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A MESOSCALE MODELING OF RECYCLED AGGREGATE CONCRETE

Marianela Ripani[a,c,e], **Daniel Félix**[a,b] **and Paula Folino**[c,d]

[a]*Departamento de Ingeniería, Universidad Nacional del Sur (UNS), Buenos Aires, Argentina. marianelaripani@gmail.com*

[b]*Instituto de Ingeniería-II-UNS (UNS-CIC). Universidad Nacional del Sur (UNS), Buenos Aires, Argentina. dhfelix@uns.edu.ar*

[c]*Universidad de Buenos Aires. Facultad de Ingeniería. Laboratorio de Métodos Numéricos en Ingeniería (LMNI-FIUBA), Buenos Aires, Argentina. pfolino@fi.uba.ar*

[d]*Instituto (UBA-CONICET) de Tecnologías y Ciencias de la Ingeniería "Hilario Fernández Long" (INTECIN). Buenos Aires, Argentina.*

[e]*CONICET. Consejo Nacional de Investigaciones Científicas y Técnicas, Buenos Aires, Argentina.*

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Abstract. In this study, a mesoscale model of Recycled Aggregate Concrete (RAC) is implemented using the Finite Element software ABAQUS. RAC is characterized by the partial or complete replacement of natural coarse aggregates with recycled aggregates obtained from crushed hardened concrete. Due to its composition, RAC exhibits a heterogeneous composite structure consisting of multiple phases: new cement paste, natural aggregates, and recycled aggregates partially or completely covered by a layer of old cement paste. In this approach each phase is modeled based on a different constitutive theory. A key objective of this work is to investigate the mechanical response of RAC, with particular focus on the degradation of the paste–aggregate interfaces. Numerical results from the mesoscale model are compared with those obtained using a macroscopic constitutive approach, the Performance Dependent Model (PDM), to evaluate the predictive capabilities and advantages of each modeling strategy.

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1 INTRODUCTION

Concrete is the most widely used construction material globally. Its massive production has significant environmental consequences due to the high consumption of natural resources and energy. In this context, the use of Recycled Aggregate Concrete (RAC) has emerged as a crucial and sustainable solution. By partially or completely replacing natural aggregates with aggregates derived from construction and demolition waste, RAC helps to conserve natural resources, reduce landfill waste, and lower the overall carbon footprint of construction (Buttler and Machado, 2005; Djerbi Tegguer, 2012; Xiao et al., 2012).

Despite its environmental benefits, RAC exhibits a more complex and heterogeneous microstructure compared to conventional concrete. The presence of old adhered mortar (OAM) on the surface of the recycled aggregates and the formation of multiple interfacial transition zones (ITZs) principally between new paste and natural aggregates, and between new paste and recycled aggregates, result in a material with increased porosity and potentially weaker interfaces (Poon et al., 2004). These microstructural features significantly influence the RAC mechanical performance, affecting properties such as compressive strength, stiffness, and durability (Etxeberria et al., 2007; Corinaldesi, 2010; Folino and Xargay, 2014).

Early research on RAC has largely focused on experimental investigations and development of macroscopic constitutive models to predict its behavior (Casuccio et al., 2012; Corinaldesi, 2010; Yang et al., 2020; Ge et al., 2024). Notable among these is the Performance-Dependent Model (PDM), which effectively captures the overall material response by introducing dependency on the replacement ratio and aggregate quality (Folino and Etse, 2012; Folino, 2014). However, these macroscopic models often treat the material as a homogeneous continuum, thereby neglecting the detailed micromechanical interactions and damage localization processes that occur at the mesoscale. Mesoscale modeling, in contrast, would provide a powerful tool to explicitly represent these individual phases and their interactions, offering a deeper insight into the material failure mechanisms, such as crack initiation and propagation (Zhuo et al., 2022; Jin et al., 2024). Nevertheless, this approach would come at the cost of significantly higher computational complexity and a substantial increase in processing time, making it less practical for large-scale structural analysis.

