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Longitudinal reinforcement ratio in lightweight aggregate concrete beams

D. Dias-da-Costa [a,b,*], R.N.F. Carmo [c,d], R. Graça-e-Costa [e], J. Valença [c,d], J. Alfaiate [c,f]

[a] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[b] INESC Coimbra, Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030–788 Coimbra, Portugal
[c] ICIST, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[d] Polytechnic Institute of Coimbra, Rua Pedro Nunes – Quinta da Nora, 3030-199 Coimbra, Portugal
[e] CEPAC, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[f] Department of Civil Engineering, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

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ABSTRACT

The development of lightweight aggregate concrete (LWAC) has brought new design opportunities. The high strength and simultaneous low densities can lead to economically competitive structural solutions, which has immediate impact on seismic construction and on the strengthening of existing structures. Currently, most studies are focused on the mechanical properties and the structural behaviour under ultimate limit states, lacking experimental and numerical data concerning the serviceability of LWAC members. In this scope, a parametric study was undertaken to address the serviceability LWAC beams under flexural loading for a complete range of longitudinal reinforcement ratios. An advanced finite element technology was validated in the simulation of the overall and localised response of the members, the latter including crack openings and patterns. It was observed that the tensile reinforcement ratio should be kept bellow 2% when the durability of the LWAC is important. Nevertheless, reinforcement ratios bellow 1% might not fulfil the design requirements for aggressive environments. The numerical findings also point out that the characteristic crack openings evaluated according to the Eurocode 2 might underestimate the actual value for LWAC beams.

1. Introduction

The possibility of producing lightweight aggregate concrete (LWAC) with high strength and low density has opened new opportunities for structural designers. LWAC has become competitive against normal-weight concrete (NWC) in the design of new constructions for seismic regions, where decreasing the overall self-weight and structural stiffness, with increasing ductility, can lead to important overall savings. LWAC has also found its way in the strengthening of buildings and bridges, where high-strength and lightweight concrete layers can easily extend the strength and durability of the existing structures [1–3].

The mechanical behaviour of LWAC can be significantly different from NWC due to the replacement of normal aggregates with lightweight aggregates exhibiting much lower strength and stiffness. This directly impacts on the stress–strain constitutive response and on the Young's modulus, tensile strength and corresponding fractured behaviour [4]. For this reason, there are already numerous publications addressing the mechanical behaviour of LWAC structures [5–11]. Experimental studies have also been carried out in the scope of the flexural behaviour of the structural members, namely in what concerns ultimate limit states. This later parameter is often measured by the ductility, which is the ability of undergoing significant plastic deformations without a critical loss of strength and that may be crucial for preventing brittle failures in seismic constructions [12–18].

In spite of all research done, structural design is still in the early stages. For instance, design codes are using coefficients for adapting NWC design expressions to LWAC that are lacking both experimental and numerical validation [19,20]. Furthermore, there is a gap concerning the knowledge about serviceability conditions of LWAC members.

In this scope, this work aims at carrying out a comprehensive numerical study focusing on the serviceability of LWAC beams under flexural loading. The following objectives are defined:

* Corresponding author at: School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia.

E-mail address: daniel.diasdacosta@sydney.edu.au (D. Dias-da-Costa).

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– Validate an advanced finite element model for the simulation and prediction of the flexural behaviour of LWAC members, which accurately models the tension stiffening effect, flexural stiffness and strength, and corresponding crack openings.
– Perform a parametric study for different longitudinal reinforcement ratios, focusing on the most relevant structural parameters, such as cracking, yielding and ultimate bending moments; and deflection, curvature, and cracking openings for service loadings.
– Verify the applicability of existing guidelines for predicting deflection and crack openings in the case of LWAC.

The manuscript is organised as follows. The finite element technology is introduced in Section 2, concerning the strategy for dealing with fracture propagation and the adopted solution-finding algorithm. The validation is presented in Section 3 using experimental data collected from flexural tests concerning overall structural response, curvatures and crack openings. The parametric study and corresponding discussion is dealt with in Section 4. Finally, the main conclusions are drawn in Section 5.

