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AN IMPROVED REDUCED -ORDER MODEL TO ACCOUNT FOR TORSIONAL EFFECTS IN EXISTING INFILLED RC BUILDINGS

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Abstract

Reduced-order models offer significant computational efficiency while preserving accuracy in predicting the structural response of buildings when properly calibrated. Recent works by the authors have led to the development and calibration of a simplified multi-degree-of-freedom model, named STICK [1], consisting of lumped nonlinear shear springs calibrated via a simplified procedure based on distinct building features.
The STICK model was proposed to simulate the behavior of existing masonry-infilled RC buildings, explicitly accounting for critical failure mechanisms, such as those in non-conforming RC elements and brittle failures induced by infill-frame interaction. However, a key limitation of the STICK model lies in its basic assumption of a regular in-plane layout, which allows for separate analysis of the building main directions while neglecting potential torsional coupling effects.
In existing buildings designed for gravity loads, in-plane irregularities can arise from non-uniform distributions of RC frames, walls, or cores, as well as from eccentric placements of staircases or irregular arrangements of exterior infill panels. Such structural irregularities often lead to significant torsional effects.
To address these limitations, an improved reduced-order model has been developed. This model adopts multiple shear springs that simulate the contribution of each frame in each direction and storey. These springs are positioned in the plane of the single original frames and connected at the floor level by rigid elements to reproduce the behavior of a rigid diaphragm. The shear springs are generated by adopting the original STICK generation frameworks by separately considering the contribution of RC frames and infill panels. This improved model allows for the proper capture of the in-plane eccentricity between the center of stiffness and masses and their evolutions during nonlinear analyses, allowing for the accurate assessment of torsional effects in unsymmetrical buildings.

Keywords: Reduced-order model, RC frame, infills, shear-type.

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1 INTRODUCTION

Reduced-order models (ROMs) have been demonstrated to be valuable tools in structural engineering for evaluating the seismic response of buildings. These models have been found particularly useful when a large number of simulations is required to account for both epistemic and aleatory uncertainties at the building level, or in large-scale seismic assessments where the response vast number of buildings must be simulated [2].

Among the available ROMs, multiple-degree-of-freedom (MDOF) systems, where certain degrees of freedom are condensed, have been found to provide sufficiently accurate results while significantly reducing computational effort compared to refined models [3]. These models can effectively capture the concentration and evolution of damage at different storeys and the contribution of higher modes of vibration.

In the context of MDOF ROMs, stick-like models have proven to provide a reliable assessment of structural response of Reinforced Concrete (RC) buildings. These models simplify the the behavior of each storey by representing it with a concentrated mass at the storey level and a single nonlinear shear spring [4] or a combination of shear and a flexural spring, to simulate the full interstorey behavior in the direction of the analysis. Stick models have been shown to be particularly effective for large-scale seismic assessment ([5], [6]) as well as for individual building-level analyses ([7], [8]), providing a significant reduction in computational cost with respect to refined models. Additionally, they can account for the effect of infills and beam-column joints with satisfactory accuracy ([1], [5]).

However, a key limitation of these models is their assumption of an uncoupled response along the principal building directions. This assumption make these models unreliable for simulating the response of irregular and torsionally-flexible buildings, whose behavior significantly different from that of regular structures [9]. In-plan irregularities have often been identified as one of the most frequent causes of severe damage and failure in RC buildings ([10], [11]). These irregularities arise from uneven mass and stiffness distributions or complex building geometries, which may create eccentricities between the stiffness and mass centers, thereby influencing torsional modes and leading to non-uniform demand in lateral resisting elements [12]. Uneven mass and stiffness distributions generally result in greater influence of higher modes and/or a different response along the two principal horizontal directions ([13], [14]).

In-plan irregularities in RC buildings can be due to irregular geometries, asymmetric distribution of RC frames, cores, walls, or the presence of staircase placed in eccentric position. In infilled RC buildings, even in case of symmetric disposition of structural members, irregularities may still emerge due to asymmetric disposition of openings along the two main building directions.

To address these limitations, Blasone [15] proposed a simplified approach to capture torsional behavior in RC bare frames. This method relies on a column-based approach in which each column is replaced by two shear springs (one per main direction), calibrated via genetic algorithm. The calibration process is necessary because, even in the case of bare frames, shear-type assumption may not fully capture the actual response of this type of structure.

However, in Italian buildings, especially those designed for gravity loads only or according to outdated seismic codes, this assumption has been proved sufficiently reliable providing acceptable results in infilled RC structures (e.g., [16], [17], [18], [19]).