This work intends to address this gap by developing and applying a conceptually simple mesoscale finite element model for RAC using ABAQUS (Dassault Systèmes, 2022a), a popular finite element commercial software. The primary objective is to investigate the material mechanical response by explicitly modeling its multiphase structure and focusing on the degradation of its interfaces. A central part of this work involves a direct comparison between the numerical results from this mesoscale model and those obtained using the macroscopic PDM. This dual-scale analysis aims to highlight the respective advantages and predictive capabilities of each modeling strategy, thereby advancing the understanding of RAC and facilitating its more reliable use in civil engineering applications.

2 PROBLEM AND MODELS DESCRIPTION

In the following, the problem to be studied is formulated and the constitutive models selected to capture the mechanical behavior of RAC are presented.

2.1 RAC as a Multiphase Composite

From a mesoscale perspective, RAC can be accurately described as a heterogeneous composite material composed of up to five distinct phases: new cement paste, natural aggregates

(NA), recycled aggregates (RA), the old adhered mortar layer (OAM) surrounding the RA, and the interfacial transition zones (ITZs). Moreover, if the percentage of replacement of natural by recycled aggregates is not 100%, the number of involved phases can increase to eight. The ITZs, particularly those at the interface between the new paste and the OAM, are widely recognized as the weakest links in the material microstructure, governing the overall mechanical response and failure behavior. This behavior is significantly influenced by the replacement percentage of recycled coarse aggregate, as its impact becomes notably evident from replacement ratios of 30% and above (Poon et al., 2004; Xu et al., 2021). In this study, the mechanical behavior of RAC, with a specific focus on the degradation of strength and stiffness at uniaxial compression tests, is numerically investigated for two different replacement percentages: 60% and 100%. This analysis is performed by evaluating the results from macroscopic and mesoscale models implemented in ABAQUS (Dassault Systèmes, 2022a) and comparing them with those from the PDM macroscopic approach (Folino, 2014) and experimental data (Folino and Xargay, 2014).

2.2 Mesoscale Finite Element Modeling

The mesoscale model presented in this study explicitly represents the RAC phases within a finite element framework. The geometry of the model consists of a 2D representation of a 100 mm x 200 mm cylindrical specimen, used to simulate uniaxial compression tests. The coarse aggregates are modeled as circles of 15 mm of diameter, and the ITZs are represented by an offset of 5 mm around the aggregates. While the coarse aggregates are arranged in an ordered distribution with regular shape and size to simplify the analysis in this work, it is understood that this approach is still suitable for the study of relative ITZ degradation. Regarding the material models, a linear elastic model was used for the natural coarse aggregates, while the matrix and ITZs were modeled using the Concrete Damage Plasticity (CDP) model available in the ABAQUS software library (Dassault Systèmes, 2022b). It is worth to note that CDP is a continuum damage-plasticity constitutive model capable to capture the nonlinear behavior, damage initiation, and stiffness degradation of concrete under both tension and compression. An unstructured finite element mesh was used for the discretization. Finally, the material properties assigned to each phase, for both Natural Aggregate Concrete (NAC) and RAC with 60% and 100% replacement ratios, were extracted from an extensive experimental work by Folino and Xargay (2014).

2.3 Macroscopic PDM Approach

For comparative purposes, this study utilizes the Performance-Dependent Model (PDM), a macroscopic constitutive formulation that was developed to characterize the behavior of concrete under various loading scenarios by introducing performance-dependent constitutive functions. Specifically, a modified version of the original PDM, as proposed by Folino (2014), is used in this work as an extension of the original model by Folino and Etse (2012). This modified PDM reformulates the constitutive functions such that the parameters, such as compressive strength and elastic modulus, are directly linked to the RAC composition. This approach treats the material as a homogeneous continuum, and its efficiency makes it highly suitable for structural analysis where the detailed representation of microstructural features is not feasible or computationally viable. Further details on the model and the specific values adopted for each of its parameters are provided in a related publication by Folino (2014).

