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A SIMPLIFIED MECHANICS-BASED MODEL FOR THE ASSESSMENT OF INFILLED RC BUILDINGS UNDER PYROCLASTIC DENSITY CURRENTS

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Abstract

Explosive volcanic eruptions are among the most catastrophic natural hazards in densely populated areas near active volcanoes. One of the most destructive phenomena during these events is the formation of Pyroclastic Density Currents (PDCs). When PDCs impact buildings, the horizontal dynamic overpressure generated can cause extensive structural and nonstructural damage, often leading to complete collapse. However, current methods for evaluating building vulnerability to volcanic overpressure events are limited, particularly in their assumptions regarding building behavior under such extreme conditions. To address these limitations, the authors proposed a new mechanics-based methodology called STAM-PYR (STructural Assessment Method for PYRoclastic density currents) [1] STAM-PYR allows explicit simulation of damage evolution as a function of dynamic overpressure intensity, accounting for the contribution of both structural and nonstructural components, including the failure modes typical of existing reinforced concrete (RC) buildings. This approach represents a significant advancement over current tools by capturing the complex interactions between PDC loadings and building response. The method is applied to a case study of a typical Italian mid-rise RC building designed for gravity loads. Results highlight the enhanced accuracy of STAM-PYR in modeling progressive damage and dynamic load redistribution compared to existing methods. STAM-PYR provides a robust and reliable tool for large-scale vulnerability assessments and probabilistic risk analysis, advancing the state-of-the-art in evaluating RC building performance under PDC loadings.

Keywords: Pyroclastic Density Current, volcanic explosion, mechanics-based assessment.

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1 INTRODUCTION

Among the various phenomena occurring during explosive volcanic eruptions, the formation of Pyroclastic Density Currents (PDCs) poses a significant threat to the build environment, especially in densely urbanized areas near active volcanoes. PDCs are gravity-driven, multiphase mixtures of hot volcanic gases and pyroclastic particles of varying sizes and concentrations, capable of transporting large volumes of ash-rich debris across the landscape [1]. Their primary hazard includes the capacity of burying large areas under thick pyrocalstic depostits, exposure to lethal temperatures, and the generation of high dynamic ovepressures, which have been recognized as the primary cause of damage to buildings [2].

Historical eruptions near urban settlements (e.g., [3], [4], [5]) have demonstrated the capacity of PDCs to destroy or severely damage many buildings along their central flow path. However, structural damage generally decreases with distance from the main flow axis and the vent, allowing some buildings to withstand the volcanic explosions, potentially offering temporary shelter for individuals unable to evacuate to safer areas given the sudden onset of the volcanic eruption. In this perspective, comprehensive studies on the vulnerabilty of buildings to PDCs are essential when forecasting their potential impact on the built environment. Such assessments play a crucial role in supporting both emergency response planning and disaster mitigation strategies, ultimately enhancing preparedness and resilience in at-risk region.

Despite their significance, only a few studies systematically addressed the vulnerability of buildings to PDCs. Valentine et al. [6], drew an analogy between PDCs and the effect of nuclear explosions, proposing a first damage scale for buildings and components based on data collected from nuclear weapon tests. Petrazzuoli and Zuccaro [7], refined these estimates proposing an analytical approach based on concepts of limit analysis to assess collapse capacity of building typical of the vesuvian area. Spence et al. [7] extended previous findings by integrating analytical and experimental data, and applying them to scenario assessments in the vesuvian area [8]

However existing analytical approaches have remarkable limitations, including oversimplified structural modeling, unrealistic pressure distributions, the neglection of the in-plane and out-of-plane infill contributions, and restricting the analysis to ductile failure mechanisms.

To address these gaps, this study introduces STAM-PYR (STructural Assessment Method for PYRoclastic density currents), a mechanics-based methodology employing a simplified pushover approach to evaluate damage evolution in infilled RC buildings under dynamic overpressure. STAM-PYR improves previous models by (1) dynamically updating load distributions depending on the progressive failure of closures and infill panels orthogonally loaded by the dynamic overpressure, (2) incorporating the contribution of both structural and nonstructural components ([9], [10]) and realistically capturing typical failure modes that can develop in existing RC buildings. Its computational efficiency makes it suitable for large-scale vulnerability assessments and probabilistic risk analyses. This paper is based on the previous work by the authors [11].