Based on this observations, this paper introduces an improved version of the STICK model to simulate the behavior of irregular buildings. While traditional STICK models neglect torsional effects and are thus results unsuitable for irregular structures, the proposed approach represents an intermediate solution between the standard STICK model and Blasone's methodology. Specifically, the assumption of a shear-type response is considered applicable for this class of buildings. However, instead of representing each story and direction with a single spring, the proposed model introduces a system of springs that condenses the contributions of parallel frame systems and infill walls at each story and along each principal direction. This way it allowing to explicitly account for the effective position of structural and nonstructural members, thereby incorporating the possible effect related to the eccentricity of the barycenter of the masses with respect to that of the stiffnesses.

Section 2 provide a brief introduction to the proposed ROM. Section 3 presents the case-study building used to generate the ROM, with a a specific focus on the derivation of member envelopes and the procedure adopted for assembling ROM spring envelopes. Section 4 compares first results obtained using the proposed approach with those from the conventional STICK model, highlighting the significant differences observed when accounting for torsional effects.

2 PROPOSED REDUCED-ORDER MODEL

This section introduces the modeling strategy used to simulate the behavior of infilled RC buildings with the proposed ROM and the simplified procedure adopted to characterize the individual springs representing the contributions of frames and infill walls, separately. For each story, the system of columns and infill walls that compose it is extracted (Figure 1).

Figure 1: Extraction of the examined storey level

The extracted system is then decomposed into a system of springs (Figure 2). Figure 2(a) illustrates the composition of the reduced-order model for the frame contribution. For each direction, the columns belonging to the same frame are summed, resulting in the characterization of a single spring for each frame in the considered direction. This process is repeated for the orthogonal direction. As shown in Figure 2(a), a spring is introduced in the plane where the frame is assumed to act, and only at the intersections of orthogonal frames are two springs included, each acting in a separate direction. The same principle is applied to the contribution of infill walls (Figure 2(b)). In this case, only the contribution of the external infill walls is considered, while the contribution of internal partitions is neglected. This assumption is justified by the differences in thickness and boundary conditions of internal partitions compared to the structural frame system, which make their influence negligible.

By adopting the shear-type behavior assumption, the contributions of elements in the same plane are summed by considering them as parallel components, assuming that they are restrained against rotation. In this initial phase, the deformability contribution of beams is considered negligible, as Italian buildings designed around the 1950s typically lack a strength hierarchy criterion, resulting in a strong beam–weak column system.

Finally, a system of distributed masses is considered for each story. These masses act in the plane where each frame system and the corresponding infill system are present. In Figure 2(c), the masses are separated by direction (X, Y) and by frame (1, 2, and 3 in the example shown in Figure 1, both along X and Y). The masses are evaluated based on influence area concepts, considering only the translational components. The rotational contribution (i.e., centrifugal mass effects) is automatically accounted for due to the actual positioning of the masses.

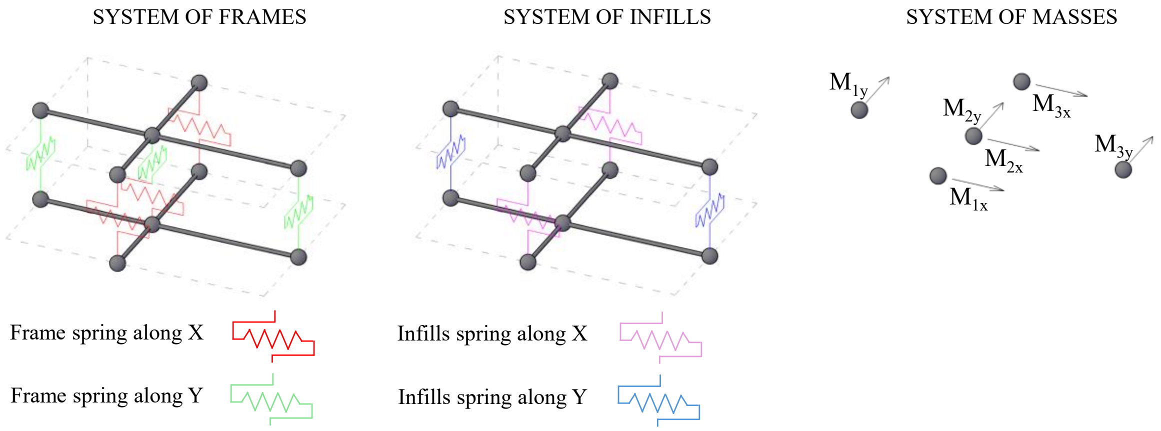


Figure 2: Generation of the reduced order model

The system of masses and springs thus constructed is connected at the story level by a set of rigid elements that replicate the effect of an infinitely rigid diaphragm. This assumption is consistent with the shear-type system hypothesis, according to which the individual springs representing the frame and infill systems are characterized.