3 METHODOLOGY OF ANALYSIS

Building upon the problem formulation and the constitutive models described in the previous section, this study follows a multi-step methodology to investigate the mechanical behavior of Recycled Aggregate Concrete (RAC) at both the macroscopic and mesoscopic scales. This process involves calibration and validation of the numerical modeling against experimental data (Folino and Xargay, 2014).

First, experimental stress-strain curves for the uniaxial compression test for Natural Aggregate Concrete (NAC) and Recycled Aggregate Concrete with 60% replacement ratio (RAC-60) were first prepared for use as input data for the numerical models. In this sense, Figures (1) and (2) show the input stress-strain curves required by the Concrete Damage Plasticity (CDP) model by ABAQUS against the experimental data by Folino and Xargay (2014) for NAC and RAC-60.

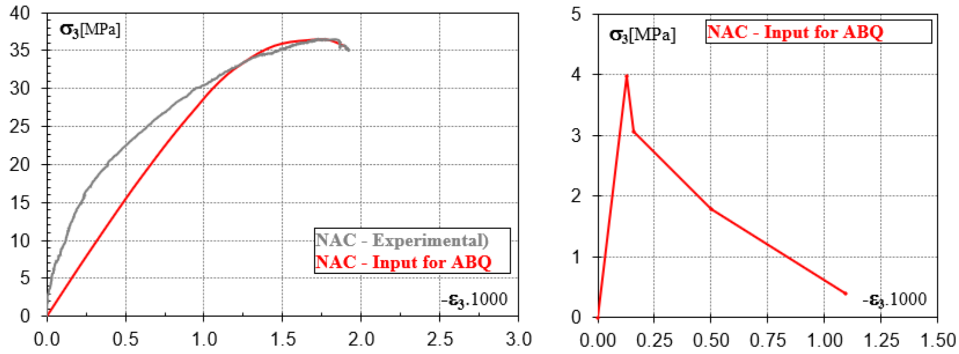

Figure 1: Experimental data and input stress-strain curves for NAC at (left): uniaxial compression test and (right): uniaxial tensile tests.

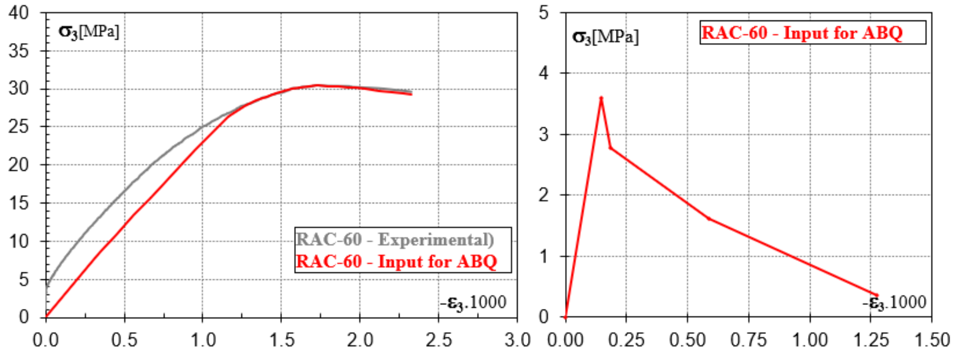

Figure 2: Experimental data and input stress-strain curves for RAC-60 at (left): uniaxial compression tests and (right) uniaxial tensile test.

Second, a uniaxial compression test was implemented using a macroscopic model for NAC. This was done to calibrate the matrix phase for the mesoscale model and to ensure the model's ability to accurately represent the material behavior at the continuum level. To proceed with the mesoscale analysis, the same specimen geometry was then modeled with discrete aggregates uniformly distributed across the 2D specimen section. A linear elastic model was assigned to the aggregates, while the previously calibrated NAC model was assigned to the matrix. It is worth noting that for the NAC mesoscale model, the ITZ rings had the same material properties as the matrix. The results of this calibration are shown in Figure (3-a). Subsequently, to represent RAC with a 60% replacement ratio, the matrix and aggregate models were kept constant, and the input data from Figure (2) was assigned as the material behavior for the ITZ rings in the mesoscale model. The results of this mesoscale simulation were then contrasted with the experimental data for RAC-60 in Figure (3-b). This final step validated the mesoscale model for RAC-60.

