DEVELOPMENT OF A SIMPLIFIED SEISMIC ASSESSMENT TOOL FOR MODERN REINFORCED MASONRY BUILDINGS IN COSTA RICA

B. González Rodrigo[1]; L. Navas-Sánchez[1]; C. Monteferrante[2]; F. Ferretti[2]; G. Alemán[3]; S. Torres-Olivares[4], M. Savoia[2]

[1] Universidad Politécnica de Madrid, Spain, beatriz.gonzález.rodrigo@upm.es

[2] *Alma Mater Studiorum - Università di Bologna,* Italy.

[3] Universidad de Costa Rica, Costa Rica,

[4] Universidad de Santiago de Chile, Chile.

Abstract: *The objective of this study is to validate a rapid assessment tool to evaluate the seismic behaviour of partially grouted reinforced concrete masonry (PG-RCM) dwellings in Costa Rica during the design phase. Since 1974, Costa Rica has had its own Technical Seismic Code, which includes a seismic-resistant design. This research analyses the feasibility and adaptation of a simplified methodology, originally developed in Italy to assess the seismic vulnerability of reinforced concrete or unreinforced masonry buildings, to the Costa Rican context. To accomplish this, 26 PG-RCM dwelling projects approved by the Federated College of Technical Engineers and Architects of Costa Rica (CFIA) between 2014 and 2022 were randomly selected and analysed. Five of these projects were simulated by numerical models according to the equivalent frame approach within the 3Muri software. The models were calibrated with previous laboratory tests on PG-RCM walls. The seismic vulnerability estimated with the simplified methodology was then validated by comparison with the capacity obtained from numerical models. The results of this study contribute to decision-making during the initial stages of the projects, possibly leading to a reduction of seismic vulnerability of the most common construction systems in Costa Rica. In conclusion, the implementation of the simplified methodology in the design stages of PG-RCM dwellings can be a useful tool for the identification of the vulnerabilities of buildings in Costa Rica and it can provide technical assistance to designers, helping them in guaranteeing the seismic resistance of dwellings and the safety of their occupants.*

1. General considerations

San Jose, the capital of Costa Rica, is a significant urban hub in Central America, situated in one of the world's highest seismic hazard zones, influenced by the subduction of the Cocos and Caribbean tectonic plates. The most prevalent construction system for single-family housing is partially grouted reinforced concrete masonry (PG-RCM), accounting for 88.2% of residential units (Esquivel-Salas, 2020). The Costa Rican Seismic Code (CRSC) (CFIA, 2014) specifies for PG-RCM buildings a construction system with horizontal and vertical reinforcements using steel bars. Local construction practises for these structures exhibit notable differences compared to those prevalent in neighbouring regions (Hidalgo-Leiva et al., 2016). In Costa Rica, the requirement for calculation reports in construction projects depends on the specific regulations of the municipality in question. In numerous locations throughout the country, such reports are required for buildings consisting of four floors or more. For all other cases, adherence to the construction prerequisites outlined by the Costa Rican Seismic Code (CRSC) is mandatory, but not the said calculation reports. For this reason, it is highly recommended that, during the structural design phase, a simplified method for determining a construction's seismic behaviour serves as a decision-making tool. In the literature, numerous simplified methods have been proposed to assess the seismic vulnerability of existing buildings, each with varying input parameters (Ceroni et al., 2020).

Among these approaches, the focus of this research is on a simplified method developed at the University of Bologna (Mazzotti et al., 2013). This method is aimed at determining the value of peak ground acceleration at which structural failure occurs, enabling both qualitative and quantitative vulnerability assessments, also employing data collected through the GNDT (Gruppo Nazionale per la Difesa dai Terremoti, 1994) form. The approach has been devised as a simplified tool to evaluate the seismic vulnerability of reinforced concrete or unreinforced masonry buildings. This method is based on the assessment of the collapse acceleration of the building, PGA_c, through a simplified evaluation of the resisting shear for each floor of the building, calculated using the Turnšek-Čačovič (1970) formula. The method accounts for the in-plane shear failure of the masonry walls, based on the fact that buildings damaged by earthquakes often exhibit a diagonal shear mechanism on masonry piers (Marques & Lourenço, 2011).

