Expert Systems with Applications 42 (2015) 376–389

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Automated serviceability prediction of NSM strengthened structure using a fuzzy logic expert system

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ARTICLE INFO

Article history:
Available online 9 August 2014

Keywords:
Steel
CFRP
Deflection
Crack width
Prediction model
Error analysis

ABSTRACT

This paper presents a simplified model using a fuzzy logic approach for predicting the serviceability of reinforced concrete (RC) beams strengthened with near surface mounted (NSM) reinforcement. Existing analytical models lack proper formulations for the prediction of deflection and crack width in NSM strengthened beams. These existing models are based on the externally bonded reinforcement (EBR) technique with fiber reinforced polymer (FRP) laminates, which presents certain limitations for application in predicting the behavior of NSM strengthened beams. In this study seven NSM strengthened RC beams were statically tested under four point bending load. The test variables were strengthening material (steel or CFRP) and bond length (1600, 1800 or 1900 mm). For fuzzification, load and bonded length were used as input parameters and the output parameters were deflection and crack width for steel bar and CFRP bar. Experimentally NSM steel strengthened beams showed better performance in terms of crack width and stiffness, although NSM FRP strengthened beams exhibited enhanced strength increment. For all parameters, the relative error of the predicted values was found to be within the acceptable limit (5%) and the goodness of fit of the predicted values was found to be close to 1.0. Hence, the developed prediction system can be said to have performed satisfactorily.

1. Introduction

Structural strengthening has become an important area of research as many existing structures underperform and require rehabilitation to meet current standards and service conditions. The near surface mounted (NSM) reinforcement technique has become a popular strengthening method due to its superior ability to increase flexural and shear strength, and to delay or avoid premature debonding failure in comparison to the externally bonded reinforcement (EBR) technique. In the NSM technique, fiber reinforced polymer (FRP) strips or steel rods are inserted into pre-sawn grooves in the concrete cover and bonded therein with epoxy adhesive.

Serviceability refers to the satisfactory performance of a structure under normal service load conditions based on the occupancy type. Deflection and cracking behavior are the most important parameters when considering the serviceability of a structure. The serviceability of a structure is significantly influenced by structural strengthening. FRP strengthening materials possess lower modulus' and linear stress–strain diagrams which significantly influence deflection and crack width patterns. Currently, there is limited information on serviceability issues of NSM strengthened structures compared to EBR strengthened structures.

ACI 318-99 (1999) recommended Branson's (Branson & Metz, 1963) semi-empirical cubic equation for effective moment of inertia to compute immediate or short-term deflection. However, this equation is based on the behavior of RC beams reinforced with steel. Researchers have found that the effective moment of inertia for FRP reinforced beam is overestimated with this equation. ACI 440 (2006) modified this expression to make it applicable to FRP reinforced beams, although they explicitly state that further modification of the bond dependent coefficient in the equation is needed. Several authors (Benmokrane, 1996; Brown & Bartholomew, 1996; Masmoudi, Theriault, & Benmokrane, 1998; Pecce, Manfredi, & Cosenza, 2000; Toutanji & Saafi, 2000) have proposed modifications of this bond dependent coefficient, while others (Bischoff, 2005; Faza & Ganga Rao, 1992; Smith & Kim, 2011) have proposed a modified equivalent moment of inertia derived from curvatures. ACI 440 (2006) and the Canadian

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http://dx.doi.org/10.1016/j.eswa.2014.07.058
0957-4174/

standard (CSA, 2002) have acknowledged these approaches. El-Mihilmy and Tedesco (2000) and Charkas, Rasheed, and Melhem (2003) have proposed a post yielding deflection model for FRP based EBR strengthened RC beams where the load–deflection curve is divided into three distinct linear stages, pre-cracking, cracking and post yielding. More recently, Visintin, Oehlers, Muhamad, and Wu (2013) have proposed a closed form solution based on the partial-interaction moment-rotation approach which can estimate all load levels from serviceability through to total collapse of a EBR strengthened RC beam.

The cracking behavior of FRP based EBR strengthened structures is quite unlike RC structures with steel due to the tension stiffening effects which develop at the steel–concrete and the FRP–concrete interface. As a result, crack widths and spacing become smaller compared to unstrengthened elements with the same service loading or same tension level in the steel (Ceroni & Pecce, 2007, 2009). Currently the Italian guideline (CNR, 2006) recommends 0.5 mm as the allowable crack width for FRP reinforced members. This guideline also provides equations to measure characteristics of crack widths.