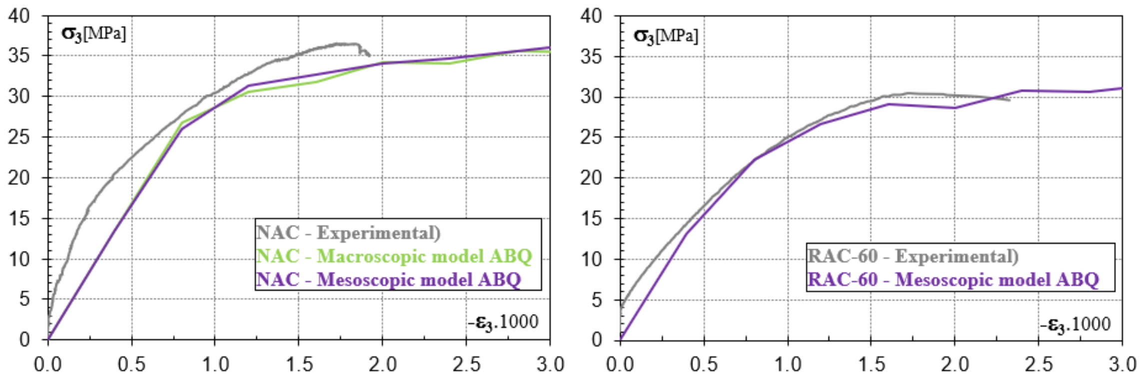

Figure 3: Experimental data and numerical stress-strain curves at uniaxial compression tests for: (left) NAC macroscopic and mesoscopic models, both in ABAQUS, and (right): RAC-60 mesoscopic model.

Third, to evaluate the mechanical behavior of RAC with a 100% replacement ratio, a linear degradation relationship for the ITZ was determined based on the results from the previous calibration steps for NAC and RAC-60. This degradation is characterized by a decrease in both the elastic modulus and the peak stress of the uniaxial compression and uniaxial tensile stress-strain curves. As a result of this analysis, the input data for RAC-100 set on the CDP model in ABAQUS is given in Figure (4).

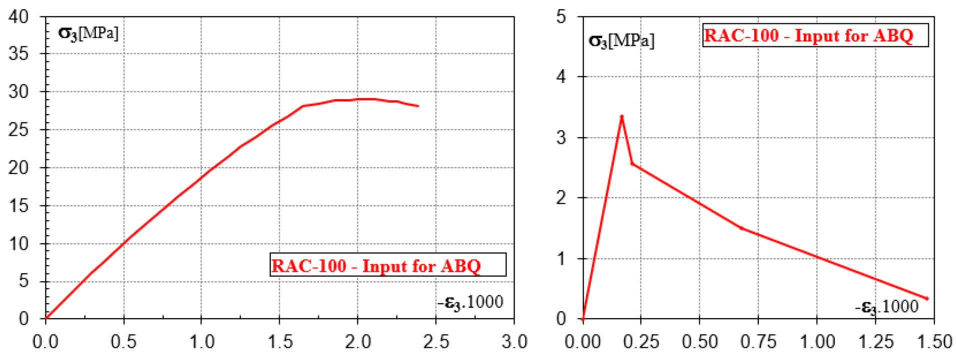

Figure 4: Input data for RAC-100 as stress-strain curves for (left): uniaxial compression and (right): uniaxial tensile tests.

