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Nonlinear dynamic response of infilled RC frames: investigating local shear demand through a full-scale test

Marilisa Di Benedetto[a,]*, Raffaele De Risi[b], Fabio Di Trapani[c], Guido Camata[d]

[a]*Department of Structural, Building and Geotechnical Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Turin, Italy*
[b]*Department of Civil Engineering, University of Bristol, Tyndall Avenue, Bristol, BS8 1TH, United Kingdom*
[c]*Department of Engineering, Università degli studi di Palermo, Viale Delle Scienze Ed. 8, Palermo 90128, Italy*
[d]*Department of Engineering and Geology, Università degli studi "G. D'Annunzio" di Chieti-Pescara, Viale Pindaro 42, Pescara, Italy*

Abstract

This paper presents a preliminary investigation on the local shear demand in masonry-infilled reinforced concrete (RC) frames subjected to nonlinear dynamic loads. A refined numerical model is developed in the STKO/OpenSees environment to simulate a full-scale experimental test, capturing the local interaction effects between infill panels and the surrounding frame. The numerical model is calibrated to replicate the global response observed during the shaking table test of a three-story RC building. The study aims to extrapolate and quantify the additional shear demand induced at the column ends due to the presence of infill walls under seismic excitation. A preliminary comparison is also made between the refined numerical outcomes and a simplified analytical formulation available in the literature for predicting local shear demand. Initial results indicate that this model may be applicable under nonlinear dynamic conditions, although further validation is needed. These findings support the potential integration of such predictive tools in seismic assessment and highlight the crucial importance of accurately modelling local infill-frame interaction to ensure reliable structural design and evaluation.

Keywords: Infilled frames; Shear; Masonry; Reinforced concrete; OpenSees; STKO

1. Introduction

The presence of masonry infills in RC frames substantially influences their seismic response, not only by increasing stiffness and strength, but also modifying internal force distribution and leading to unexpected local failure

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* Corresponding author.
E-mail address: marilisa.dibenedetto@polito.it

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mechanisms. Among these, the amplification of shear forces at column ends and beam-to-column joints due to infill-frame interaction has been observed in seismic-prone areas during earthquakes and confirmed in experimental and numerical simulations (Mehrabi and Shing, 1996; Blackard et al., 2008; D'Ayala et al., 2009; Stavridis et al., 2011; Milanesi et al., 2018; Di Trapani et al., 2024a). Despite the growing literature on this topic (e.g. Fiore et al., 2012; Morandi et al., 2018; De Risi et al., 2018; Di Trapani et al., 2023; Kallioras et al., 2023; Di Trapani et al., 2024b), the analytical and simplified numerical tools currently available for predicting such local effects, thereby avoiding the use of refined models, remain limited. Existing predictive models typically rely on single-strut macro-models and are often calibrated under static loading conditions. Technical codes, such as Eurocode 8 (2004) and FEMA 356 (2000), provide general guidelines to account for the additional shear demand through the explicit modelling of equivalent struts. More recently, analytical expressions linking the additional shear demand to the current axial force acting on the equivalent struts have been proposed (Di Trapani et al., 2018; Di Trapani et al., 2025). While these models have shown promising results when applied to monotonic pushover analyses, their applicability to nonlinear dynamic scenarios, which better reflect actual seismic conditions, remains largely untested. This study aims to address this gap by exploring the dynamic behaviour of a full-scale, masonry-infilled RC building subjected to shake table testing. A refined 3D numerical model with shell elements is developed using the STKO suite (Petracca et al., 2017a) for OpenSees (McKenna et al., 2000) to replicate the observed experimental response and assess the infill-frame interaction mechanisms. The current shear demand experienced during the tests is extracted from the model by the introduction of “section cuts” at the ends of the columns adjacent to the masonry infills. An equivalent strut model of the specimen was also developed, and the additional shear demand was evaluated by simplified predictive formulation (Di Trapani et al., 2025) within a dynamic context. By comparing the refined numerical results with the analytical prediction, the study provides a preliminary insight into the validity and limitations of the existing formulation to a real dynamic case study, offering a step forward toward a more accurate and feasible representation of local interaction effects in infilled RC frames.