The assessment of deflection and crack width is required in order to meet the serviceability requirements. At the moment, a complete theoretical model for the deflection behavior of NSM strengthened RC structures is scarce. Finite Element Modeling (FEM) may provide a possible solution, although this method is quite expensive in terms of computational aspects, especially for geometrically complicated forms. The present crack width formulations do not allow for the prediction of crack width at each loading step in controlled laboratory conditions or even for actual field crack size. Therefore, there is a need for a simple and rapid, yet reliable and accurate alternative method to predict the serviceability of NSM strengthened structures. At present, various artificial intelligence techniques, such as Artificial Neural Networks (ANN) and Genetic Algorithms (GA), have been used in various FRP strengthened RC structures (Cevik, 2011; Nehdi, Chabib, & Said, 2006). However, these techniques require extensive experimental results to optimize parameters, which is a challenging, labor intensive and time consuming process (Bashir & Ashour, 2012; Kara, 2011). Conversely, the Fuzzy Logic Expert System (FLES) offers an effective solution as it depends on expert knowledge (Kim, Kim, & Shin, 2014; Liu, Han, & Lu, 2013; Nasir, Lim, Nahavandi, & Creighton, 2014). It uses expert appraisals as well as a logical system closer to human reasoning rather than extensive experimental results. Cevik (2011) applied several soft computing techniques, such as neuro-fuzzy, genetic programming, stepwise regression and neural network to model the influence of FRP on confined concrete cylinders. The model was based on collected experimental data from open literature, which showed superior accuracy. Their formulation also conforms to the existing 10 models. Zheng, Li, and Wang (2011) predicted the delamination size and location of glass/epoxy laminate beams using a combination of fuzzy logic theory, neural networks and genetic algorithms. Modal frequencies were obtained from finite element analysis and the parameters were fed in this genetic fuzzy hybrid learning algorithm. The model demonstrated robust and promising applications in the structural health monitoring system. Nasrollahzadeh and Basiri (2014) developed a model to predict the shear strength of FRP reinforced RC structures using the Fuzzy Inference System (FIS). The study samples were 197 RC beams and slabs for which they utilized the subtractive clustering approach for partitioning the numerical data. The output of their model was only compared with the shear design guidelines (e.g., ACI and CAN/CSA). However, no work was found in the literature concerning flexural strengthened NSM-RC beams using FLES. Therefore, this study proposes an innovative approach based on FLES to predict the serviceability of RC structures flexurally strengthened with NSM reinforcement. This study consists of two approaches:

(1) The experimental method: Seven full sized RC beams were strengthened with CFRP and steel using the NSM technique. The beams were tested under four point bending load conditions. The deflection and crack width of steel and CFRP strengthened RC beams were measured with variable bonded lengths.
(2) The intelligent method: The study comprises deflection and crack width as the output parameters while applied force and bonded lengths are the input parameters for FLES. This system uses expert logic using IF-THEN rules, which connects the input and output variables with linguistic concepts.

The goal of the study was to determine the viability of using the FLES approach to achieve an accurate yet rapid prediction model for the deflection and crack width of NSM strengthened RC beams. It was expected that this approach would allow the predicted values to be obtained within a short period of time, which, in turn, would make it possible for a large number of alternative strengthening configurations to be evaluated, and thus beam specifications could be easily optimized for future use. The importance of the FLES approach is that it is possible to make flexural strengthened NSM-RC beam application, more viable and thus more attractive to potential users, such as design engineers and the Expert Systems with Applications (ESWA) community, etc.

2. Experimental methodology

2.1. Test matrix

Various parameters affect the flexural behavior of NSM strengthened beams. This study concentrates on the effect of length variation (1600, 1800 and 1900 mm) and the type of strengthening material (steel and CFRP bar) applied in strengthening the RC beams. A total of seven RC beam specimens were tested under static loading conditions in four point bending until failure. The specimens were divided into two main groups based on different strengthening material (CFRP and steel bar) and within the groups bond length was also varied. The test matrix is presented below in Table 1.

2.2. Materials

Ready mixed concrete was used for the construction of the RC beam specimens. Crushed stone, 20 mm in diameter, was used as coarse aggregate and natural river sand was used as fine aggregate. The concrete cube compressive strength at 28 days was 43.24 MPa and cylinder strength was 35.63 MPa. Flexural strength was found to be 5.01 MPa. Compressive and flexural strengths of the concrete were determined according to BS EN (2009a), ASTM (2014) and BS EN (2009b). The dimensions of the cube, cylinder and prism were $100 \times 100 \times 100$ mm, 200×100 mm diameter and $500 \times 100 \times 100$ mm, respectively.

Deformed steel bars, 12 mm in diameter, were used for internal longitudinal reinforcement in the beams. The deformed bars were tested for tensile strength in the laboratory to confirm the mechanical properties supplied by the manufacturer. The yield stress and modulus of elasticity were found to be 400 MPa and 200 GPa respectively. 8 mm steel bars with yield stress of 380 MPa and modulus of elasticity of 200 GPa were used as shear reinforcement. 12 mm deformed steel bars with yield stress and modulus of elasticity of 520 MPa and 200 GPa respectively, were used for NSM strengthening.