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IIMPACT OF GEOMETRY, INTER-UNIT CONNECTIONS AND FLOOR DEFORMABILITY ON THE DYNAMIC RESPONSE OF UNREINFORCED MASONRY AGGREGATE BUILDINGS

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Abstract

Unreinforced masonry aggregate buildings are a characteristic feature of the Mediterranean architectural landscape, characterized by their heterogeneous configurations resulting from incremental expansions over time. These expansions lead to complex structural systems composed of interconnected units with varying geometries, materials, and slab typologies, making their modeling and assessment particularly challenging. This study focuses on analyzing these structures, independent of the case-specific uncertainties associated with their geometrical variations. To achieve this, an elementary aggregate model consisting of three similar units is proposed and analyzed under varying boundary conditions and geometric configurations, allowing for the isolation of each variable's contribution to the seismic response of the individual units. The STKO platform for OpenSees is used to develop the model, which employs a homogenized 2D layered shell element approach to balance computational efficiency with an accurate representation of masonry wall behavior. Nonlinear dynamic analyses provide critical insights into damage distribution and failure mechanisms, emphasizing the role of connection strength and floor deformability in the formation of these mechanisms.

Keywords: Masonry, Aggregate Buildings, Non-linear dynamic analysis, Opensees, FEM.

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1 INTRODUCTION

Recent and past seismic events have highlighted the vulnerability of unreinforced masonry (URM) building aggregates, a common feature in the historic centers of Italy and other Mediterranean countries. These aggregates typically develop over time as structural units are progressively added to existing buildings. The outcome is often a non-uniform assembly of construction phases, rarely aligned with a cohesive structural design. As a result, these buildings usually exhibit a variety of masonry types and construction techniques, depending on the period in which each unit was built.

The assessment of such systems presents significant challenges. Geometric uncertainties (including incomplete documentation of the layout, variable slab flexibility, and unknown slab-to-wall connection quality) complicate the structural modeling process. Material uncertainties, particularly those related to the orthotropic and nonlinear nature of masonry, further affect the seismic response [1]. A particularly influential and often poorly understood factor is the interaction between adjacent structural units. These may be fully integrated, partially connected, or mechanically independent. Moreover, the condition of these interfaces often changes over time due to degradation or local modifications. The ability (or lack thereof) of these connections to transfer loads significantly influences the behavior of the aggregate under seismic excitation, yet remains difficult to characterize without invasive investigation.

From a performance-based perspective, modeling efforts are best directed at capturing the mechanisms most relevant to damage progression and structural safety, rather than aiming for exhaustive geometric or material fidelity [2]. This becomes especially important in large-scale analyses, where computational constraints limit the feasibility of detailed models. While micro-modeling—where individual masonry units and mortar joints are represented explicitly—can offer high accuracy (e.g., [3], [4]), it is generally impractical for entire aggregates subjected to dynamic loading due to small time-step requirements, nonlinearities, and long-duration input motions.

To address these limitations, simplified approaches based on homogenized masonry are widely adopted. These treat masonry as a continuum, reducing the number of elements and enabling more efficient computation. Examples include two- and three-dimensional macro-elements and the Equivalent Frame Method (EFM), which simplifies walls into systems of piers and spandrels modeled as 1D elements. EFM has proven effective for buildings with regular openings [5], but tends to lose accuracy in irregular configurations or where interactions between non-orthogonal walls are significant.

In such cases, continuum models offer a more robust solution. By representing distributed contact behavior between adjoining walls, they can more effectively capture interaction mechanisms even in complex or deteriorated configurations. This study proposes a simplified aggregate structure composed of three adjacent units, purposefully designed to isolate the influence of slab flexibility and inter-unit interaction. Eight models were developed in STKO [6], a pre-/post-processor for OpenSees [7], adopting a homogenized masonry material approach. A continuum interface material was introduced to simulate the degrading mechanical connection between adjacent units. The interface behavior was characterized, and a parametric analysis was carried out by varying the interface strength to assess its impact on displacement and damage distribution.