3 APPLICATION TO CASE-STUDY BUILDING

The case-study building considered in this work is shown in Figure 3. It consists of a 4-storey structure having a constant interstory height of 3.2 m, a total length along X equal to L_X =18.7m and along Y equal to L_y=15.9m. The building features an L-shaped floor plan, which is characteristic of irregular structures in plan. The percentage of openings is approximately 20% and remains constant across the elevation.

The span lengths are not uniform. Along the X direction, the spans are 3.3m except for the last span that is 5.5m. Along the Y direction, spans vary between 3.4m and 5.0m. This irregular plan configuration, combined with the non-uniform span lengths, is expected to induce significant torsional behavior. Such effects cannot be properly captured by the conventional STICK model due to the considerable eccentricity between the mass center and the stiffness center.

The building geometry is predefined, while the sectional dimensions and reinforcement details of the structural members are determined using a simulated design procedure [20] in compliance with design code prescriptions, professional practice, and the seismic classification considered for the site of interest. It has been calibrated to generate a structural model representative of Italian construction practices, particularly gravity-load-designed buildings from the 1970s.

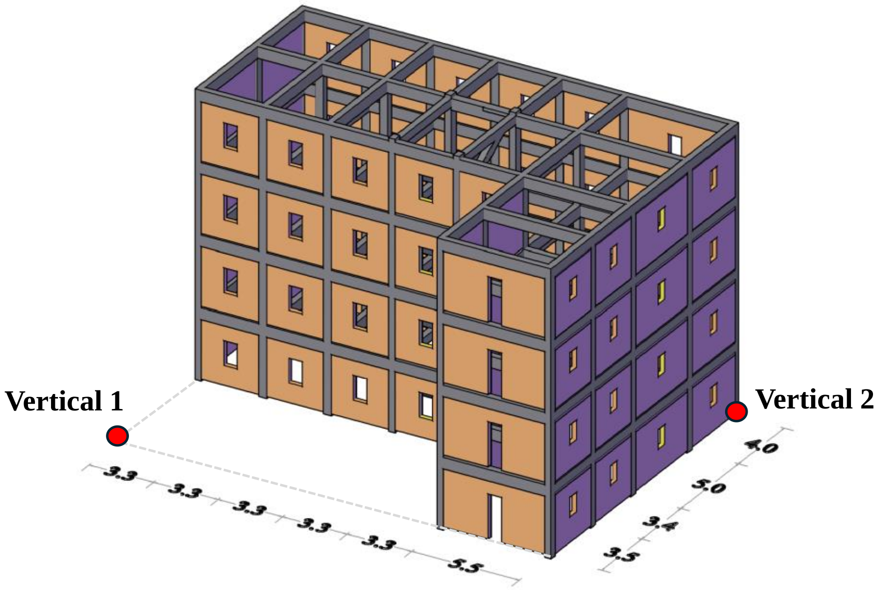


Figure 3: 3D geometry of the case-study building

Once the geometric-structural model is obtained, the mechanical response for the main structural members and non-structural components is characterized in terms of capacity curves. The expected mechanical properties are f_c=20MPa for concrete and f_y=449.6MPa for steel, while τ_{cr}=0.36MPa for masonry infills considering Medium consistency infill panels (t_w=24cm) according to Hak et al. [21].