Finally, the results obtained from this simulation are compared with the experimental uniaxial compression stress-strain curve for RAC with a 100% replacement ratio. These results are presented in the following section. In the following, a summary of mechanical properties and CDP material parameters used in all simulations are presented in Tables (1) and (2), respectively. In Table (1) UCT, UTT and NCA correspond to uniaxial compression and tensile tests, and Normal Concrete Aggregates, respectively. Poisson coeficient and density are set for all materials as 0.2 and 2.4E-06 kg.m/s^2, respectively. In table (2) the non-dimensional variables

Ψ, ϵ, f_{bc}/f'_c and K_c are the dilation angle, the eccentricity, the biaxial to uniaxial compression strength relationship and the deviatoric eccentricity, respectively.

Table 1: Mechanical properties of NAC, RAC at 60% and 100% replacement ratios and NCA.

Property	NAC	RAC-60	RAC-100	NCA
Peak Strength at UCT (MPa)	36.52	30.42	26.35	-
Peak Strength at UTT (MPa)	3.97	3.60	3.34	-
Elasticity Modulus (GPa)	31.67	24.53	19.78	40

Table 2: Concrete Damage Plasticity (CDP) model parameters used in the numerical simulations.

Ψ	ϵ	f_{bc}/f'_c	K_c
40	0.1	1.16	0.67

4 RESULTS AND DISCUSSION

The results from each step were systematically compared with the stress-strain curves from the macroscopic PDM approach for uniaxial compression tests, as referenced by Folino (2014) and shown in Figure (5). Additionally, Figure (6) presents the distribution of equivalent plastic strains (PEEQ), which were captured from the macro and mesoscale models to provide visual insights into the failure mechanisms.

As shown in Figure (5), the mesoscale model successfully captured the compressive peak strength for both RACs with 60% and 100% replacement ratios. Figure (6) provides a detailed visual representation of the failure process for NAC and RAC-60 and RAC-100, as obtained from the simulation.

In the mesoscale models, the results clearly showed that damage initiated primarily within the weaker ITZs, leading to a progressive debonding of the aggregates from the new cement paste. Furthermore, the RAC-100 model showed a greater number of affected ITZs compared to the RAC-60 model. The magnitude of plastic strains is also higher in the RAC-100 model compared to both the NAC and RAC-60 models. It can also be observed that the matrix in the mesoscale models, in general, exhibits a lower magnitude of plastic strains compared to the macro model. This behavior is consistent with experimental observations, where, as the load increases, microcracks initiated in the ITZs coalesce and propagate, eventually forming a macroscopic crack pattern that leads to the final failure of the specimen.

The model also accurately demonstrated that the overall compressive strength and stiffness of the material decreased as the replacement ratio of RA increased, which aligns well with experimental observations. This decrease is directly attributed to the increased presence of weaker ITZs. A key finding of this study is the good agreement between the mesoscale and macroscopic PDM predictions regarding the overall mechanical response. Both models accurately predicted the peak compressive strength and the general shape of the stress-strain curve. This demonstrates that for macroscopic-level predictions, the PDM is a highly effective and computationally efficient tool. However, the mesoscale model provided an extra level of detail regarding the damage localization originating from the ITZs. The ability of the mesoscale model to show where and how damage initiates and propagates provides critical insights into the underlying physical failure mechanisms of RAC.