Results show that the effect of connection strength is not uniform across the aggregate and depends strongly on the unit's position within the system. Rigid diaphragms played a crucial role in distributing forces across the aggregate, leading to a clear correlation between interface strength and displacement. In contrast, with flexible diaphragms, this relationship is less consistent due to the activation of other deformation mechanisms.

2 MODELLING STRATEGIES FOR AGGREGATE BUILDINGS

The numerical model adopts a homogenized masonry approach, where walls are treated as a continuum without distinguishing between bricks and mortar. All masonry elements are modeled using *ASDShellQ4* thick shell elements [8], combined with *LayeredShell* [9] fiber sections to capture membrane, bending, and out-of-plane shear behavior efficiently. This setup allows for a reduced computational cost compared to 3D solid elements while still capturing the global and local response mechanisms relevant to seismic loading.

Material behavior is defined through the *ASDConcrete3D* constitutive model [10], which employs a tension-compression damage framework with distinct criteria and scalar damage indices for each stress state. This model includes auto-regularization of fracture energy to reduce mesh sensitivity and an *IMPL-EX* integration scheme for stable convergence under strong nonlinearities [11]. The main advantage of the *ASDConcrete3D* model lies in the incorporation of the crack planes command. If defined, it enables the anisotropy of internal variables. They are stored in crack-planes that are equally spaced according to the number of crack planes chosen in tension and compression (n_{ct}, n_{cc}). The active crack-plane is chosen based on the current principal stress directions, then the smoothing angle is used to smooth the internal variables on crack planes around the active one. This prevents the damage from generalizing in all directions due to a failure in one direction, making the *ASDConcrete3D* suitable for homogenized masonry. Interfaces between adjacent structural units are modeled using a 3 cm thick shell element embedded with the *DamageTC3D* constitutive model, designed to simulate degrading cohesive behavior. These interface elements are connected to adjacent walls via *embedded* constraints, enabling mesh compatibility and realistic force transfer (Figure 1).

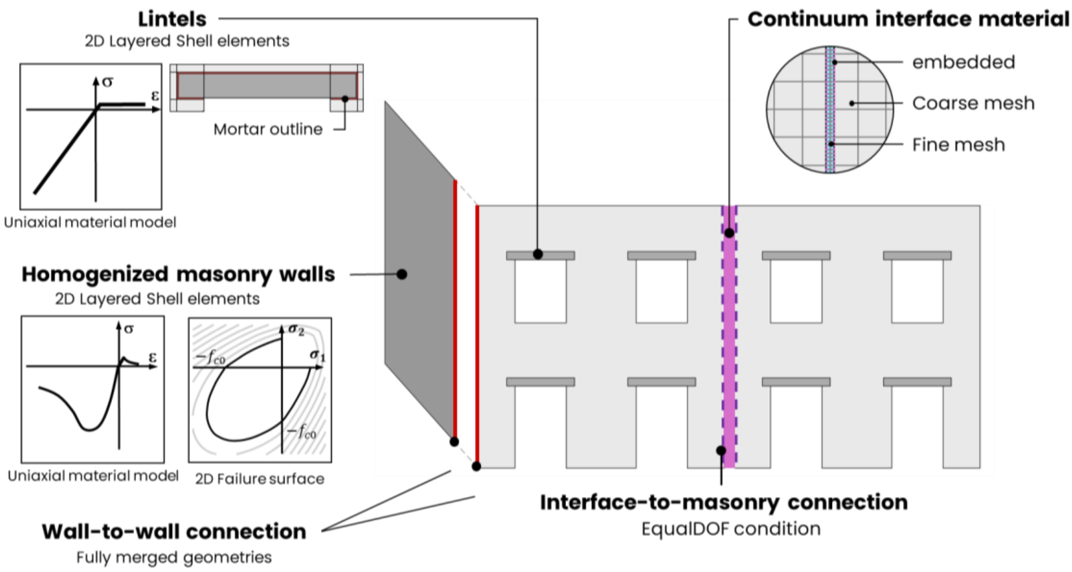

Figure 1: Modelling strategies for aggregate buildings.