3.1 Envelope calibration

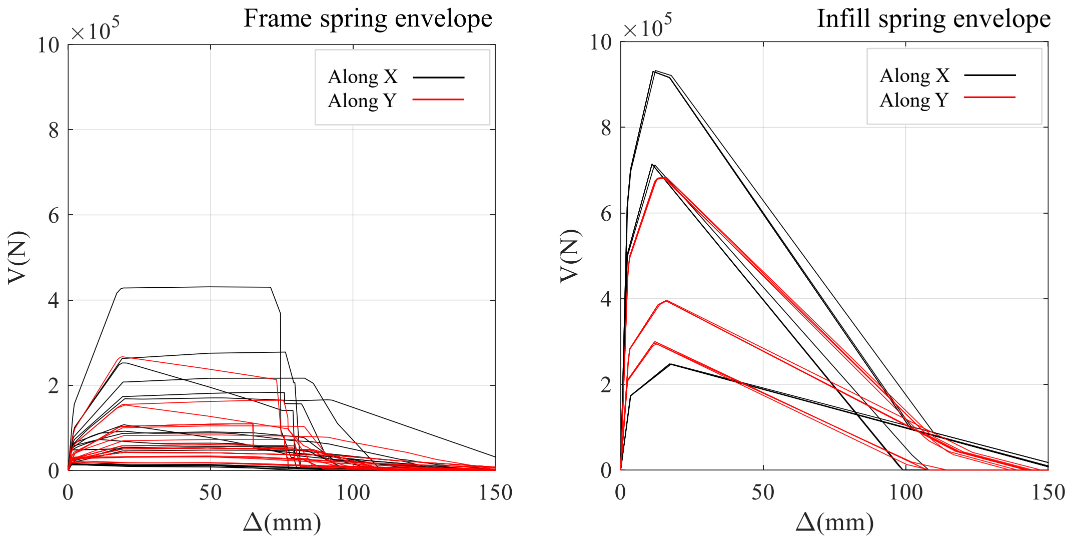
As outlined in Section 2, each frame system (i.e., a system of columns acting within the same plane, direction, and alignment) and each infill system are modeled separately. A shear-type behavior assumption is adopted to determine the envelope relationships for each spring, considering its direction, alignment, and story level.

The frame and infill contributions are kept separate (modeled as two distinct springs) because these components exhibit significantly different envelope responses. Using a single element to represent both the infill and the frame would not allow for a proper characterization of all key points in the final envelope curve. Additionally, the hysteretic behavior of frames and infills differs substantially, further justifying their separate modeling.

For RC columns the presence of deformed rebars has been considered, and the adopted backbone depends on the expected failure mode. For ductile members, multi-linear envelopes for deformed rebars proposed in Haselton et al. [22] are adopted. The brittle failure of RC members can be triggered in case of reduced shear strength capacity. In this case, the original envelope for columns is modified to account for flexure-shear or pure shear failure ([1], [23], [24]). For infill panels, the multi-linear envelope proposed in De Risi et al. [25] is adopted and reduced to account for the presence of perforation in infill panels. For further details regarding the generation of the STICK model, the reader is referred to Gaetani d'Aragona et al. [1]. Note that in the original calibration procedure the contribution of beams, and beam-column joints can be introduced in the model as well as the local infill-frame interaction, but has been neglected in this study.

3.2 Assemblage at the storey level

As previously specified, for each story and direction, the system is subdivided into shear springs, each representing the behavior of an individual frame and infill alignment, modeled separately. The envelope curve for each shear spring is derived by considering the parallel contribution of the corresponding structural elements.



(a) (b)

Figure 4: Spring envelope for (a) frames and (b) infill panels.

Figure 4 presents the shear-displacement relationships obtained for each story and direction, distinguishing between frame contribution (Figure 4a) and infill panel contribution (Figure 4b). These envelope curves are subsequently multi-linearized to facilitate their numerical implementation in the ROM.

4 NONLINEAR TIME-HISTORY ANALYSES

The ROM model outlined in Section 2 is implemented in the OpenSees [26] software. Each spring adopts the Pinching4 material with the envelope obtained in §3.2 and hysteretic parameters for RC elements [27] and for infills [28].

To test the proposed model, the response of the ROM is analyzed via Nonlinear time-history analysis and is compared with that of the STICK model (obtained for the same structure in Figure 3 via the procedure outlined in Gaetani d'Aragona et al. [1]) for a single earthquake ground motion selected within the set of the far field record set included in FEMA-P695 [29]. The ground motion record "21_68_PEL" consisting of two components is applied along the main building directions ("21_68_PEL_090" along X and "21_68_PEL_180" along Y) and the response has been recorded. Specifically, for the ROM, the response of two verticals indicated in Figure 3 have been recorded to account for the increased response with respect to the vertical corresponding to the barycenter of the masses. For the STICK model the response is analyzed separately for the two main direction (i.e., the barycenter of the masses is assumed equal to those of the stiffnesses).

Note that for the ROM model, the first mode is along Y, and the fundamental period of vibration is T_Y=0.37s, while the second mode is along X, and T_X=0.32. For the STICK along X, the fundamental period is T_X=0.36s, while for the STICK along Y, it is equal to T_Y=0.31s.

Figure 5 and 6 shows the response at the roof nodes along the X and Y directions, respectively. The peak displacement for the ROM along X is equal to 10.32mm and 8.86mm for the vertical 1 and 2, respectively. While along Y to 11.95mm and 6.19mm for vertical 1 and 2, respectively. This evidences that especially along Y, the lack of symmetry in structural layout led to a significant variation in lateral response that significantly increases for the less stiffened side.