2. Reference experimental campaign

2.1. Case study building

The reference experimental campaign, carried out at the EUCENTRE Shake-LAB (Italy), involved two identical full-scale reinforced concrete (RC) frame buildings, constructed side by side and anchored to a standard RC foundation slab using post-tensioned steel bars (Rebecchi et al., 2022). In the current study, only one of the two structures, referred to as the *East Building*, is considered. The latter is a three-storey, single-bay frame, extending in both directions, with overall plan dimensions of 5.0 m × 2.1 m and a total height of 8.7 m. The structural-resisting system consists of 200 × 200 mm RC columns, 400 mm-thick slabs at the first and second floors, and a 540 mm-thick slab at the roof level. Each column is reinforced with four longitudinal Ø16 mm bars placed at the corners and Ø8 mm closed stirrups with an average spacing of 100 mm, increasing to 50 mm at critical sections. A schematic representation of the building configuration and details is provided in Fig. 1.

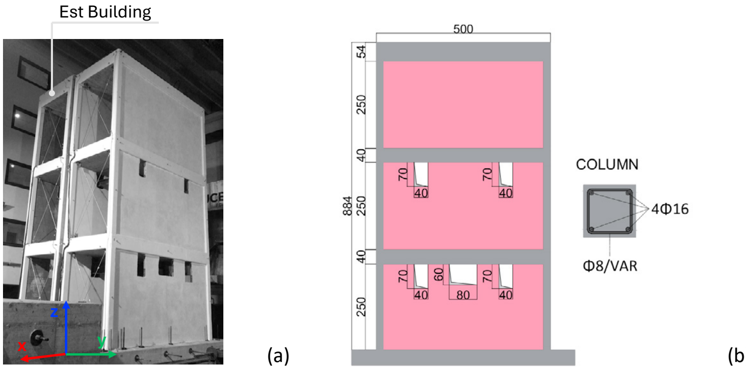


Fig. 1. Overview of the reference specimen and structural details: (a) Full-scale twin buildings of the reference experimental campaign; (b) Geometry and column reinforcement layout.

The infill walls were constructed using clay masonry blocks with nominal dimensions of 250 × 250 × 80 mm, assembled with cement mortar. No separation joints were introduced between the infills and the surrounding RC frame, allowing full mechanical interaction under seismic loads. The key mechanical properties adopted for the numerical modelling are summarised in Table 1.

Table 1. Mechanical parameters of concrete and masonry components.

Concrete compressive strength f_{cc} (MPa)	41.59
Masonry compressive strength perpendicular to the holes f_{mv} (MPa)	2.25
Masonry compressive strength parallel to the holes f_{mh} (MPa)	1.93
Masonry elastic modulus perpendicular to the holes E_{mv} (MPa)	4004
Masonry elastic modulus parallel to the holes E_{mh} (MPa)	4535
Masonry shear modulus G (MPa)	855

2.2. Test setup and dynamic input

The experimental campaign consisted of a series of incremental shake table tests performed along the x-direction. The input motion was the E–W component of the 1980 Irpinia earthquake, characterised by a Peak Ground Acceleration (PGA) of 0.32 g (Fig. 2). The ground motion was progressively scaled over a total of 19 tests, to induce increasing levels of damage in both the infill panels and the RC frame elements (Rebecchi et al., 2022).

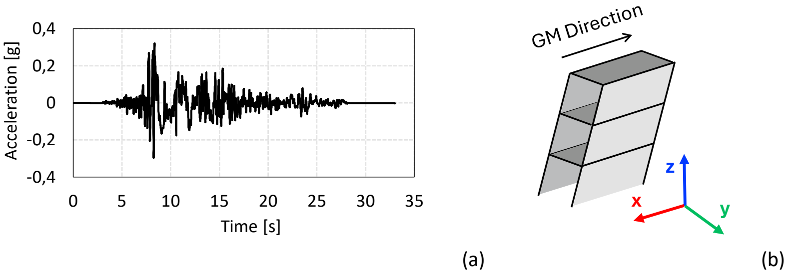


Fig. 2. Representation of the seismic input: (a) Ground motion record from the 1980 Irpinia earthquake; (b) Schematic deformation shape of the structure along the GM direction.