To investigate the role of slab flexibility, two configurations were developed. In one, a rigid diaphragm is imposed using the *rigidDiaphragm* condition; in the other, the slab is modeled explicitly using shell elements with an *elasticOrthotropic* material representing 3 cm thick wooden planks, with in-plane shear modulus set at 300 MPa. The flexible diaphragm setup allows the activation of additional mechanisms such as in-plane distortion and wall out-of-plane mechanisms.

3 DEFINITION OF THE INTERFACE MATERIAL

The connection between masonry units in aggregates is often poorly documented, with unknown interlocking or bonding details. To account for this uncertainty without explicitly modeling interlocking, a continuum interface material is introduced to simulate a degraded, low-strength mechanical connection between adjacent units. In this study, the interface material (m_1) is analyzed in detail. It is modeled using the *DamageTC3D* constitutive law, which incorporates tension-compression damage mechanics and regularized fracture energy to minimize mesh sensitivity. The key material parameters used are: compressive strength f_c = 1.00 MPa, tensile strength f_t = 0.04 MPa, elastic modulus E = 100 MPa, tensile fracture energy G_t = 0.005 N/mm, and compressive fracture energy G_c = 18.25 N/mm. To characterize the shear response, numerical monotonic shear tests were conducted under constant axial loads ranging from 0 to 0.5 MPa, limited to this range due to the relatively low compressive strength of m1. The resulting tangential stress–displacement curves were used to extract friction angle and cohesion values via linear regression.

Results show that material m1 exhibits a sliding-dominated failure mode, particularly under lower axial stress. The response is characterized by a relatively ductile curve with limited peak strength and gradual softening, consistent with the expected behavior of a weak inter-unit interface. As axial stress increases, a more brittle trend begins to emerge, with sharper post-peak decay and reduced energy dissipation, indicating the onset of a softening-driven failure mechanism.

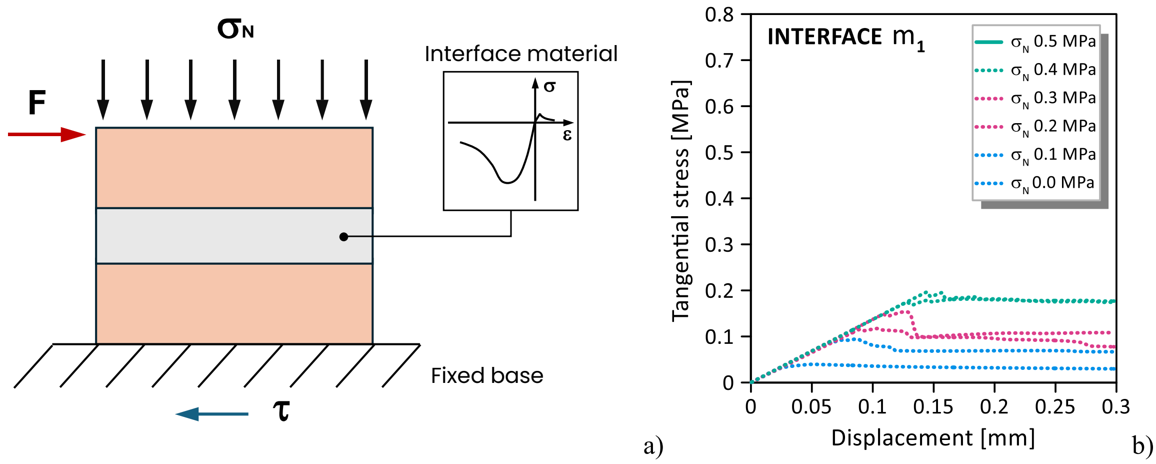

Figure 2: Characterization of the interface material. a) modelling scheme. b) results of numerical analysis

The maximum tangetial stress values are taken from each analysis and correlated with the axial stress applied to obtain the friction angle and cohesion values according to the coulomb law (Eq. 1):

$$\tau = \mu\sigma N + c \quad (1)$$

Results exhibit a friction angle μ equal to 0.31 and a cohesion c of 0.065 MPa as shown in Figure 3.

