Engineering Applications of Artificial Intelligence 38 (2015) 79–87

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

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

Survey Paper

A simple formulation for effective flexural stiffness of circular reinforced concrete columns

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ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form
6 August 2014
Accepted 12 October 2014
Available online 18 November 2014

Keywords:
Effective flexural stiffness
Moment–curvature
Reinforced concrete
Genetic programming
Eurocode-8
TEC-2007

ABSTRACT

Concrete cracking reduces flexural and shear stiffness of reinforced concrete (RC) members. Therefore analyzing RC structures without considering the cracking effect may not represent actual behavior. Effective flexural stiffness resulting from concrete cracking depends on some important parameters such as confinement, axial load level, section dimensions and material properties of concrete and reinforcing steel.

In this study, a simple formula as a securer, quicker and more robust is proposed to determine the effective flexural stiffness of cracked sections of circular RC columns. This formula is generated by genetic programming (GP). The generalization capabilities of the explicit formulations are compared by cross sectional analysis results and confirmed on a 3-D building model. Moreover the results from GP based formulation are compared with EC-8 and TEC-2007. It is demonstrated that the GP based model is highly successful to determine the effective flexural stiffness of circular RC columns.

1. Introduction

It is known that concrete cracking affects the behavior of reinforced concrete (RC) members primarily by reducing their flexural and shear stiffness. Linear elastic analysis of RC structures without considering the cracking effect or using constant coefficients given in some current codes for cracking may not represent actual behavior of RC members.

In current codes such as Eurocode and Turkish Earthquake Code for the seismic design and performance evaluation of RC structures, effective flexural stiffness of RC members (beams, columns and shear walls etc.) stemming from concrete cracking can be calculated usually by reducing their moment of inertia to specified values or using some empirical formulations. These equations do not take into account the most important parameters affecting the inelastic behavior of RC members such as confinement, axial load level, section dimensions and material properties of concrete and reinforcing steel (Dogangun, 2013).

The structural analyses not being inclusive of the effective flexural stiffness with these major parameters will not represent actual behavior of the structures. It can be observed as an important deviation in periods of structures and inelastic displacement demand of earthquake. That will cause faulty determination of seismic performance of the structures.

A lot of studies have been performed to determine the effective flexural stiffness, EI_{eff}, of RC members. While some of them have ignored the most important parameters affecting ductile and inelastic behavior of RC elements, others have proposed very complex and not practical formulations. Because of these reasons it is highly important to propose a formula consisting of both features being simple to be used easily in practice by design engineers and including the parameters representing actual behavior of RC members.

Due to the low tensile strength of concrete, cracking, which is primarily load dependent, may occur at service loads and reduce the flexural and shear stiffness of RC members. The effective flexural stiffness of a structural concrete column is significantly affected by cracking along its length and by inelastic behavior of the concrete, reinforcing steel, and structural steel. EI_{eff} is, therefore, a complex function of a number of variables that cannot be readily transformed into a unique and simple analytical equation (Tikka and Mirza, 2008).

However, the analysis of reinforced concrete structures is usually carried out by linear elastic models which either neglect the concrete cracking effect or consider it by reducing the stiffness of members arbitrarily. It is also quite possible that the design of tall reinforced concrete structures on the basis of linear elastic theory may not satisfy serviceability requirements. For accurate determination of the deflections, cracked members in reinforced concrete structures need to be identified and their effective flexural and shear rigidities determined (Dundar and Kara, 2007).

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http://dx.doi.org/10.1016/j.engappai.2014.10.011
0952-1976/

In the design and seismic performance evaluation of RC structures, the moments of inertia of the beams and columns are usually reduced at the specified ratios to compute the lateral drift by considering the cracking effects on the stiffness of the structural frame. The gross moment of inertia of columns is generally reduced to 80% of their uncracked values while the gross moment of inertia of beams is reduced to 50%, without considering the type, history and magnitude of loading, and the reinforcement ratios in the members (Stafford-Smith and Coull, 1991).

In Eurocode 8 (EC-8), the stiffness of the load bearing elements of RC buildings should be evaluated taking into account the effect of cracking corresponding to the initiation of yielding of the reinforcement. It is advised that the elastic flexural and shear stiffness properties of concrete and masonry elements may be taken to be equal to one-half of the corresponding stiffness of the uncracked elements (Eurocode-8, 2004). It can be said that dimension, concrete compressive strength, reinforcement of sections and axial force acting on the sections are ignored and just given a constant coefficient.

In Turkish Earthquake Code 2007 (TEC-2007), there are some empirical formulae to consider the effective flexural stiffness of cracked sections in modeling of buildings. Parameters to calculate EI_{eff} are related to the axial force acting on column, cross-section area and compressive strength of the concrete. It should be noted that reinforcing ratio of the section is ignored.