The building was equipped with accelerometers and displacement transducers. The experimental outputs were primarily used to identify the modal parameters and validate the global dynamic response of the numerical model, ensuring a reliable basis for assessing local force distributions at critical sections. The adopted modelling strategies, the procedure for extrapolating local internal forces, and the application of a predictive formulation for shear demand are presented in the following sections.

3. Numerical modelling

3.1. Refined model

The refined finite element model of the specimen was developed using the STKO platform for OpenSees (Petracca et al., 2017), aiming to simulate the nonlinear dynamic response of the full-scale infilled RC building presented in Section 2. The modelling strategy adopts a homogenised approach for masonry to balance computational efficiency and accuracy, and a continuum layer as an interface between the RC frame and the infill, focusing on local interaction mechanisms. Masonry infills were modelled using orthotropic, homogenised layered *ASDShellT3* elements with nonlinear constitutive behaviour assigned via the *ASDConcrete3D* material model (Petracca et al., 2017b; Di Trapani et al., 2024c). This formulation enables an accurate simulation of in-plane cracking, crushing, and degradation under cyclic loading, capturing both tensile and compressive failure modes. The model implements a two-index damage-plasticity formulation, with independent degradation indices for tension (d^+) and compression (d^-). A representation of the modelling assumptions is illustrated in Fig. 3.

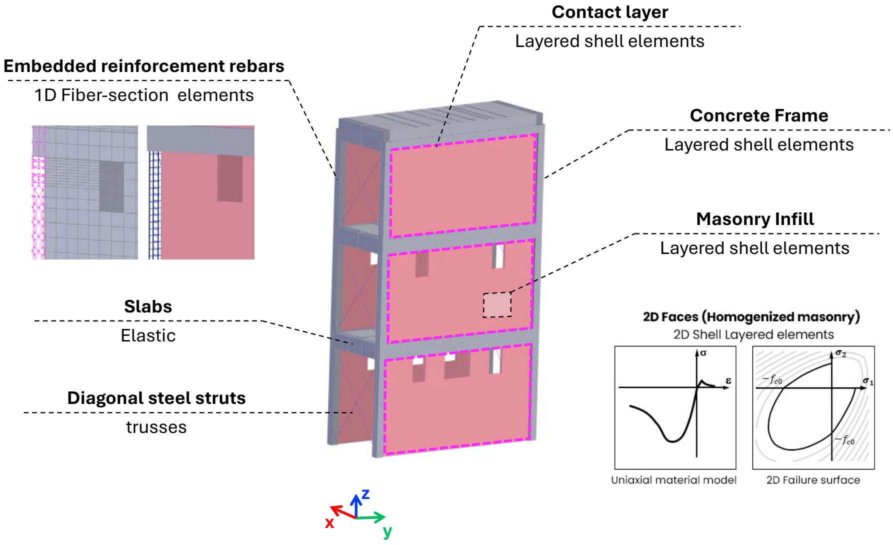


Fig. 3. Refined model details.

The RC frame elements were modelled using homogenised layered A*SDShellT3* elements and *ASDConcrete3D* as the material constitutive model, while floor slabs were modelled as elastic diaphragms. A continuum contact layer with a compression-only constitutive law, utilising the User-defined *ASDConcrete3D* material, ensured a fully connected interface between the infill panels and the frame. The adopted mesh size was approximately 200 mm, refining at critical sections, enabling a good compromise between computational demand and model accuracy. The model was calibrated in both the linear and nonlinear range to ensure consistency with the experimental results; however, the detailed calibration procedure is omitted here for brevity.