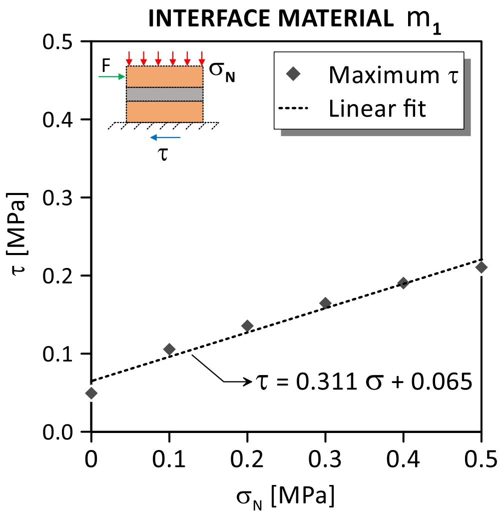

Figure 3: Results of the characterization of the interface material in terms of friction angle and cohesion.

4 AGGREGATE CONFIGURATIONS AND MODELING SETUP

The proposed modeling strategies were applied to a simplified but representative aggregate structure composed of three adjacent, identical structural units (SUs). This configuration was intentionally designed to investigate the influence of slab flexibility and inter-unit connection on the seismic response of each individual unit. The building covers a plan area of 24×12.6 m and has an overall height of 11.20 m. A detailed description of the geometry and base configuration is available in a previous study [12]. A total of six numerical models were developed using STKO [5] incorporating two distinct floor system types: a rigid and a flexible diaphragm. For each slab type, three interconnection scenarios between the units were modeled:

- FC: units fully connected (monolithic behavior),
- SC: units connected through the non-linear interface material m1, and
- SU: units modeled as structurally independent.

The three structural units are labeled U1, U2, and U3, from left to right. A summary of all model configurations is shown in Fig. 5. The introduction of the continuum interface material in the SC configuration required careful reconsideration of boundary conditions. All isolated SU models include the shared longitudinal wall, so assumptions must be made in the semi-connected model about which unit "owns" the shared wall. In real-world scenarios, this is determined by construction sequence, but adopting such an assumption in modeling introduces inconsistencies: the unit assigned the transverse wall gains additional stiffness, making comparisons with SU and AB cases incompatible. Additionally, when beams align along the longitudinal direction, they implicitly reinforce the connection across units, further complicating the boundary condition. To avoid case-specific assumptions and maintain consistency across configurations, the SCAB model was constructed as three standalone SU models, linked exclusively by the interface material, as illustrated in Fig. 11. This abstraction ensures compatibility and isolates the effects of the interface and diaphragm conditions.

All simulations were parallelized using OpenSeesMP, resulting in computational times of approximately 3–4 hours for dynamic runs.

The material properties of the masonry were obtained during previous calibration [10] using a quasi-static cyclic experimental test [13] on a two-story full-scale masonry building, and are presented in Table 1.

Compressive strength f_m (MPa)	Tensile strength f_t (MPa)	Young Modulus E_m (MPa)	Fracture energy in compression G_c (N/mm)	Fracture energy in tension G_t (N/mm)
6.2	0.16	1490	20.0	0.12

Table 1: Example of the construction of one table.

