
Investigating Damage and Plasticity in RC Nuclear Facilities Under Seismic Loading

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Abstract

Reinforced concrete (RC) structures in the nuclear field are subject to stringent regulations, particularly for seismic demands. Understanding RC behavior under mechanical loads especially during earthquakes, and modeling this behavior numerically is crucial for assessing the robustness and safety of the structures and the hosted equipment, both at the design and reassessment stages.

Our research focuses on developing a multi-layer, multi-material plate model (Love-Kirchhoff kinematics) within the finite element (FE) framework, designed for large-scale simulations of RC structures in nuclear facilities and capable of representing engineering key quantities such as the floor spectra and the energy dissipation. The model aims to reflect the effects of microscopic non-linearities at a macroscopic level: the top and bottom layers in the thickness of the RC plate will be modeled as an equivalent homogenized material representative of the steel grids, the surrounding concrete, and the interface between the two materials; while the core will be modeled using a non-linear damage model for concrete. The model will strive to strike a crucial balance between accurately representing the complex material behavior and ensuring computational efficiency, practical usability, and parameter calibration.

RC's composite nature and the steel-concrete interaction at the interface are critical for the understanding of the stress redistribution, the tension stiffening, and the energy balance in RC elements under seismic loading. Therefore, a detailed investigation into the non-linear behavior of the steel-concrete interface and its interaction with the surrounding damaged concrete is at the core of this study.

We have conducted an extensive bibliographic review and we have performed several numerical tests to identify the most critical features influencing the macroscopic response. These tests help us understand interface behavior aspects (interlocking effect of steel ribs causing

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concrete compression and plastic deformation, frictional degradation in the post-peak phase, cumulative damage effect during cyclic loading) and their interaction with the surrounding damageable concrete and how they impact the overall structural performance.

A simple rheological model representative of a 1D reinforced concrete tie has been analyzed under various load conditions (static, dynamic, monotonic, and cyclic) to assess the role of different modeling assumptions on global (response spectra, energy balance) and local (stress redistribution) responses. The results, validated using experimental references, have confirmed the necessity of including the non-linear interface in numerical models for RC and have emphasized the need for a comprehensive understanding of non-linear phenomena and their interactions.

These initial results have been extended to the study of a Representative Elementary Volume (REV) representative of the top and bottom layers of an RC plate, including the steel bars, the surrounding concrete, and the interface. The REV has been tested under various loading conditions to investigate the concrete damage field and the coupled effects of concrete damage and steel-concrete relative sliding. The primary objectives of this analysis are to propose a macroscopic damage description and understand concrete damage and interface sliding interaction.

All the collected results will be integrated in the homogenization process for the plate's membrane behavior under the hypothesis of periodic media and using the averaging method (1) (2) (3). The homogenization will be conducted in the linear elastic framework, at fixed values of the internal variables and integrating the effect of the steel-concrete interface (4)(5). Particular attention will be given to the definition of the thermodynamic framework of the model for the homogenized RC layer to ensure its validity for ideally any kind of cyclic loading; and to the identification of the parameters defining the macroscopic constitutive relation, employing optimization algorithms in order to ensure the convexity of the free energy potential.

Presentation key points: bibliographic review, the homogenization methodology: the linear framework and the taking into account of damage and plasticity, results of the numerical simulations on the REV

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