The following section outlines the STAM-PYR methodology, with a focus on the key features of the adopted mechanics-based structural model, the performance of exterior claddings, and the relevant loading conditions. The methodology is applied to a case study representative of a 1970s gravity-load-designed building to show the first results of the application of the proposed approach.

2 THE STAM-PYR PROCEDURE

The STAM-PYR method is a mechanics-based nonlinear procedure implemented in MATLAB© to simulate the structural behavior of infilled RC frame structures subjected to PDC loadings.

The proposed mechanics-based methodology employs a simplified nonlinear static approach to predict the damage evolution of infilled RC buildings under dynamic overpressure. It applies an increasing lateral pressure distribution to the exterior cladding of building until the formation of a global collapse mechanism. It allows assessing the performance of buildings for increasing values of the dynamic overpressure accounting for the contribution of both structural and nonstructural components to the lateral behavior, also considering the possible failure of fenestration and infill walls exposed to orthogonally-acting pressure loadings.

The process starts with the generation of the geometric and structural model through a simulated design process. The interstorey shear-displacement relationships for each storey and direction are then established according to the proposal of Gaetani d'Aragona et al. [12], by adopting the assumption of shear-type behavior. Then, the nonlinear lateral (pushover) response of the building under PDCs is obtained in closed form, accounting for progressive damage to exterior closures and infill walls, load redistribution due to component failure, and the limited out-of-plane (OOP) capacity of these elements.

The global pushover curve, expressed in terms of dynamic overpressure-top displacement (P_{dyn}-Δ_{top}) is computed using a mixed force-displacement control approach. Initially, a force-controlled procedure is applied until peak lateral response occurs at a given storey. At this stage, a displacement-controlled procedure takes over, where the failing storey exhibits post-peak softening behavior, increasing interstorey displacement while unloading occurs in other storeys with elastic stiffness. During the application of dynamic overpressure, exterior closures and infill walls may fail due to the formation of an OOP mechanism. Failure of exterior claddings modifies the pressure distribution. At this step, the base shear for a given value of the pressure suddenly drops due to a reduction of the loading resultant, also resulting in a reduction of the top displacement at a constant value of the dynamic overpressure. Note that when an infill panel fails, it is considered that the columns of the surrounding frame are still loaded by the PDC lateral pressure. The procedure iterates by progressively increasing dynamic overpressure until system-level collapse occurs.

Figure 1 illustrates sample outputs from STAM-PYR, showing the evolution of structural and non-structural damage in terms of (a) base shear-top displacement and (b) dynamic overpressure-top displacement.

2.1 Structural model

The STAM-PYR framework employs as structural model, the reduced-order model originally developed for simulating the seismic performance of infilled RC buildings, named STICK ([12], [13]). STICK is a multi-degree-of-freedom system with lumped masses connected by nonlinear interstorey shear springs, concentrating inelastic behavior at the storey level. These springs are calibrated under a shear-type behavior assumption, allowing for multi-linear interstorey displacement-shear relationships that integrate the contributions of structural (columns, beams, beam-column joints) and non-structural (infills) elements, as well as their interactions. The model also accounts for brittle failure mechanisms at both the member (e.g., buckling, spalling, shear, and axial failure) and sub-assembly (e.g., beam-column joints) levels. The STICK model has demonstrated to realistically reproduce building performance under earthquake shakings both at the building-level [14] and large-scale ([15], [16]).

