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Fuzzy logic approach to predict stress–strain curves of steel fiber-reinforced concretes in compression

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Abstract

In this study, a new approach is developed for predicting stress–strain curve of steel fiber-reinforced concrete (SFRC) under compression, by use of fuzzy logic system (FLS). In the coverage of study, firstly, experimental studies were carried out. Cylindrical specimens were prepared in size of Ø150 × 300 mm with and without steel fiber. Two different steel fiber types (both are hooked end) were used as ratios 0 (control), 15, 30, 45 and 60 kg/m^3. The stress–strain curves were defined for 28 ages of the cylindrical specimens. Secondly, the stress–strain curves for SFRC were modeled by use of fuzzy logic approach, and the results that were obtained from experiments and modeling were compared. As a result close relationship between both results was seen.

Keywords: Fuzzy logic; Stress–strain curve; Steel fiber; Concrete

1. Introduction

Steel fiber-reinforced concrete (SFRC) is currently used in a wide range of applications, including bridge decks, airport pavements, tunnels and others. SFRC is concrete made primarily from hydraulic cements, aggregates and discrete steel-reinforcing fibers. A variety of tests have been performed to determine the actual characteristics and advantages of fibrous materials. SFRC has advantages over traditionally reinforced concrete in civil engineering. Steel fibers are added to the concrete mix and they become an integral part of the wet concrete [1–6].

The addition of steel fibers aids in converting the brittle characteristics to ductile ones. The principal role of fibers is resisting the formation and growth of cracks by providing pinching forces at crack tips. In addition, a marginal improvement in tensile strength also results, and SFRC has higher ultimate strain than plain concrete [7–9]. SFRC always possesses a steeper descending stress–strain curve in compression, than does the normal-strength concrete. The rapid decrease in compressive strength in the post-peak load region brings about a pronouncedly brittle mode of failure. To foster the compressive strength without sacrificing the ductility, a strategy adopted is to add discrete steel fibers as reinforcement in concrete [10,11].

It is obvious that the behavior of SFRC depends on the orientations, distributions, aspect ratios, geometrical shapes and mechanical properties of steel fibers in concrete mixtures. The orientations and distributions of fibers affect the properties of SFRC such as toughness, strength, ductility and crack width. Concrete can be assumed to be highly heterogeneous material because of its composite structure. As orientations and distributions of steel fibers in concrete mixture are random, SFRC is considered more heterogeneous than plain concrete. When the results of the experimental study are carefully compared, it reveals that there are numerous parameters of concrete and of steel which affect the behavior of SFRC. For this reason, the behavior of SFRC varies from one research to another depending also on the experimental setup. Also, the concrete market is generally very competitive and it turns

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out that concrete companies have only restricted budgets to spend on mix design, although from this fundamental stage emerge a great deal of consequences for the site operations and for the structure to be built. Furthermore, in the laboratory, to obtain desired concrete properties with suitable workability, technical personnel must try several proportions of the mix. This time-consuming procedure increases the wastage of material and cost of concrete production. The more we know about the concrete composition versus strength, and of the stress–strain behavior changes that occur with addition of steel fibers in the concrete, the better we can understand the nature of concrete and also we can optimize the concrete mixture well. [12–14].

Many studies [1,7,15,16] have been conducted to investigate the stress–strain behavior of SFRC. Teng et al. [1] adopted the equivalent inclusion method for studying the characteristics of the equivalent material properties of SFRC as a function of the volume fraction and the length-to-diameter ratio of the fibers. It is found that the equivalent materials moduli of concrete reinforce with randomly oriented and distributed fibers and they are insensitive to the length-to-diameter ratio of the steel fibers. Furthermore, the empirical formulae represent an alternative means of quickly calculating the effective elastic modulus of SFRC materials. Padmarajaiah and Ramaswamy [15] investigated an assessment of the flexural behavior of prestressed high-strength concrete beams containing steel fibers by using three-dimensional nonlinear finite elemental analysis (ANSYS) for simulating the effect of steel fibers in a concrete matrix behavior. Li and Li [17] developed a model for the behavior of FRC, which shows a hardening response in tension, based on the continuum damage mechanics. Their results show that the model-predicted stress–strain curves agree well with those obtained experimentally. Lim and Oh [18] developed an analytical method to predict the shear strength of reinforced concrete beams containing steel fibers and obtained results comparable to experimental data as well as predicted data. Fanella and Naaman [19] proposed an analytical model to predict the complete stress–strain curve of SFRC taking into account the fiber shape, the volume fraction and the fiber geometry. Extensive experimental research has been carried out to study the SFRC stress–strain behavior for the compressive strength range 30–50 MPa by Nataraja et al. [16]. The influence of the fiber amount on the peak stress and the corresponding strain on the toughness of concrete and on the nature of the stress–strain curve was studied for crimped steel fibers, with three fiber volume fractions and two aspect ratios. Moreover, an analytical expression similar to that given by Ezeldin and Balaguru [20] is proposed by Nataraja et al. [16]. This expression gives the complete stress–strain curves for reinforced concrete with crimped steel fibers.

In this study, a new approach for prediction of stress–strain behavior of SFRC by using of fuzzy logic modeling was developed and it has an important application in many fields including civil engineering [12,21,22].

2. Fuzzy sets and logic

The fuzzy logic concept provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria rather than the presence of random variables. The fuzzy approach considers the cases where linguistic uncertainties play some role in the control mechanism of the phenomena concerned [23]. In this study, however, a simplified view is adopted for linguistic variables of modulus reinforcing index (RI) of the concrete strain and stress. In the following, the fuzzy logic definition is tailored to concrete stress modeling, which in many ways is very similar to the established use of fuzzy logic in the control of dynamic systems, which are also known as "fuzzy logic control". In both contexts, fuzzy propositions, i.e., IF and THEN statements are used to characterize the state of a system and the truth–value of the proposition is a measure of how well the description matches the state of the system.

In the present study, fuzzy logic system (FLS) is used for predicting the SFRC stress–strain from compressive strain and RI of concrete. For control purposes, fuzzy sets can be used to set up rules as follows:

R: ***IF*** the value of variable $\boldsymbol{X_1}$ is "large" and variable of $\boldsymbol{X_2}$ is "medium"

THEN the result Y is "small" (1)

This statement resembles human thinking more closely than any explicit mathematical rules. Therefore, FLS can be used for modeling the behavior of a human expert. Besides, it is also very effective in relating a set of outputs to a set of inputs without specifying a mathematical model, and here a "fuzzy inference procedure" becomes dominant. In the modeling of human expert thinking, the input variables are first specified by fuzzy subsets such as "large" and then fuzzy rules similar to Eq. (1) are developed on the basis of the experts' knowledge and experience. In the fuzzy inference method, sets of corresponding input and output measurements are provided to the FLS, and it learns how to transform a set of inputs to the corresponding set of outputs through a Fuzzy Associative Map. The fuzzy logic approach does not provide a rigorous way for developing or combining fuzzy rules, which can be achieved through many ways. The method adopted in this paper is outlined below.

First, the input and output variables are divided into a number of subsets with simple triangular fuzzy membership functions. Generally, there are n^m fuzzy rules where n and m are the numbers of subsets and input variables, respectively. In the case, say of two inputs X_1 and X_2 with m subsets each, the rule base takes the form of an output Y_k ($k = 1,2,...,m^2$). If there are two input variables, say X_1 with "very small" and "small" fuzzy subsets, and X_2 with