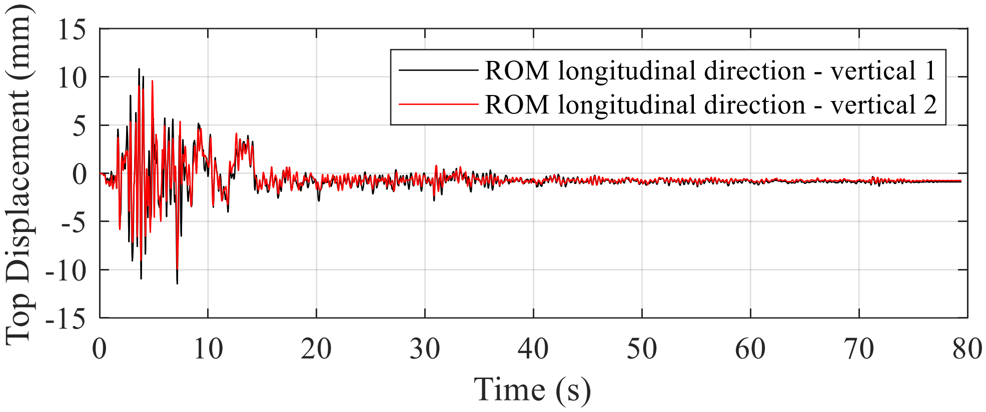


Figure 5: Time-history for the reduced-order model along the longitudinal directions, considering two verticals.

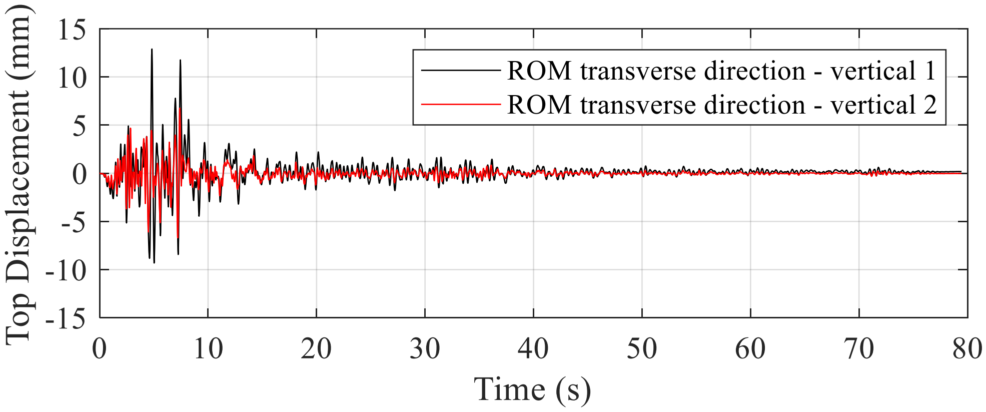


Figure 6: Time-history for the reduced-order model along the transverse directions, considering two verticals.

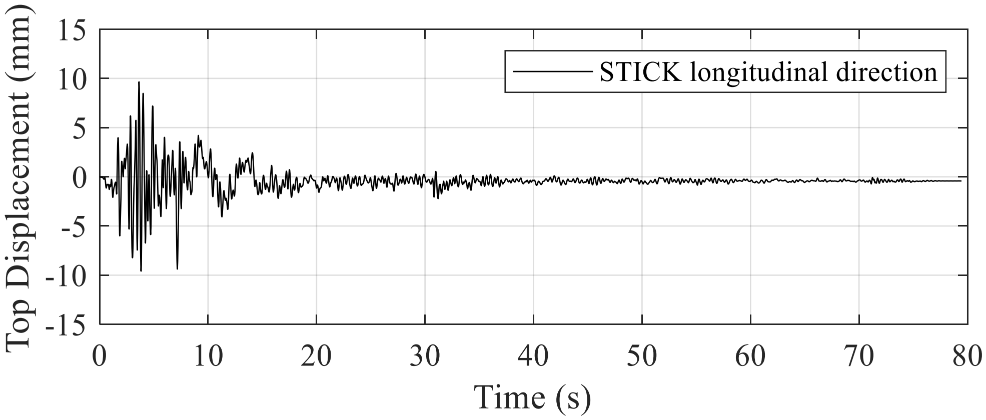


Figure 7: Time-history for the STICK model along the longitudinal direction.