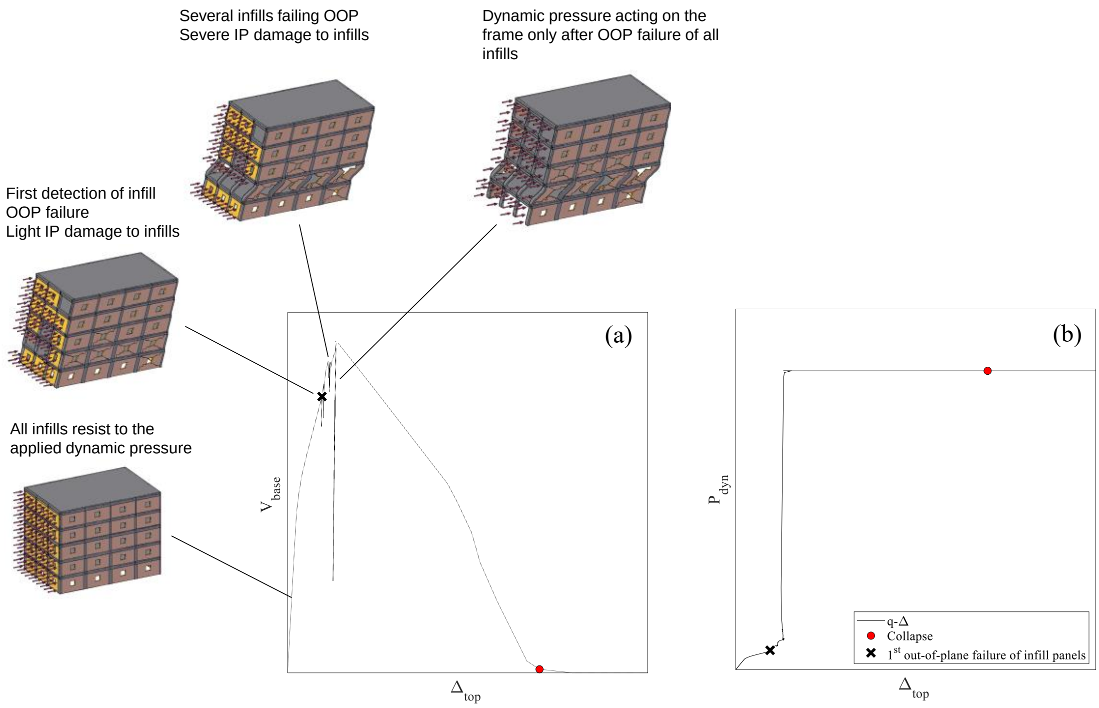
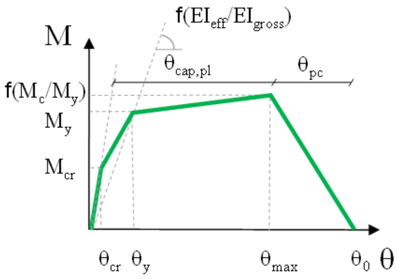


Figure 1: Example of the STAM-PYR procedure output considering the evolution of damage to structural and non-structural components in terms of (a) base shear-top displacement and (b) dynamic overpressure-top displacement (adapted from [11]).

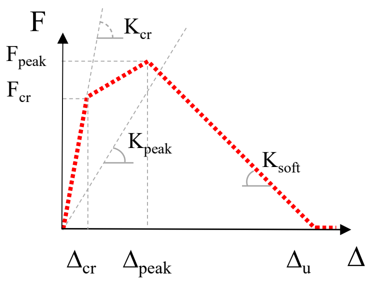
The model is generated using a built-in Matlab® routine, requiring minimal input data such as storey count, plan dimensions, construction age, and design level. Geometrical features are derived from statistical data, while element dimensions and reinforcement details are assigned based on simulated design procedures [17] according to design codes and professional practices.

For this study, only the contribution of RC columns and infill panels is explicitly considered in the derivation of interstorey relationships, while the contribution of beams, beam-column joints, and infill-frame local interactions are neglected.

Column backbone curves are derived from literature studies for RC members with deformed rebars [18] (Figure 2(a)). The possible development of brittle failure due to low shear strength is incorporated by modifying the original envelope ([12], [19], [20]). Infill panels follow the multi-linear model proposed by De Risi et al. [21] (Figure 2(b)).



(a) RC columns



(b) Infill panels

Figure 1: Nonlinear envelopes adopted for (a) RC columns and (b) Infill panels.