2. Finite element technology

In this section the finite element technology is addressed for the simulation of the structural behaviour of the lightweight aggregate concrete beams. The analysis of the serviceability of these members requires the modelling of the tension-stiffening phenomenon, which is highly related with the process of crack propagation and localisation. Therefore, a discrete crack approach with embedded discontinuities is adopted to trace the complete structural behaviour. In the following sections the discrete crack framework is briefly reviewed, as well as the embedment strategy and the solution-finding algorithm. A detailed description of the procedures adopted can be found in [21–24].

2.1. Discrete crack approach

According to the discrete crack approach, microcracking is supposed to localise in a surface of discontinuity with initial zero width, as soon as the tensile strength of the material is reached. This fictitious crack [25] will evolve as damage progresses, gradually opening and undergoing softening. Simultaneously, the stresses in its vicinity progressively decrease towards zero, until a true crack is formed. In the presence of other reinforcing materials, such as steel, stresses propagate along the rebar, triggering the tension stiffening effect.

The incremental system of equations for the finite element with an embedded discontinuity represented in Fig. 1a can be written as:

$$\begin{bmatrix} \mathbf{K}^e_{\hat{a}\hat{a}} & -\mathbf{K}^e_{\mathbf{aw}} \\ -\mathbf{K}^e_{\mathbf{aw}} & \mathbf{K}^e_{\mathbf{ww}} + \mathbf{K}^e_d + \mathbf{K}^e_p \end{bmatrix} \begin{Bmatrix} \mathrm{d}\mathbf{a}^e \\ \mathrm{d}\mathbf{w}^e \end{Bmatrix} = \begin{Bmatrix} \mathrm{d}\hat{\mathbf{f}}^e \\ \mathrm{d}\mathbf{f}^e_w - \left(\mathbf{H}^e_{\Gamma_d}\mathbf{M}^{ek}_w\right)^T \mathrm{d}\hat{\mathbf{f}}^e \end{Bmatrix}, \tag{1}$$

where $\mathbf{a}^e$ are the nodal degrees of freedom associated with the total displacements; $\mathbf{w}^e$ are the nodal degrees of freedom measuring the opening of the discontinuity; $\mathbf{K}^e_{\hat{a}\hat{a}}$ is the regular stiffness matrix; $\mathbf{K}^e_d$ is the stiffness matrix of the discontinuity; $\mathbf{K}^e_{\mathbf{aw}}$, $\mathbf{K}^e_{\mathbf{aw}}$ and $\mathbf{K}^e_{\mathbf{ww}}$ are matrices coupling the bulk element with the embedded discontinuity; and $\hat{\mathbf{f}}^e$ and $\mathbf{f}^e_w$ are, respectively, the regular nodal forces and the forces at the discontinuity. These terms are defined according to:

$$\mathbf{K}^e_{\hat{a}\hat{a}} = \int_{\Omega^e \setminus \Gamma^e_d} \mathbf{B}^{eT}\mathbf{D}^e\mathbf{B}^e \mathrm{d}\Omega^e \text{ and } \mathbf{K}^e_d = \int_{\Gamma^e_d} \mathbf{N}^{eT}_w \mathbf{T}^e \mathbf{N}^e_w \mathrm{d}\Gamma^e, \tag{2}$$

$$\mathbf{K}^e_{\mathbf{aw}} = \int_{\Omega^e \setminus \Gamma^e_d} \mathbf{B}^{eT}\mathbf{D}^e\mathbf{B}^e_w \mathrm{d}\Omega^e,\ \mathbf{K}^e_{\mathbf{wa}} = \mathbf{K}^{eT}_{\mathbf{aw}},\ \mathbf{K}^e_{\mathbf{ww}} = \int_{\Omega^e \setminus \Gamma^e_d} \mathbf{B}^{eT}_w\mathbf{D}^e\mathbf{B}^e_w \mathrm{d}\Omega^e \text{ with } \mathbf{B}^e_w = \mathbf{B}\mathbf{H}^e_{\Gamma_d}\mathbf{M}^{ek}_w, \tag{3}$$