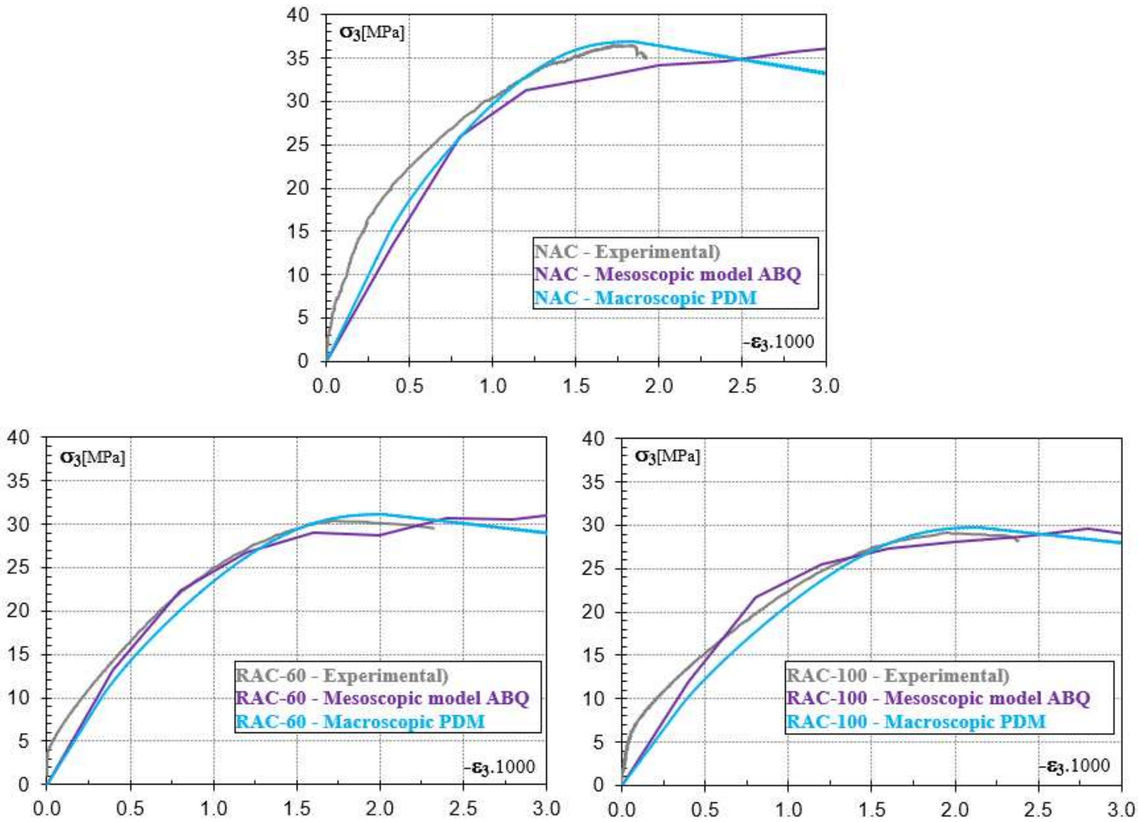

Figure 5: Comparison between experimental and numerical results by PDM macroscopic approach and CDP mesoscale for (top): NAC, (bottom-left): RAC-60 and (bottom-right): RAC-100 at the uniaxial compression test.

5 CONCLUSIONS

In this work, a mesoscale finite element model of Recycled Aggregate Concrete (RAC) was successfully implemented. A thorough comparison with a macroscopic approach, the Performance-Dependent Model (PDM) (Folino, 2014), was conducted, and both models demonstrated good predictive capabilities in line with experimental data (Folino and Xargay, 2014), validating their use in the analysis of RAC.

The mesoscale model, while being more computationally demanding, provides a rich and detailed understanding of RAC mechanical behavior. This approach explicitly captures the material heterogeneous nature, offering critical insights into the degradation of the interfacial transition zones (ITZs), progressive damage mechanisms, and intricate crack patterns.

On the other hand, the macroscopic approach proved to be an efficient and effective tool for predicting the overall response of RAC. Its lower computational cost makes it a more suitable option for scenarios where a detailed representation of every microcrack is not necessary.

The findings from this study highlight the complementary nature of these two modeling approaches. The mesoscale model provides the fundamental insights necessary to validate and refine macroscopic models, while the macroscopic view offers a practical and efficient solution for large-scale engineering problems. Future work will focus on using aggregates of varied and irregular sizes, distributed randomly and with ITZs of different thicknesses, to deepen the analysis.

