An investigation of meso-scale crack propagation process in concrete beams using topology optimization

Ali Permanoon[1], Amir houshang Akhaveissy[2*]

[1]PhD student of structural engineering, Razi University
[2] Associate professor, Razi University

ABSTRACT

The current research seeks to investigate a novel method for reducing computational costs of concrete modeling in the meso scale. Two separate scales, macro and meso, were used to evaluate concrete behavior. As the stress distribution at the macro scale can be a good indicator to determine the crack critical zones (onset and growth of crack), the numerical model is analyzed at the macro scale using the extended finite element method (XFEM), and then, critical zones are specified in each step using macro-optimization. Afterwards, the sum of the zones is modeled in the main model at the meso scale. At the meso scale, the three parts of aggregate are modeled with linear behavior, and cement mortar and transfer zone with nonlinear behavior. Aggregates are distributed in cement mortar by a random algorithm and Fuller curve in a circular shape. For meso-scale discretization, piecemeal discretization method was used considering the adhesive zone for all elements. Using this method, crack onset and growth are properly modeled. To validate this method, two numerical examples were examined in 2D. The numerical analysis results were in perfect agreement with the laboratory results, and the volume of the calculations was reduced by an average of 35% while maintaining accuracy.

KEYWORDS

Crack growth, meso-scale, topology optimization, finite elements method, extended finite element method

[*] Corresponding Author: Email: Ahakhaveissy@razi.ac.ir

1. Introduction

The structure of concrete at the meso scale plays a critical role in the onset and spread of cracks. Due to the great impact of the internal structure of heterogeneous materials on their mechanical behavior, various models for concrete behavior at the meso scale have been proposed nowadays with the help of numerical calculation methods [1-4]. Different algorithms have been established to produce aggregate shape and location [5]. Various algorithms are proposed for optimization methods. One of these algorithms is to minimize von Mises stress or to maximize stiffness in the studied structure under applied restrictions [6]. In the current research, as meso-scale analysis is computationally highly expensive, some parts of the structure that are prone to crack growth (critical zones) are identified at the macro scale using topology optimization algorithm and XFEM. Critical zones are modeled at the meso scale, and other zones at the macro scale.

2. Methodology

To model a numerical sample on a meso scale using topology optimization, the following steps must be pursued:

(a) Numerical sample modeling on macro scale using macro discretization and solution via XFEM. (b) Save the stress and strain results of each step relevant to the previous stage. These results are entered as input (initial stress and initial strain) in the optimization model, and the numerical model is analyzed under topology optimization. (c) Save all the results of topology optimization analysis and extraction of the whole material (critical stress levels) required in each step taking into account crack propagation. (d) Meso-scale modeling using the results of topology optimization. In this stage, the areas required for topology optimization are modeled as meso and the rest of the areas as macro. (e) Distribution of aggregates at meso scale, design of fractional discretization, analysis of numerical model and comparison of numerical model results using topology optimization, and modeling of the whole numerical sample at meso scale. It should be noted that FEM and XFEM available in Ansys software were used in the present study, and the topology optimization part was coded with Fortran language and added in the form of macro to Ansys software to be able to specify the required parts using the results of the XFEM at each step. In addition, the discretization part was produced by coding in Fortran programming language.

3.Results and Numerical examples

(a) Crack propagation in concrete beam under three-point bending

In this example, crack propagation in concrete beam was investigated in 2D using topology optimization. Two samples of the beam in question were experimentally tested by Skarzianski et al [7]. To compare the results, the numerical model that was fully modeled on the meso scale was designated as Model 1 (Direct Meso-scale), and the numerical model that was modelled using numerical optimization on the meso scale was designated model 2 (Adaptive Meso-scale).