$$\hat{\mathbf{f}}^e = \int_{\Omega^e \setminus \Gamma^e_d} \mathbf{N}^{eT}\bar{\mathbf{b}}^e \mathrm{d}\Omega^e + \int_{\Gamma^e_t} \mathbf{N}^{eT}\bar{\mathbf{t}}^e \mathrm{d}\Gamma^e, \tag{4}$$

where $\mathbf{B}^e$ is the strain-nodal displacement matrix; $\mathbf{D}^e$ and $\mathbf{T}^e$ are the tangent constitutive matrices, respectively for bulk and discontinuity; $\mathbf{N}^e$ and $\mathbf{N}^e_w$ contain the shape functions of the regular element and discontinuity; $\mathbf{H}^e_{\Gamma_d}$ is a diagonal matrix containing '1' in the degrees of freedom belonging to one side of the discontinuity, and '0' otherwise; and $\bar{\mathbf{b}}^e$ and $\bar{\mathbf{t}}^e$ are, respectively, the vectors of body forces and stresses applied on Γ^e_t.

In Eq. (3), $\mathbf{M}^{ek}_w$ is the matrix that transmits the opening of the discontinuity to the nodes of the element [22]. In the case of concrete, it can be argued that: (i) the discontinuities are significantly softer than the bulk due to the quasi-brittle nature of the material; and that (ii) the failure mechanism for flexural loading is dominated by mode-I fracture, in which case the opening of the crack is transmitted by rigid body motion to their neighbourhood. This significantly simplifies the implementation of the method and leads to:

$$\mathbf{M}^e_w(\mathbf{x}) = \begin{bmatrix} 1 - \frac{(x_2 - x^i_2)\sin\alpha^e}{l^e_d} & \frac{(x_2 - x^i_2)\cos\alpha^e}{l^e_d} & \frac{(x_2 - x^i_2)\sin\alpha^e}{l^e_d} & -\frac{(x_2 - x^i_2)\cos\alpha^e}{l^e_d} \\ \frac{(x_1 - x^i_1)\sin\alpha^e}{l^e_d} & 1 - \frac{(x_1 - x^i_1)\cos\alpha^e}{l^e_d} & -\frac{(x_1 - x^i_1)\sin\alpha^e}{l^e_d} & \frac{(x_1 - x^i_1)\cos\alpha^e}{l^e_d} \end{bmatrix}, \tag{5}$$

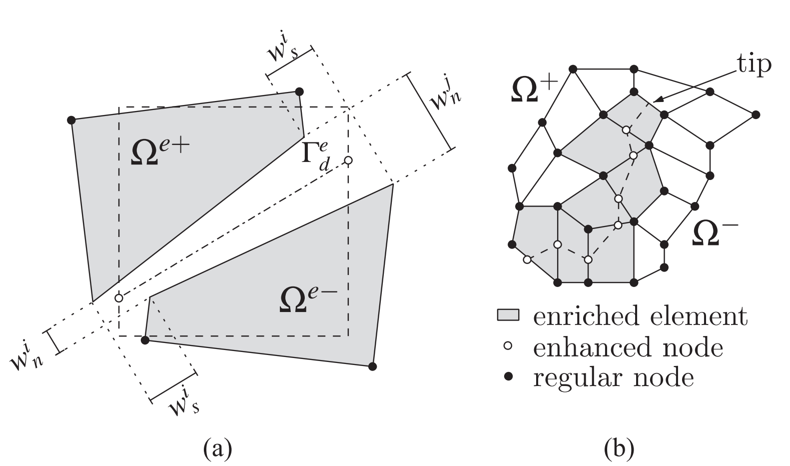

Fig. 1. (a) Finite element with an embedded discontinuity; and (b) crack propagation.