes have been proposed and their performance researched. Among them, steel-fibre-reinforced concrete (SFRC) has received increasing research attention, due to such advantages as the increased tensile strength [1], the improved toughness and the resistance against dynamic load [2], and reduced cracking [3].

The SFRC with spiral-shaped fibres has demonstrated to outperform SFRC with other types of steel fibres [4–10], due to its better

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bonds to concrete than other fibre types. Despite observations of good performance of concrete materials reinforced with spiral-shaped steel fibres, like concrete reinforced with other fibre types, fluctuations of mechanical properties of the SFRC materials have been observed in all the previous studies. This is because of the random distributions of fibres and aggregates in concrete matrix, fluctuations of material properties of each component in SFRC, and fluctuations in quality control of preparing the testing specimens, etc. Since these random fluctuations are inevitable in practice, to more reliably model the material performance it is better to derive the statistical material properties of SFRC.

To investigate the dynamic properties of SFRC, the current literature shows that there are two streams of methods, i.e., experimental tests and numerical simulations. Due to the high costs of experimental tests, only a limited number of high-speed impact tests were performed to obtain SFRC material properties corresponding to the relatively high strain rates. Thus, the dynamic increase factor (DIF) of SFRC as a function of strain rate for different SFRC is rarely available. Moreover, owing to the inevitable random fluctuations as discussed above, the limited testing data show random variations of obtained material properties. For example, 48 specimens were tested in an experimental study of the impact resistance capacities of SFRC and hybrid FRC subjected to drop weight impacts [11]. It showed that the coefficients of variations of the number of blows to cause the first crack and the total failure of the disc specimens were 0.59 and 0.52, respectively, indicating significant variations of the SFRC capacities in resisting impact loads. In [12], the fibre distribution characteristics were found to depend on the direction of placing. Fibre distribution characteristics, including the degree of fibre dispersion, fibre unit number, and packing density, were found to strongly influence the ultimate flexural strength, while hardly affect the first cracking strength. In [8], extensive impact tests were conducted on SFRC specimens and a number of dynamic stress-strain curves under different strain rates obtained. The corresponding empirical DIF relations for spiral SFRC were proposed based on the testing data. Although those relations can be used to model dynamic strength increment with strain rate of SFRC, they cannot be unified and could be biased because they were derived from limited number of tests and the random fluctuations were not considered.

Computer modelling, or numerical testing, has been regarded as a reliable and cost effective approach to investigate the behaviour and properties of materials and structures under different loading conditions. To account for the randomly distributed coarse aggregates and steel fibres, modelling the SFRC specimens in mesoscale is needed. A number of researchers have performed mesoscale modelling of SFRC materials under static loading [13,14], impact loading [7,14,15] and blast loading [16]. With distinctive consideration of steel fibres, coarse aggregates and mortar matrix, detailed observations such as stress and strain distributions, crack initiation and propagation, fibre-matrix interaction, can be made through these studies. However, as the distributions and orientations of discrete steel fibres and aggregates in SFRC mix are intrinsically random, which affect the simulated material properties, the mesoscale models adopted in the above studies can only represent the typical specimens with specific distributions and orientations of steel fibres and aggregates considered in the respective studies. To better understand the mechanical properties of SFRC materials with less biased results, statistical analysis accounting for random distributions of steel fibres and coarse aggregates are deemed necessary. To conduct statistical analysis and obtain unbiased results, traditional sampling techniques such as Monte Carlo simulations require as many, ideally infinite, samples as possible. This is very time consuming and not possible in practice.

To solve the above problems, efficient statistical analysis of the SFRC material properties accounting for the random distributions of steel fibres and aggregates is needed. Almost all the existing studies for efficient quantification of the statistical parameters of various problems use parametric statistics, which requires a predefined distribution, such as Weibull distribution, normal distribution, and log-normal distribution. Although Weibull distribution is used predominantly, its effectiveness was challenged against gamma or log-normal distribution function [17]. Alternatively, nonparametric statistics could be an efficient approach to derive the statistical properties of material properties. It is found that when the maximum likelihood point of kernel density estimation (KDE) stabilizes, the estimated distribution is usually close to the real distribution. This approach requires a much smaller number of samples than those using Monte Carlo method, therefore leading to significant savings in deriving the statistical parameters based on the number of testing and/or numerical data. To further reduce the computational efforts, a kernel regression method was developed and applied to derive the DIF variation according to the change of strain rate, based on limited number of test results [18]. In the latter study, reliable predication of DIF values under different strain rates, which are not available from tests or simulations, can be made. This preliminary study paved the way towards the establishment of an efficient statistical model for random materials.

In this paper, limited numerical simulations on the response of spiral-shaped SFRC in dynamic splitting tensile tests are performed using LS-DYNA. The accuracy of numerical model is verified by laboratory testing data. KDE is used to derive an unbiased statistical distribution of the dynamic tensile strength of spiral-shaped SFRC specimens at different strain rates with different ratios of fibres. Then, kernel regression is used to derive the prediction model of material properties to account for the random distributions of locations and orientations of aggregates and fibres in concrete based on the limited number of simulated data. A generalised model of DIF with respect to the strain rate and split tensile strength of SFRC is proposed to predict the dynamic strengths of SFRC under different strain rate.

2. Methodology

2.1. Overview

This study mainly involves the following six tasks:

(1) Experimental tests of SFRC specimens with 1% steel fibre under impact are first conducted for validation purposes.
(2) A commercial software LS-DYNA is used to simulate the behaviour of SFRC under dynamic splitting tension test in mesoscale considering coarse aggregates, spiral steel fibres and mortar matrix. The accuracy of the model predictions is verified by experimental test data. The validated model is then used to perform parametric studies on SFRC with different ratios of fibres and under different strain rates to provide data for the statistical analysis.
(3) To provide a reliable distribution of dynamic strength of SFRC, KDE is used to analyse the static performance of SFRC with different ratios of fibres.
(4) Kernel regression method is used to derive the predication models for tensile DIF of spiral SFRC material as a function of strain rate and static strength. Specifically, a 5-step method is proposed, which can achieve any prediction precision as requested. This prediction model is verified by the numerical simulation results.
(5) KDE is used to derive the distribution of tensile DIF of SFRC at each strain rate.
(6) Kernel regression method is used to derive the statistical model for the mechanical properties of SFRC.