3.2. Simplified single-equivalent strut model

The case study building was also modelled using a simplified single equivalent strut macro-model, implemented in STKO. The struts, modelled as truss elements, follow the no-tension fiber-section approach proposed by Di Trapani et al. (2018), using the *Concrete02* material model to simulate the nonlinear compressive response. A representation of the adopted modelling strategy is shown in Fig. 4. The constitutive law is defined by four empirical stress–strain parameters, peak and ultimate strengths and corresponding strains, derived from masonry mechanical properties. The cross-section of each strut adopts the infill panel's thickness, and an effective width is estimated through geometric correlations. RC frame members are modelled using force-based beam-column elements with fiber sections, where the *ASDConcrete1D* material model is adopted to describe the uniaxial behaviour of concrete.

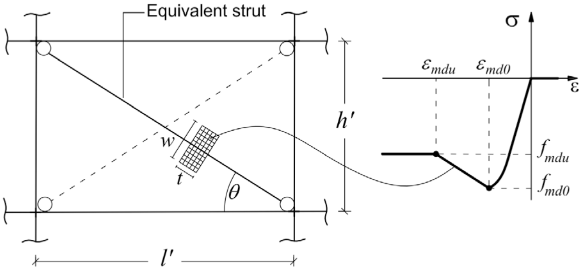


Fig. 4. Single equivalent strut macro-model (Di Trapani et al., 2018).

4. Preliminary results

4.1. Identification of modal response

The vibration modes of the structure were assessed through Experimental Modal Analysis (EMA), based on the response to low-amplitude vibration tests. The identification of modal parameters was carried out using the *LSCF* method, which is a frequency-domain Linear Least Squares estimator optimised for modal parameter estimation. The analysis of all output channels (each floor) and the input in the frequency domain, illustrated in Fig. 5, allowed the extraction of the most consistent modal parameters: frequency, damping, and mode shapes. Three dominant vibration modes of the system were identified, with experimental frequencies equal to approximately 8.03 Hz (Mode 1) and 27.40 Hz (Mode 2). These values served as reference benchmarks for calibrating the numerical model in the elastic range.

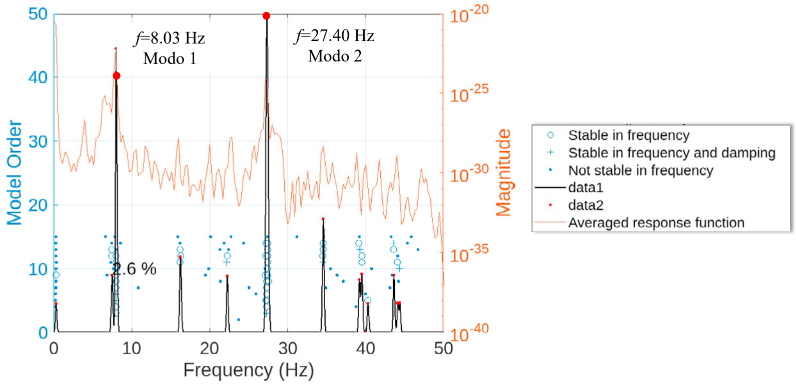
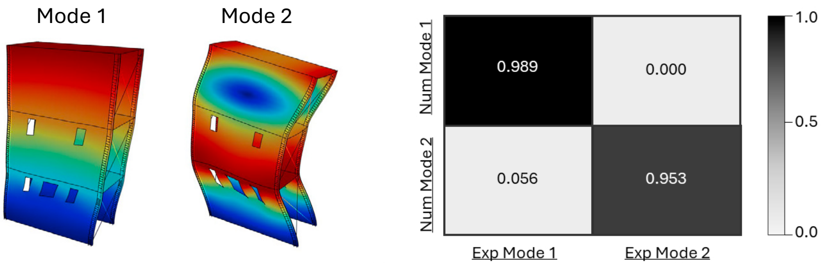


Fig. 5. Experimental modal identification through the stabilisation diagram.

The same modes were computed via eigenvalue analysis on the refined numerical model and are illustrated in Fig. 6. A good agreement was observed between the experimental and numerical modal frequencies, as summarised in Table 2, confirming the accuracy of the model in capturing the global stiffness and boundary conditions. This consistency was further supported by a comparison of mode shapes and the evaluation of the Modal Assurance Criterion (MAC; Allemang & Brown, 1982), which demonstrated the model's capability to reproduce the experimentally identified vibration modes.