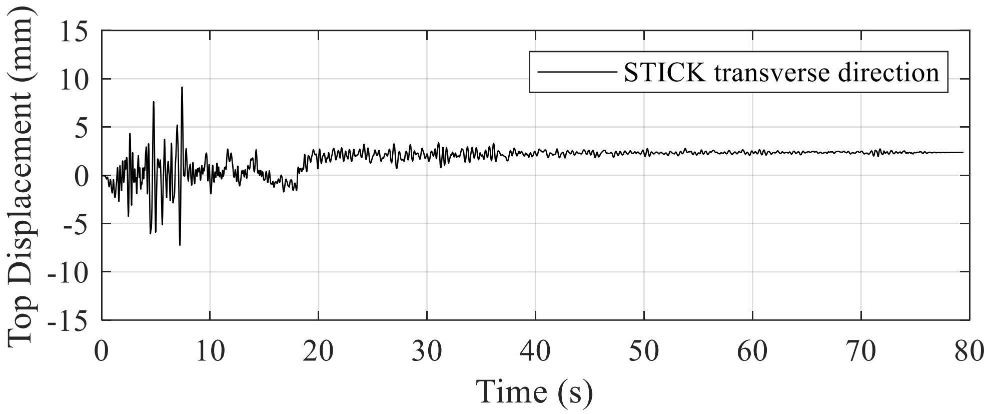
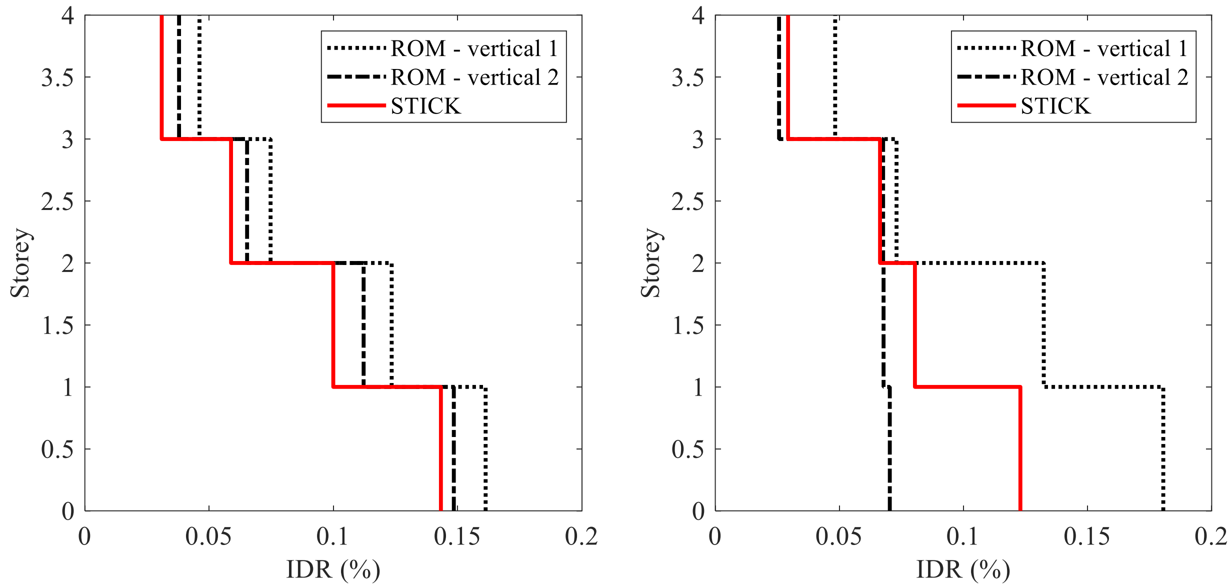


Figure 8: Time-history for the STICK model along the transverse direction.

On the other hand, the STICK model predicts top displacement that is equal to 8.88mm along X, and 8.49mm along Y (see Figure 7).

The comparison between the response obtained via ROM model and STICK model is reported in Figure 9, where the interstorey drift distribution along the height is shown considering the X direction (Figure 9(a)) and Y direction (Figure 9(b)) for the two verticals.

Along the X direction the STICK model always underpredict the building response compared to the ROM model in particular for the vertical 1 (i.e., the most flexible).



(a) (b)

Figure 9: Interstorey drift profile for the ROM model considering two verticals, and for the STICK model, along (a) X and (b) Y directions.

Along the Y direction the torsional effects considered by the ROM model are more pronounced, since the vertical 1 has higher lateral deformation with respect to the STICK model, while the vertical 2 lower, evidencing the presence of torsional effects.

5 CONCLUSIONS

A reduced-order model introduced for the rapid assessment of engineering demand parameters in existing infilled reinforced concrete buildings with an irregular layout. The proposed model is a multiple-degree-of-freedom system, consisting of a set of nonlinear shear springs, each representing the contribution of individual RC frames and infill alignments, separately, for each story and direction.