2.2 Performance of exterior claddings

Exterior closures such as windows and doors may be the first elements of the building envelope to fail due to overpressures generated during PDCs.

Under the assumption that the pressure distribution over each single panel can be approximated by constant one, the OOP of infill panels can be evaluated according to the proposal by Liberatore et al. [22]

$$q = 0.26 f_m'^{\,0.9} \left(\frac{h_w}{l_w}\right) \left(\frac{h_w}{t_w}\right)^{-1.23} \quad (1)$$

Where q is the uniform pressure causing out-of-plane failure, f'_m is the masonry compressive strength, h_w and l_w are the panel clear height and length, respectively, and t_w is the thickness of the infill panel.

The presence of opening generally reduces the OOP capacity of infill panels. In this case, Liberatore et al. suggested reducing the original OOP strength by the factor:

$$R_{op} = \min\left(1; 0.64 - 0.124 \cdot ln\left(\frac{A_{op}}{A} \frac{l_w}{h_w} \frac{t_w}{h_w} f_m'\right)\right) \quad (2)$$

Being A_{op} and A the opening and the bay area, respectively.

3 APPLICATION TO CASE-STUDY BUILDING

A 5 storey RC building, constructed and designed in the 1970s for gravity loads only, is selected to assess the effects of dynamic overpressures from PDCs. The building has a total in-plan area of 360 m², with longitudinal and transverse dimensions of 25.44m and 14.13m, respectively.

Based on a simulated design procedure geometrical and structural features are firstly determined. The building consists of six spans along the longitudinal direction (4.24m each) and three spans along the transverse direction (4.71m each), with an interstorey height of 3.2m (Figure 2a).

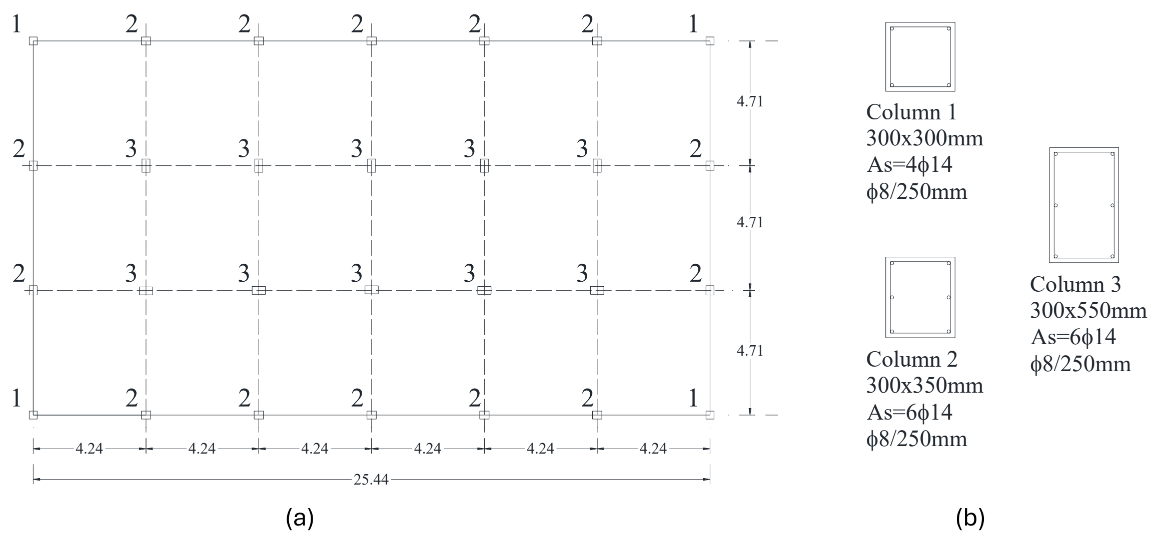


Figure 2. Case-study building: (a) in-plan view and (b) column cross-section and reinforcement details for the first storey (Adapted from Gaetani d'Aragona et al. [11]).

Structural elements are designed using R_{ck}=200 Kg/cm^2 concrete and FeB38k deformed rebars. Beam cross-sections range from 300×500 mm (exterior) to 300×550 mm (interior). First-story columns vary by location: 300×300 mm (corner), 350×300 mm (perimeter), and 300×550 mm (interior), reducing to 300×300 mm at the top story (Figure 2b).