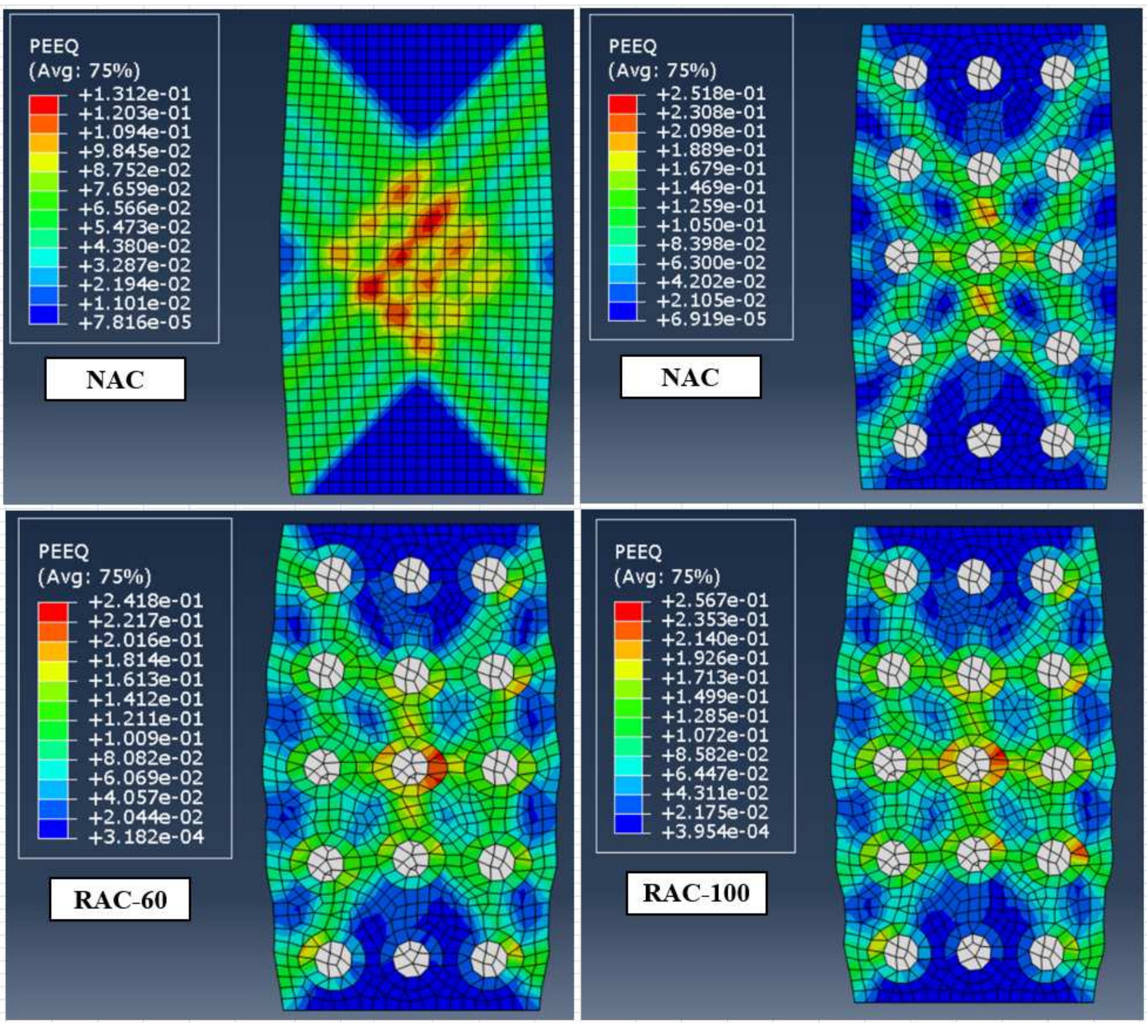

Figure 6: Comparison of plastic equivalent strains (PEEQ) patterns, on deformed specimens, between NAC macro and mesoscale models and RAC-60 and RAC-100 mesoscale models.

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