The primary objective of this work is to develop a simplified modeling framework capable of accurately representing the response of irregular structures while maintaining low computational cost and sufficient accuracy for large-scale applications. The procedure for constructing the simplified model for multi-span, multi-story infilled RC frames is detailed. The interstory nonlinear envelopes are derived from the individual component behavior under the simplified assumption that column ends are restrained against rotation.

The proposed approach is demonstrated for an existing four-story irregular building, designed using a simulated design procedure. The results are compared with those from a previously developed reduced-order model (STICK), which neglects torsional effects.

The simplified model demonstrated its potential to capture the torsional response of irregular RC buildings. However, further studies and comparisons with more refined models are necessary to fully validate the proposed modeling approach.

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REFERENCES

[1] M. Gaetani d'Aragona, M. Polese, and A. Prota, "Stick model for as-built and retrofitted infilled RC frames," *Eng Struct*, vol. 268, 2022, doi: 10.1016/j.engstruct.2022.114735.

[2] C. Xiong, X. Lu, H. Guan, and Z. Xu, "A nonlinear computational model for regional seismic simulation of tall buildings," *Bulletin of Earthquake Engineering*, vol. 14, no. 4, pp. 1047–1069, Apr. 2016, doi: 10.1007/s10518-016-9880-0.

[3] M. Gaetani d'Aragona, M. Polese, and A. Prota, "Seismic fragility curves for infilled RC building classes considering multiple sources of uncertainty," *Eng Struct*, vol. 321, Dec. 2024, doi: https://doi.org/10.1016/j.engstruct.2024.118888.

[4] X. Lu, Q. Cheng, Z. Xu, Y. Xu, and C. Sun, "Real-Time City-Scale Time-History Analysis and Its Application in Resilience-Oriented Earthquake Emergency Responses," *Applied Sciences*, vol. 9, no. 17, p. 3497, Aug. 2019, doi: 10.3390/app9173497.

[5] M. Gaetani d'Aragona, M. Polese, and A. Prota, "Stick-IT: A simplified model for rapid estimation of IDR and PFA for existing low-rise symmetric infilled RC building typologies," *Eng Struct*, vol. 223, 2020, doi: 10.1016/j.engstruct.2020.111182.

[6] M. Gaetani d'Aragona, M. Polese, M. Di Ludovico, and A. Prota, "The use of Stick-IT model for the prediction of direct economic losses," *Earthq Eng Struct Dyn*, vol. 50, no. 7, 2021, doi: 10.1002/eqe.3429.

[7] M. Gaetani d'Aragona, M. Polese, M. Di Ludovico, and A. Prota, "Large scale loss assessment using stick-it model: A comparison with actual cost data," *Soil Dynamics and Earthquake Engineering*, vol. 160, 2022, doi: 10.1016/j.soildyn.2022.107363.

[8] M. G. d'Aragona, M. Polese, M. Di Ludovico, and A. Prota, "The use of Stick-IT model in loss assessment at the large scale," in *Procedia Structural Integrity*, 2022. doi: 10.1016/j.prostr.2023.01.225.