Several studies have been conducted to determine the effective flexural stiffness of RC columns. Avsar et al. (2012) have studied effective flexural rigidities for ordinary RC columns by performing a parametric analysis of the sectional response of a wide range of column sections. Using a multilinear regression analysis they have proposed a parameter, α_{eff}, representing the ratio of effective flexural stiffness to uncracked flexural stiffness of the section. The proposed equations for α_{eff} yield better results for the members with lower concrete strength and longitudinal reinforcement ratio at any axial load level. Thus, they are recommended to be used in the evaluation of older-type structures having inadequate reinforcement with low strength concrete.

Tikka and Mirza (2008) have made a statistical research on effective flexural stiffness of slender structural concrete columns to develop a general equation that could be used to compute EI_{eff} of both reinforced concrete and composite columns by using a multilinear regression analysis. With the proposed formulae they have tried to improve efficiency of EI_{eff} equations given in The Canadian Standards Association (CSA) code for the design of concrete structures.

The aim of this paper is to introduce a simple formula as a securer, quicker and more robust to determine the effective flexural stiffness of cracked sections of circular RC columns. This formula has been generated by using genetic programming (GP). The advantages of GP based formulation are attributed to its simplicity and usage for different kinds of structural engineering problems for which sufficient experimental results exist. The results from GP based formulation are compared with TEC-2007 and EC-8. It is demonstrated that the GP based model is highly successful to determine the effective flexural stiffness of circular RC columns.

GP is one of the soft-computing approaches and a relatively new form of artificial intelligence. Since it was first proposed by Koza (1992), GP has garnered considerable attention due to its ability to model nonlinear relationships for input–output mappings. In recent years, the GP has been effectively applied in many engineering applications (Gandomi et al., 2010; Ashour et al., 2003; Cevik et al., 2010; Soh and Yang, 2000; Chen et al., 2012).

Gandomi et al. (2010) have proposed a novel approach for the formulation of elastic modulus of both normal-strength concrete (NSC) and high-strength concrete (HSC) using a variant of GP, namely linear genetic programming (LGP). They have developed the models based on experimental results collected from the literature and carried out a subsequent parametric analysis to evaluate the sensitivity of the elastic modulus to the compressive strength variations. They have exposed the LGP results to be more accurate than those obtained using the building codes and various solutions reported in the literature.

Ashour et al. (2003) have investigated the feasibility of using GP to create an empirical model for the complicated non-linear relationship between various input parameters associated with RC deep beams and their ultimate shear strength. They have constructed the GP model from a set of experimental results available in the literature. They have showed the predictions obtained from GP agree well with experimental observations.

Cevik et al. (2010) have studied the use of GP to model RC beam torsional strength. They used experimental data of 76 rectangular RC beams from an existing database to develop the GP model. They have compared the accuracy of the codes in predicting the RC beam torsional strength with the proposed GP model using the same test data. They have concluded that the proposed GP model predicts RC beam torsional strength more accurately than building codes.

Soh and Yang (2000) have described a GP-based approach for simultaneous sizing, geometry, and topology optimization of structures. They have presented an encoding strategy to map between the real structures and the GP parse trees. They have revealed that the proposed approach is capable of producing the topology and shape of the desired trusses and the sizing of all the structural components. They have also discovered that this approach can potentially be a powerful search and optimization technique in solving civil engineering problems.

Chen et al. (2012) developed a weighted GP system to construct the relation models between the aseismic capacity of school buildings, and their basic design parameters. They constructed numerical models to obtain aseismic abilities of buildings and simulated stress responses and behaviors of the numerical models based on the structural configuration and material properties of buildings. They suggested this system to predict the aseismic capacity of the school buildings.

In this study, a simple formulation is proposed for η_{eff}, to be called as effective flexural stiffness ratio which is the proportion of effective flexural stiffness (EI_{eff}) to gross sectional flexural stiffness (EI_0) of RC columns through the following steps: (i) Moment–curvature relationship of several commonly used circular reinforced concrete sections is obtained by using a cross sectional analysis program, XTRACT, (ii) the data to perform GP analysis are produced by taking into account the most important parameters affecting EI_{eff} of RC columns, (iii) a GP-based analysis is conducted to estimate η_{eff} accurately, (iv) the GP-based estimates are compared with the numerical study results, EC-8 and TEC-2007 and later the performance of the proposed formulae is verified on a 3-D building by a pushover analysis, and (v) finally the results are presented in graphical form.

2. Overview of moment–curvature relationship

The behavior of an RC member subjected to bending or combined bending and axial load can be understood if the moment–curvature relationship is available. By studying this relationship one can predict the strength and the stiffness, as well as the ductility characteristics of the cross-sections (Ersoy et al., 2008).

The curvature which is one of the geometrical parameters representing deformation is defined as unit rotation angle. It is the derivative of the inclination of the tangent with respect to