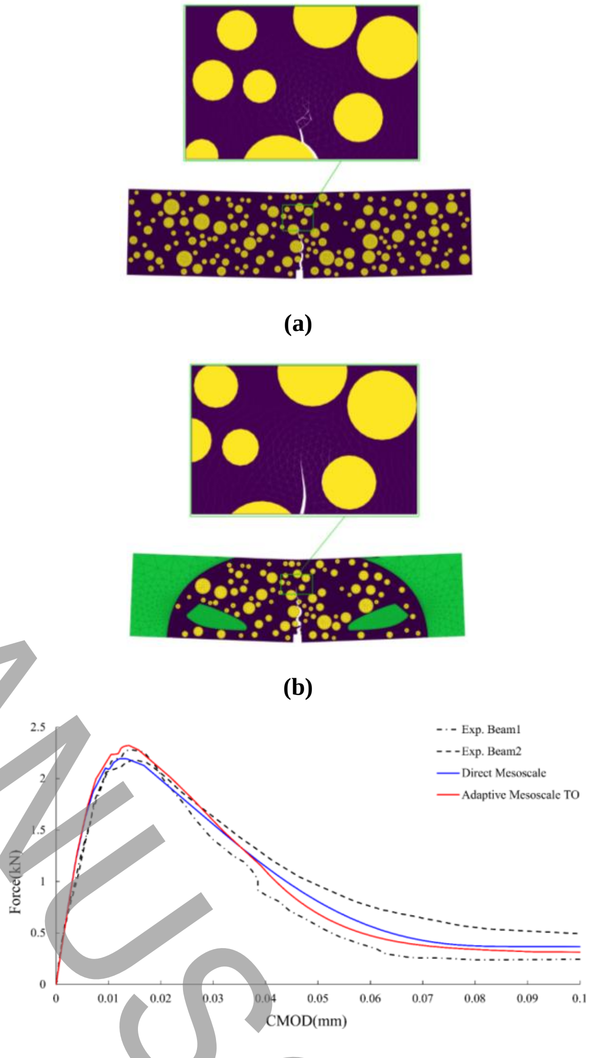
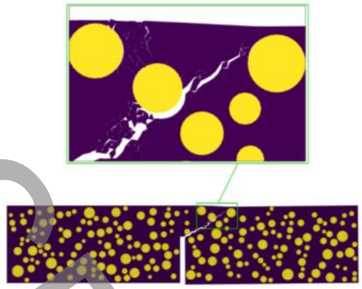


Figure 1. (a) Crack propagation in DM numerical model, (b) Crack propagation in AM numerical model, (c) Force-CMOD

(b) Crack propagation in concrete beam under four-point bending

In this example, crack propagation in concrete beams under four-point bending was investigated in 2D using topological optimization. Two examples of this beam were tested in the laboratory by Galvez et al. [8].



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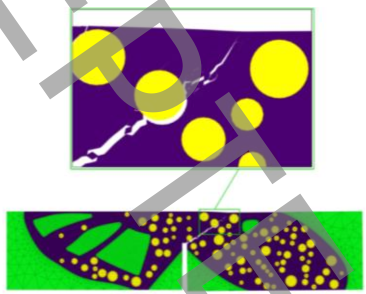

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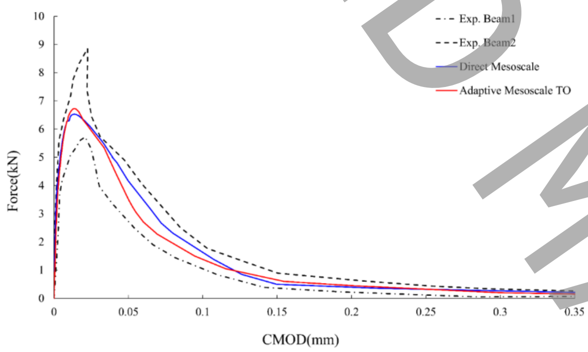

(d)

Figure 2. (a) Crack propagation in DM numerical model, (b) Crack propagation in AM numerical model, (c) Force-CMOD

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4.Conclusions

A numerical method for concrete beams modeling at meso scale was presented. This method works on two separate scales, macro and meso. The model was first analyzed at the macro scale using the XFEM, and the results of crack analysis and growth were stored at each step (stress, strain and crack growth), These results were entered as input into the macro topology optimization using maximum stiffness formulation. Therefore, in each step of the macro-scale analysis, the model was analyzed using the topology optimization method, and critical stress zones were identified. In the current study, two numerical samples were modeled in 2D by this method on meso scale. Crack onset and growth in both models were in good agreement with laboratory results. In general, this method has the following two advantages:

1- Conformity of the general pattern of crack growth with laboratory results.

2- Reduction in computational costs on the meso scale

In two numerical samples, thanks to topology optimization, computational cost for three-point beam and four-point beam reduced by 32.8% and 37.3%, respectively, in comparison with the overall modeling ratio at the meso scale.

5.References

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