[9] S. A. Anagnostopoulos, M. T. Kyrkos, and K. G. Stathopoulos, "Earthquake induced torsion in buildings: critical review and state of the art," *Earthquakes and Structures*, vol. 8, no. 2, pp. 305–377, Feb. 2015, doi: 10.12989/eas.2015.8.2.305.
[10] G. Manfredi, A. Prota, G. M. Verderame, F. De Luca, and P. Ricci, "2012 Emilia earthquake, Italy: reinforced concrete buildings response," *Bulletin of Earthquake Engineering*, vol. 12, no. 5, pp. 2275–2298, Oct. 2014, doi: 10.1007/s10518-013-9512-x.
[11] G. M. Verderame, F. De Luca, P. Ricci, and G. Manfredi, "Preliminary analysis of a soft-storey mechanism after the 2009 L'Aquila earthquake," *Earthq Eng Struct Dyn*, vol. 40, no. 8, pp. 925–944, Jul. 2011, doi: 10.1002/eqe.1069.
[12] A. Masi, V. Manfredi, and A. Digrisolo, "Seismic Assessment of RC Existing Irregular Buildings," in *The 15th World Conference on Earthquake Engineering*, Lisboa, 2012.
[13] F. Pachla, A. Kowalska-Koczwara, T. Tatara, and K. Stypuła, "The influence of vibration duration on the structure of irregular RC buildings," *Bulletin of Earthquake Engineering*, vol. 17, no. 6, pp. 3119–3138, Jun. 2019, doi: 10.1007/s10518-018-00546-4.
[14] H. Gokdemir, H. Ozbasaran, M. Dogan, E. Unluoglu, and U. Albayrak, "Effects of torsional irregularity to structures during earthquakes," *Eng Fail Anal*, vol. 35, pp. 713–717, Dec. 2013, doi: 10.1016/j.engfailanal.2013.06.028.
[15] V. Blasone, A. Basaglia, R. De Risi, F. De Luca, and E. Spacone, "A simplified model for seismic safety assessment of reinforced concrete buildings: framework and application to a 3-storey plan-irregular moment resisting frame," *Eng Struct*, vol. 250, p. 113348, Jan. 2022, doi: 10.1016/j.engstruct.2021.113348.
[16] C. Del Gaudio, P. Ricci, and G. M. Verderame, "A class-oriented mechanical approach for seismic damage assessment of RC buildings subjected to the 2009 L'Aquila earthquake," *Bulletin of Earthquake Engineering*, vol. 16, no. 10, 2018, doi: 10.1007/s10518-018-0365-1.
[17] M. Polese, M. Gaetani d'Aragona, and A. Prota, "Simplified approach for building inventory and seismic damage assessment at the territorial scale: An application for a town in southern Italy," *Soil Dynamics and Earthquake Engineering*, vol. 121, 2019, doi: 10.1016/j.soildyn.2019.03.028.
[18] M. Polese, M. Gaetani d'Aragona, M. Di Ludovico, and A. Prota, "Sustainable selective mitigation interventions towards effective earthquake risk reduction at the community scale," *Sustainability (Switzerland)*, vol. 10, no. 8, 2018, doi: 10.3390/su10082894.
[19] M. G. d'Aragona, M. Polese, M. Di Ludovico, and A. Prota, "Seismic vulnerability for RC infilled frames: Simplified evaluation for As-built and retrofitted building typologies," *Buildings*, vol. 8, no. 10, 2018, doi: 10.3390/buildings8100137.
[20] G. M. Verderame, M. Polese, C. Mariniello, and G. Manfredi, "A simulated design procedure for the assessment of seismic capacity of existing reinforced concrete buildings," *Advances in Engineering Software*, vol. 41, no. 2, 2010, doi: 10.1016/j.advengsoft.2009.06.011.
[21] S. Hak, P. Morandi, G. Magenes, and T. J. Sullivan, "Damage control for clay masonry infills in the design of RC frame structures," *Journal of Earthquake Engineering*, vol. 16, no. SUPPL. 1, 2012, doi: 10.1080/13632469.2012.670575.
[22] C. B. Haselton, A. B. Liel, S. C. Taylor-Lange, and G. G. Deierlein, "Calibration of model to simulate response of reinforced concrete beam-columns to collapse," *ACI Struct J*, vol. 113, no. 6, 2016, doi: 10.14359/51689245.
[23] D. E. Biskinis, G. K. Roupakias, and M. N. Fardis, "Degradation of shear strength of reinforced concrete members with inelastic cyclic displacements," *ACI Struct J*, vol. 101, no. 6, 2004, doi: 10.14359/13452.

[24] K. J. Elwood, "Modelling failures in existing reinforced concrete columns," *Canadian Journal of Civil Engineering*, vol. 31, no. 5, 2004, doi: 10.1139/L04-040.
[25] M. T. De Risi, C. Del Gaudio, P. Ricci, and G. M. Verderame, "In-plane behaviour and damage assessment of masonry infills with hollow clay bricks in RC frames," *Eng Struct*, vol. 168, 2018, doi: 10.1016/j.engstruct.2018.04.065.
[26] S. Mazzoni, F. McKenna, M. H. Scott, and G. L. Fenves, "OpenSees command language manual," 2006.
[27] C. S. Lee and S. W. Han, "Computationally effective and accurate simulation of cyclic behaviour of old reinforced concrete columns," *Eng Struct*, vol. 173, pp. 892–907, Oct. 2018, doi: 10.1016/j.engstruct.2018.07.020.
[28] N. Mohammad Noh, L. Liberatore, F. Mollaioli, and S. Tesfamariam, "Modelling of masonry infilled RC frames subjected to cyclic loads: State of the art review and modelling with OpenSees," *Eng Struct*, vol. 150, pp. 599–621, Nov. 2017, doi: 10.1016/j.engstruct.2017.07.002.
[29] FEMA P-695, "Quantification of building seismic performance factors," Washington, DC, 2009.