To assess structural performance nonlinear dynamic analyses (NLDA) were conducted in the longitudinal direction. The ground motion used in this study is a recording from the 2009 L'Aquila earthquake, captured at the Colle Grilli station in the northwest direction (Fig. 16). This event had a significant impact on masonry structures and is extensively documented in the literature. The frequency content of the record is concentrated in the low-period range (0.1 s to 0.4 s), which is particularly relevant as it coincides with the fundamental period of the aggregate models (approximately 0.2 s). Rayleigh damping with a 3% damping ratio (ξ = 0.03) was applied, with the frequency range calibrated between the first and fifth modal frequencies obtained from eigenvalue analysis. For comparability between configurations, especially in the SC case, where the units are only connected through the interface, force-displacement responses were extracted from the longitudinal walls of each unit individually. All simulations were parallelized using OpenSeesMP, resulting in computational times of approximately 3–4 hours for dynamic runs.

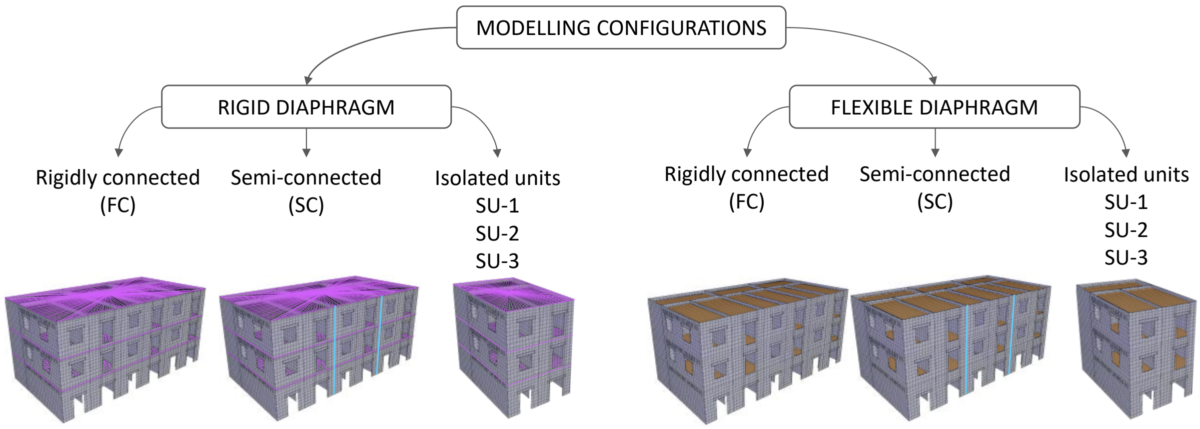

Figure 4: Numerical models developed in STKO

5 NON LINEAR DYNAMIC ANALYSIS

To evaluate the seismic performance of the aggregate configurations, nonlinear time history analyses were carried out on all six models. The objective was to assess how slab flexibility and unit interconnection influence the global and local response under realistic ground motion. The discussion focuses on unit U1, which is particularly sensitive to boundary conditions due to its edge position, offering clear insight into the role of diaphragm behavior and interface strength. For models with a rigid diaphragm (RD), the analysis was run with a time step of 0.005 s, matching the sampling rate of the input motion. For flexible diaphragm (FD) models, the time step was reduced to improve convergence under stronger non-linearities. Displacements were measured at the barycenter of the building for RD cases and at the centre of the front wall for FD cases. Figures 5 and 6 illustrate the force–displacement response of Unit U1 under dynamic loading, comparing isolated (SU), semi-connected (SC), and fully-connected (FC) cases for both rigid (RD) and flexible (FD) diaphragm configurations.

In the RD models (Fig. 5), the SU case exhibits the largest displacement demand, with symmetric cycles and no restraint from neighboring units. In contrast, both SC and FC models show clear asymmetry in the response, with significantly higher displacements when the motion is directed toward the X− direction. This is due to the absence of a neighboring unit on that side, allowing greater deformation. When displacement occurs in the X+ direction, Unit U2 provides confinement, effectively limiting movement and increasing stiffness. This directional difference becomes more evident as the connection strength increases. The FC model remains largely within the elastic range, while the SC model shows moderate nonlinearity and improved control compared to SU.

