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A concrete–steel interface element for damage detection of reinforced concrete structures

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Abstract

The interface between concrete and steel in reinforced concrete governs the interaction between the two types of materials under loading. When the interface is seriously damaged, e.g. when a macro-crack is formed, de-bonding takes place with large slip, and the load-transferring capacity of the interface will drop dramatically. In this study, a damaged reinforced concrete beam finite element based on the constitutive law of the lumped model on the concrete–steel interface is developed. Scalar damage parameters characterizing changes in the interface are incorporated into the formulation of the finite element that is used in the damage identification procedure from static responses. Numerical simulations show that the method is effective to detect failure at the interface between concrete and steel bar in the reinforced concrete beam.

Keywords: Reinforced concrete; Beam; Bond interface; Damage detection; Inverse problem; Finite element; Crack; Static; Deflection

1. Introduction

In recent years, damage assessment of structures has drawn great attention from various engineering practitioners. Depending on the nature of the experimental data, the damage detection methods can be classified into two major categories: the dynamic identification methods using dynamic test data and the static identification methods using static test data. Compared with the static identification techniques, the dynamic methods have been developed more maturely [1]. To obtain good estimates of the damage parameters, many difficulties inherent in the dynamic identification methods should be overcome, such as the damping and mass changes due to the damage and the accurate measurements of higher vibration modes and frequencies. This may be very difficult from an experimental point of view. On the other hand, static identification method is usually simpler since the static equilibrium equation is relevant only to the stiffness properties of a structure. Also, the equipment in static testing is comparatively cheaper and many advanced techniques have been developed recently. Deformation or strain of the structure can be obtained rapidly and economically. Therefore, this group of methods has attracted much attention in the civil engineering industry. Sanayei and Onipede [2] presented an iterative optimization-based method for damage identification at element level using static test data. Incomplete measures of the structural degrees-of-freedom have been taken into account through condensation of system matrices. Banan and Hjelmstad [3,4] have done extensive work on the parameter estimation of structures using static test data with incomplete sets of applied forces and displacements by a recursive quadratic programming method. The method is extended to identify the element properties of a truss using static strains [5]. Wang et al. [6] used the static test data and changes in natural frequencies together in the structural damage identification algorithm. Di Paola and Bilello [7] presented a continuum formulation for damage identification of Euler–Bernoulli beams under static loads.

Most researchers have dealt with homogeneous structural members, where damage is represented by a local reduction in stiffness due to a crack or cut. Not much attention has been paid to problems involving nonhomogeneous elements, such as reinforced concrete members. Owing to the nature of cracks in reinforced concrete, the length of the damage zone is not

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small and, depending on other factors, it may be many times the height of the beam. Casas and Aparicio [8] used the equivalent second moment of area of section to evaluate the amount of damage in a cross-section based on finite-element analysis. The second moment of area in an element is assumed to be uniform. Cerri and Vestroni [9] modelled the damage zone as a beam element with a reduced flexural stiffness. Three parameters are used to define the damage, i.e. the position, the extent of the damage and the reduction of the elemental flexural stiffness. Frequency change is used to determine the three damage parameters of the reinforced concrete beams [10]. Wahab et al. [11] also used three parameters to describe the damage zone in reinforced concrete beams, which are, the length of the damage zone, the magnitude of the damage and the variation of the damage magnitude from the centre to the end of the damage zone. Maeck et al. [12] presented two techniques to calculate the stiffness degradation of the damaged reinforced concrete beam based on this damage model. Ren and De Roeck [13,14] identified the damage at an element level with a conventional finite-element model using the regularization algorithm. Law and Zhu [15] also studied the dynamic behaviour of damaged reinforced concrete bridge structures under moving vehicular loads using this model.

The interface between concrete and steel in reinforced concrete governs the interaction between the two types of materials under loading. When the interface is seriously damaged, such that a macro-crack is formed. De-bonding takes place or large slip occurs, and the load-transferring capacity of the interface will drop dramatically. Neild et al. [16] presented the nonlinear behaviour of reinforced concrete beams under low-amplitude cyclic vibration. He proposed four mechanisms which are responsible for the nonlinear vibration characteristics, i.e. crack closure leading to a bilinear stiffness mechanism, friction across the crack due to matrix–aggregate interaction, slip between the steel bar and the concrete and the nonlinear behaviour of concrete in compression. The most important one is the bonding damage between the reinforcing bar and the concrete. Soh et al. [17] presented a damage model, which included the normal and tangential damage factors, to describe the concrete–steel interface mechanism. A reinforced concrete element is developed based on this damage model to simulate the bond deterioration in reinforced concrete structures [18]. Spacone and Limkatanyu [19] and Salari and Spacone [20] showed the importance of including the bond slip in the response of reinforced concrete members by displacement-based formulation. They [21] have presented the general theoretical framework of the displacement-based, force-based, and mixed formulations of reinforced concrete frame elements with bond slip in the reinforcing bars.