Exterior infill panels consist of hollow clay bricks with strong (S) consistency according to Hak et al. [23]). (t_w=300 mm) and 20% openings. The mechanical response of RC columns and infill panels is characterized by capacity curves indicated in Section 2. Material properties include f_c=20MPa for concrete, f_y=449.6MPa for steel, and τ_{cr}=0.36 MPa for masonry. The OOP strength of openings ($q_{op,OOP}$) is assumed to be 4.5 kPa [24], while infill OOP capacity follows Liberatore et al. [22] according to Equations (1) and (2).

By applying the STAM-PYR procedure, the corresponding nonlinear response curves are obtained in terms of dynamic overpressure versus top displacement (Figure 3(a)-(c)) and base shear versus top displacement (Figure 3(b)-(d)). The building response is analyzed separately along the longitudinal (Figure 3(a)-(b)) and transverse (Figure 3(c)-(d)) directions.

The first notable difference is the value of P_{dyn} corresponding to the onset of lateral instability in the two principal directions. This significant variation in the building capacity to withstand PDC can be explained by its in-plan geometry. Specifically, when the PDC flow acts along the longitudinal direction, the out-of-plane resistance of the infill panels to be considered is that of those oriented along the transverse direction. Conversely, the infills aligned longitudinally contribute to the overall resistance of the frame through their in-plane stiffness. The same observation applies when the PDC flow acts in the transverse direction.

Since the building extends considerably in the longitudinal direction but is narrower in the transverse direction, the contribution of in-plane infills to base shear capacity is significantly higher when the flow is longitudinal. As a result, the maximum base shear that can be sustained before OOP failure of all infills is much greater in this case.

Because the P_{dyn} associated with the attainment of base shear capacity exceeds that corresponding to the OOP failure of the infills, the latter phenomenon occurs on the loading branch (see Figure 3(a)-(b), marked with a cross). At this point, the structure begins to unload (see Figure 3(b)) since, once the infill elements fail, the dynamic overpressure can no longer be exerted on them. Consequently, for the same P_{dyn}, the resultant base shear decreases. This unloading effect is also observed due to the failure of exterior closures, though its influence is less pronounced (Figure 3(b)-(d)).

To reach the same base shear experienced at the onset of the first element failure, the dynamic overpressure must increase significantly. This triggers the rapid and progressive out-of-plane collapse of all infill panels exposed to the flow (transverse ones). Due to the slight variation in out-of-plane infill capacity, as P_{dyn} increases, these elements fail before producing any significant increase in base shear. At this stage, dynamic overpressure can act only on the bare frame, meaning that exceptionally high values of P_{dyn} (=122.3 kPa) could lead to lateral instability.

In contrast, along the transverse direction, the opposite phenomenon occurs, allowing lateral instability to develop at much lower values Pdyn (=12.38 kPa). This highlights the strong influence of flow directionality on the building's capacity to resist PDCs, as previously observed in past events.