For the FD cases (Fig. 6), the SU model failed to reach convergence, likely due to excessive drift demands in the absence of both diaphragm stiffness and inter-unit restraint. The SC case shows a similar asymmetry to the RD counterpart, with amplified displacement toward X− and more constrained movement toward X+, though with overall lower force levels and increased deformability. The FC model exhibits the most stable response among the flexible diaphragm cases, but still shows larger displacements than its RD equivalent due to the reduced in-plane stiffness of the floor system.

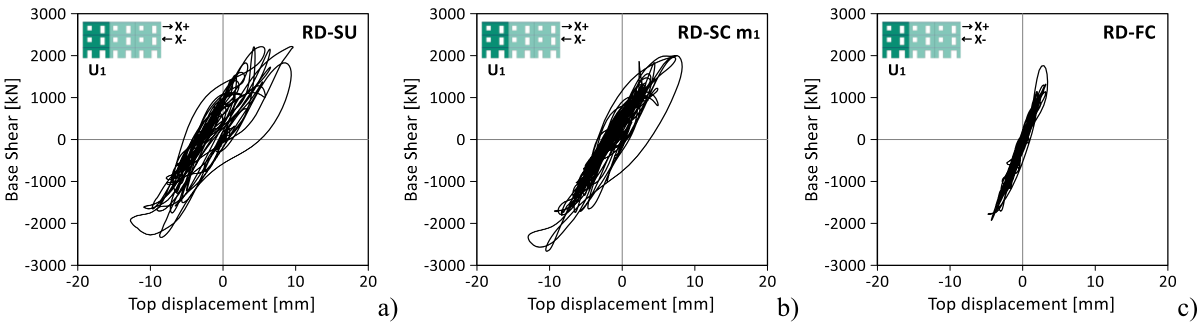

Figure 5: Force-Displacement curves obtained in RD cases for U1. a) Isolated case; b) semi-connected case and c) fully-connected case.

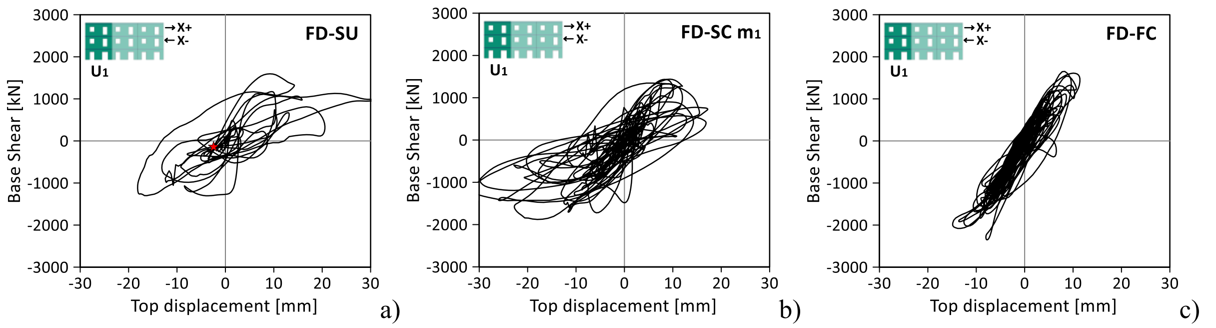

Figure 6: Force-Displacement curves obtained in FD cases for U1. a) Isolated case; b) semi-connected case and c) fully-connected case.

A comparison of final damage states across all six cases is provided in Fig. 9, showing how slab flexibility and connection level influence failure modes and energy dissipation. As expected, improved connectivity consistently leads to reduced damage, while flexible slabs tend to activate more localized or independent failure mechanisms.