(a) (b)

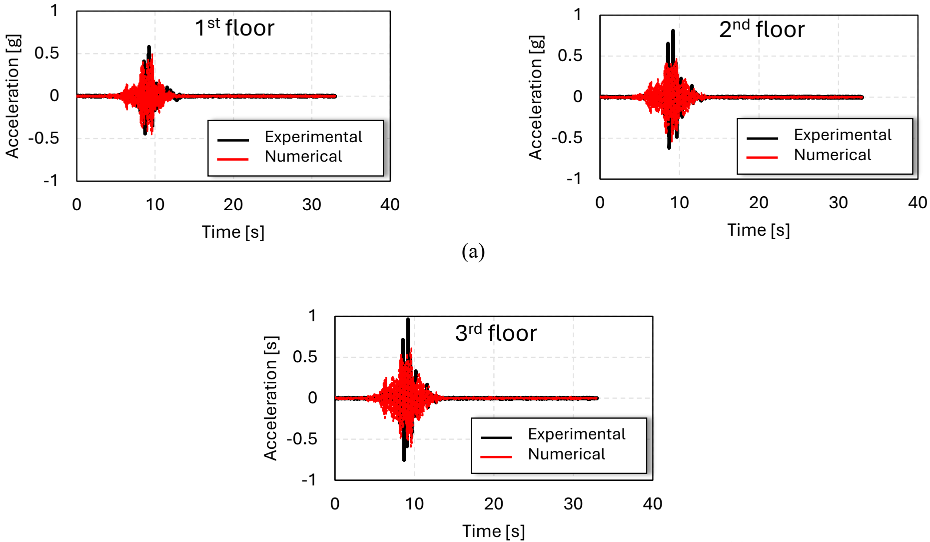
Fig. 6. Modal response of the refined model: (a) First and second mode shapes of vibration along the *x* direction; (b) MAC matrix.

Table 2. Modal properties of the first two vibration modes of the case study building in the x direction.

	Experimental frequency (Hz)	Numerical frequency (Hz)
Mode 1	8.03	8.77
Mode 2	27.40	27.37

4.2. Nonlinear dynamic simulation response

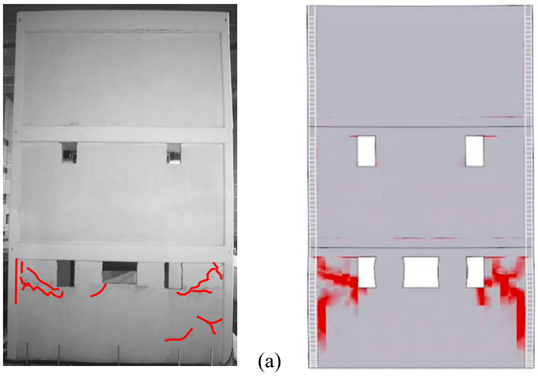
An incremental time history analysis was conducted on the refined model using the input sequence employed during the experimental campaign. The time-history accelerations at the first, second, and third floors are compared between the experimental and numerical results, as depicted in Fig. 7. The model captures the amplitude and general trend of the response accurately. However, slight discrepancies in frequency content are observed, likely due to damage accumulation in the tested structure.



(a) (b) (c)

Fig. 7. Global response comparison (Test 10) in terms of acceleration: (a) First Floor; (b) Second Floor; (c) Third Floor.

Additionally, the observed damage patterns in the numerical model, particularly in the infill panels and column ends, were consistent with those reported during the experimental tests (Fig. 8).



(a) (b)

Fig. 8. Damage comparison at the end of test 10: (a) Experimental crack pattern; (b) Numerical crack pattern.