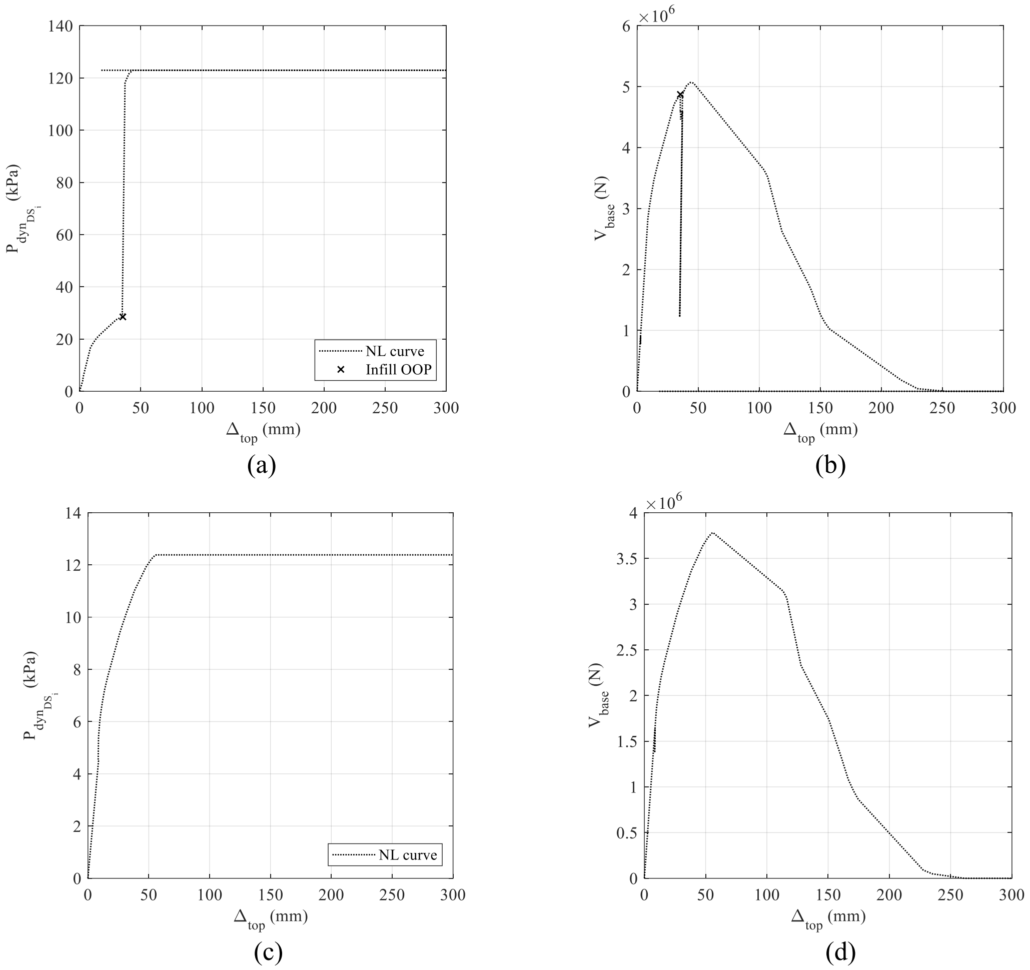


Figure 3. Nonlinear response curve obtained by means of the STAM-PYR procedure applied to the case-study building, considering the PDC flow acting along the (a,b) longitudinal and (b,c) transverse direction in terms of (a,c) dynamic overpressure-top displacement and (b,d) base shear-top displacement.

4 CONCLUSIONS

This study presents a mechanics-based approach named STAM-PYR (Structural Assessment Method for Pyroclastic Density Currents) for evaluating the structural performance of reinforced concrete (RC) buildings subjected to PDCs along one of their primary directions. This study is based on the previous work by the authors [11].

The STAM-PYR framework utilizes a pushover analysis on a simplified shear-type structural model, allowing for the prediction of damage progression in infilled RC buildings as a function of dynamic overpressure induced by PDCs. A key aspect of the methodology is its explicit consideration of the progressive out-of-plane failure of external enclosures, including windows, doors, and infill walls, which are exposed to dynamic overpressures. This is achieved by adapting the applied pressure profile throughout the analysis. Despite its simplicity, the model effectively captures the key characteristics of older RC buildings designed under outdated code provisions, incorporating structural vulnerabilities, failure patterns in non-ductile elements, and global collapse mechanisms. By integrating both structural and non-structural components, the model accounts for their respective contributions to the lateral stiffness and strength of the frame, as well as their interactions at the sub-assembly level.

STAM-PYR serves as a practical tool for disaster risk reduction and emergency response planning, aiding in the identification of vulnerable building typologies and high-risk areas. By pinpointing structural weaknesses, the method can support the development of targeted retrofitting strategies to mitigate building vulnerability to PDCs.

To illustrate the applicability of the STAM-PYR approach, it was employed in a case study assessing the response of a representative Italian mid-rise RC building designed exclusively for gravity loads showing first results of the proposed methodology.

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