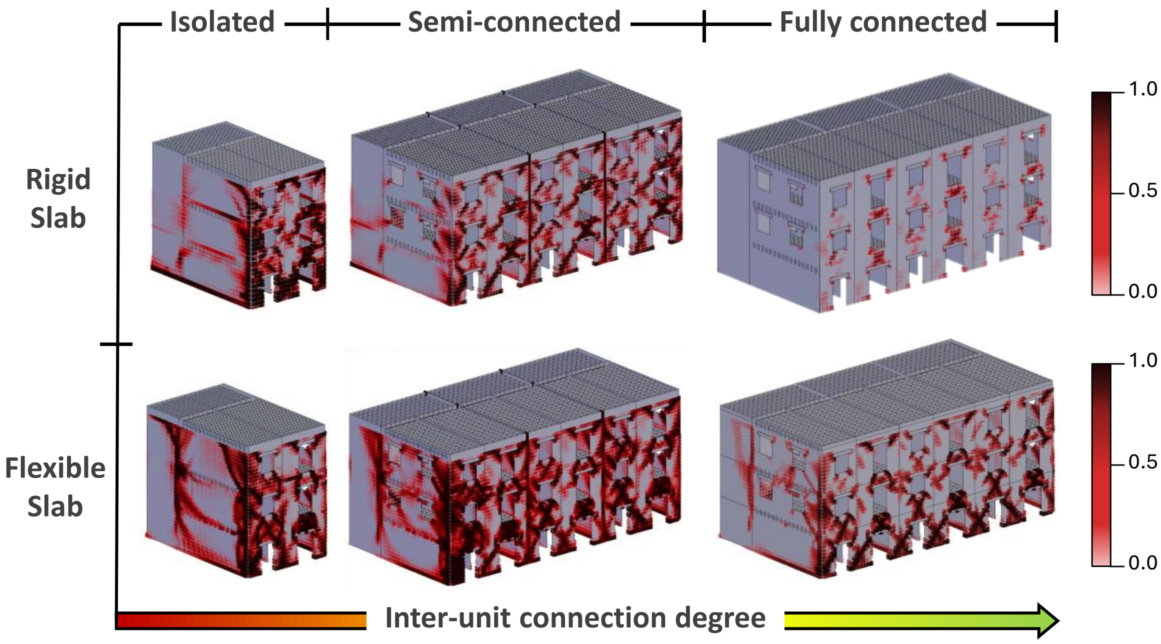

Figure 7: Damage comparison between different degrees of unit-interconnectivity and slab typology

6 CONCLUSIONS

This study investigated the dynamic response of unreinforced masonry aggregates using a simplified three-unit model, specifically designed to isolate the effects of inter-unit connection strength and slab flexibility. Through nonlinear dynamic analyses, the role of these variables was assessed under consistent geometric and material conditions. The introduction of a continuum interface material allowed for the simulation of degraded, non-linear connections between adjacent units without relying on case-specific assumptions about construction sequence or interlocking patterns. The results highlight the crucial influence of diaphragm behavior in governing both global and local response. Rigid diaphragms promoted coherent in-plane force distribution and allowed the beneficial effect of inter-unit connectivity to be fully activated, resulting in reduced displacements and minimal damage concentration. In these cases, both semi-connected and fully connected models showed improved performance compared to isolated units, with the latter remaining mostly within the elastic range. On the other hand, flexible diaphragms permitted more localized deformation and wall decoupling, significantly reducing the effectiveness of the connections and revealing the importance of unit positioning. Unit U1 reflected the asymmetric displacement patterns showcased by external units in an aggregate, with greater movement toward the free edge (X–) due to the absence of a neighboring unit, while the presence of Unit U2 on the opposite side constrained motion toward X+. While the simplified aggregate model adopted in this study enabled a clear interpretation of global trends, several aspects remain to be addressed in future work. The use of a single ground motion input limits the generalizability of the findings, particularly in relation to variability in frequency content, duration, and directionality. As more geometric and material complexities are introduced, such as irregular wall layouts, asymmetrical openings, or heterogeneous materials, local failure mechanisms are likely to become more dominant, and global indicators may no longer adequately reflect performance. In such cases, the role of multi-directional input becomes increasingly relevant, as bidirectional excitation can trigger coupled in-plane and out-of-plane responses, especially in units with flexible diaphragms or torsional asymmetry.

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