In this study, a method is presented to detect damage in the reinforced concrete structures using a damage model based on the constitutive law of the lumped model on the concrete–steel interface. Scalar damage parameters characterizing changes in the interface are incorporated into the formulation of the finite-element model that is compatible with the damage identification procedure from static responses. Numerical simulations show that the method is effective to detect failure at the interface between concrete and steel bar in the reinforced concrete beam. This method would enable damage detection of a structure making use of results from a proof load test.

2. Beam element with damage at the concrete–steel interface

2.1. Equilibrium and compatibility

A reinforced concrete beam element with n bars and bonding interfaces is shown in Fig. 1. Only bond stresses tangential to the bars are considered. $u_B(x) = \{u_B(x), v_B(x)\}^{\mathrm{T}}$ and $u_S(x) = \{u_1(x), \ldots, u_n(x)\}^{\mathrm{T}}$ are the section displacements, where $u_B(x), v_B(x), u_i(x)$ are the concrete beam axial and transverse displacements and the axial displacement of the ith bar. The section deformations are grouped in vectors $d_B(x) = \{\varepsilon_B(x), \kappa_B(x)\}^{\mathrm{T}}$ and $d_S(x) = \{\varepsilon_1(x), \ldots, \varepsilon_n(x)\}^{\mathrm{T}}$, where $\varepsilon_B(x) = \mathrm{d}u_B(x)/\mathrm{d}x$ is the concrete beam axial strain, $\kappa_B(x) = \mathrm{d}^2 v_B(x)/\mathrm{d}x^2$ is the concrete beam curvature, and $\varepsilon_i(x) = \mathrm{d}u_i(x)/\mathrm{d}x$ is the axial strain of the ith bar. They can be written in matrix form as

$$\begin{cases} \mathbf{d}_B(x) = \partial_B \mathbf{u}_B(x) \\ \mathbf{d}_S(x) = \partial_S \mathbf{u}_S(x) \end{cases} \tag{1}$$

where

$$\partial_B = \begin{bmatrix} \mathrm{d}/\mathrm{d}x & 0 \\ 0 & \mathrm{d}^2/\mathrm{d}x^2 \end{bmatrix}, \qquad \partial_S = \begin{bmatrix} \mathrm{d}/\mathrm{d}x & \cdots & 0 \\ \vdots & \cdots & \vdots \\ 0 & \cdots & \mathrm{d}/\mathrm{d}x \end{bmatrix}.$$

The forces correspond to the section deformations $\mathbf{d}_B(x)$ and $\mathbf{d}_S(x)$ are $\mathbf{D}_B(x) = \{N_B(x), M_B(x)\}^{\mathrm{T}}$ and $\mathbf{D}_S(x) = \{N_1(x), \ldots, N_n(x)\}^{\mathrm{T}}$, where $N_B(x), M_B(x), N_i(x)$ are the beam-sectional axial force and bending moment and the axial force of the ith bar, respectively. Based on the small-deformation assumption, the equilibrium conditions can be obtained

$$\begin{cases} \dfrac{\mathrm{d}N_B(x)}{\mathrm{d}x} + \displaystyle\sum_{i=1}^{n} D_{bi}(x) = 0 \\ \dfrac{\mathrm{d}N_i(x)}{\mathrm{d}x} - D_{bi}(x) = 0, \quad (i = 1, 2, \ldots, n) \\ \dfrac{\mathrm{d}^2 M_B(x)}{\mathrm{d}x^2} - p(x) - \displaystyle\sum_{i=1}^{n} y_i D_{bi}(x) = 0 \end{cases} \tag{2}$$

where $p(x)$ is the transverse distribution load. Eq. (2) represents the governing equilibrium equations of the reinforced concrete beam element with bond slip and it can be written in the following matrix form:

$$\left\{\partial_B^{\mathrm{T}} \mathbf{D}_B(x), \partial_S^{\mathrm{T}} \mathbf{D}_S(x)\right\}^{\mathrm{T}} - \partial_b^{\mathrm{T}} \mathbf{D}_b(x) - \mathbf{p}(x) = 0, \tag{3}$$

where

$$\partial_b = \begin{bmatrix} -1 & y_1 \dfrac{\mathrm{d}}{\mathrm{d}x} & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -1 & y_n \dfrac{\mathrm{d}}{\mathrm{d}x} & 0 & \cdots & 1 \end{bmatrix},$$

$$\mathbf{p}(x) = \left\{0, p_y(x), 0, \ldots, 0\right\}^{\mathrm{T}}.$$