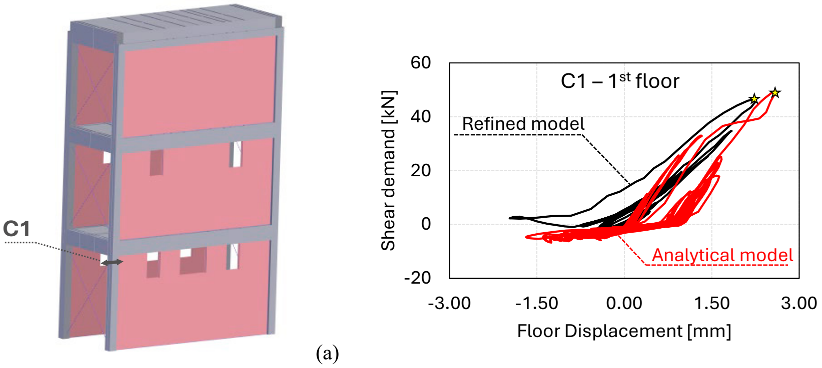
This validation supports the model's capability to capture the essential features of the nonlinear seismic response, enabling further investigation of internal force distributions and local interaction effects not directly measurable during testing.

5. Local shear demand assessment: application and comparison of an available literature model

The assessment of local shear demand at critical sections of infilled RC frames was carried out by integrating the nodal forces at selected section cuts. Furthermore, the local shear demand was also compared against the predictions of an analytical model available in the literature (Di Trapani et al., 2025). The latter assumes that the additional shear due to frame-infill interaction ($V_{d,inf}$) could be computed from the axial force in the equivalent strut, considering the horizontal equilibrium of a contact portion of the infill and the friction resistance at the interface. The resulting expression (Eq. 1) links $V_{d,\mathrm{inf}}$ to the strut's axial load (N), geometry, and contact length (αl), providing a practical tool to quantify infill-induced shear amplification. More details can be found in Di Trapani et al. (2025).

$$V_{d,\mathrm{inf}} = N\left(\cos\theta - \frac{\mu \cdot \sin\theta \cdot \alpha l}{w}\right) \tag{1}$$

The model was initially validated under monotonic loads, and its extension to dynamic scenarios is preliminarily explored in this study. To benchmark these results, a simplified single-strut macro-model, previously described in Section 3, was employed. In this configuration, local shear effects are not explicitly represented, since the infill action is modelled at the global level. Nevertheless, the axial force developed in the equivalent strut during the dynamic analysis can be used, after appropriate calibration, to indirectly estimate the additional shear demand at column ends. Preliminary results (Fig. 9) indicate that the analytical model provides a reasonable approximation of the additional shear demand, accurately capturing both the overall trend and magnitude. However, some differences are observed in the hysteretic behaviour.



(a) (b)

Fig. 9. Shear demand evaluation at column C1: (a) Selected section cut; (b) Comparison between the refined numerical model and the analytical prediction by Di Trapani et al. (2025).

This comparison highlights the potential applicability of the analytical model in seismic assessment frameworks, particularly as a complement to macro-modelling approaches where local force estimations are otherwise neglected.

6. Conclusions

This study presented a refined numerical investigation on the local shear demand induced by masonry infills in RC frames subjected to nonlinear dynamic excitation. The analysis was based on a full-scale experimental campaign performed on a three-storey RC structure tested with the Irpinia 1980 earthquake as the reference ground motion. A refined FE model was developed in STKO/OpenSees to reproduce the global behaviour of the structure and assess the local response. Experimental modal analysis was employed to extract the dynamic properties of the structure, which were then used as a benchmark for calibrating the numerical model. Nonlinear time-history simulations successfully captured both the global response and local damage mechanisms observed during testing, validating the modelling approach and the chosen constitutive formulations. Internal shear forces at the critical column ends were extracted from the refined model, revealing the presence of significant additional shear demand associated with the infill contribution. To complement this analysis, a simplified macro-model was employed using an equivalent diagonal strut. The axial force in the strut was then used as input to an analytical formulation proposed by Di Trapani et al. (2025), which estimates the infill-induced shear based on mechanical equilibrium considerations. The comparison between the analytical predictions and the detailed numerical results showed promising agreement, indicating that the analytical model can serve as a practical tool for estimating local shear demand in infilled frames, even under dynamic loading conditions. However, further validation is needed to account for variations in geometry, material properties, and seismic input. Overall, the study emphasises the importance of considering local infill-frame interaction in seismic assessments and advocates for the integration of simplified predictive tools into performance-based design procedures.

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