To validate the simplified approach for its application to the Costa Rican context, comparisons with the results of nonlinear static analyses were carried out. The numerical analyses were performed with the 3Muri software, based on an equivalent frame modelling strategy, also accounting for the inherent nonlinear characteristics of the masonry materials. Elastic analysis is, indeed, considered unrealistic for masonry (Heyman, 1966). Macro-element modelling techniques have proven to be effective in the investigation of various types of structures, including reinforced masonry (Belmouden & Lestuzzi, 2009)(Cattari & Lagomarsino, 2013). The simplicity of these methodologies allows the seismic behavior of structures to be characterized using nonlinear static or dynamic analyses, offering the additional advantage of significantly reduced computational costs and time compared to alternative methods such as finite or discrete elements (Parisse et al., 2022)

Numerous strategies for macro-element modelling have been proposed in the existing literature to idealise three-dimensional masonry structures. Among these, the equivalent frame method is particularly notable, as it divides the structure into vertical (piers), horizontal (spandrels), and rigid macro-elements that exhibit nonlinear material properties and require only two nodes for each element (Roca et al., 2005)(Penna et al., 2014). This approach facilitates the execution of numerous analyses with variations in the desired parameters, it simplifies the calibration with experimental data, and it enables the exploration of various factors influencing the outcome. The effectiveness of the method is more pronounced when investigating structures that exhibit box-like behaviour, such as PG-RCM structures (Grillanda et al., 2020). In the context of this study, macro element methods are implemented using the 3Muri software (S.T.A. DATA 2023) (version 13.2.0.14), which employs an equivalent frame model (Lagomarsino et al., 2013).

Therefore, the objective of this study is to validate a rapid assessment tool to evaluate the seismic behaviour of partially grouted reinforced concrete masonry buildings in Costa Rica during the design phase.

2. Methodology

The Federated College of Technical Engineers and Architects of Costa Rica (CFIA) selected randomly a sample of 26 PG-RCM housing projects among all approved projects over the period 2014 to 2022. The construction projects records were anonymized maintaining the relevant data that included geometric specifications, area measurements, material properties, weight distributions, and complex construction details. All the sample buildings were analysed with the simplified methodology for the vulnerability assessment (Mazzotti et al, 2013). From this sample, we selected five buildings that were simulated by means of nonlinear static analyses performed on equivalent frame models with the software 3Muri. The results obtained with the two different approaches were then compared in terms of resisting shear of the buildings and failure mode of the wall panels, with the objective of validating the simplified method with respect to the building typology considered (PG-RCM).

Among the 26 homes subject to analysis, all were single-family residences with either one or two storeys, and only 3 of them were isolated houses; the rest were part of residential developments and shared at least one façade with another dwelling. The total constructed area ranged from 80 to 220 m^2, with an average of 132.9 m^2. To modelling using the equivalent frame approach, 5 dwellings were selected. All of them were designed to be part of aggregates, with one being single-storey and the remaining four having two storeys. The constructed area in this group varied between 84 and 180 m^2.

The simplified methodology is based on the collection of a limited amount of information about the investigated buildings, i.e., the geometry of the resisting elements, the acting loads, the type of materials adopted (with information about mechanical properties, when available), constructive details identifiable through visual inspections or non-destructive testing. Then, the evaluation of the resisting shear $V_{r,i}$ on the i-th floor can be performed according to the diagonal cracking failure criterion (Turnšek & Čačovič, 1970), (Ecuation 1). The maximum shear capacity of the investigated reinforced masonry walls depends on both the masonry contribution and the steel contribution (Hidalgo-Leiva et al., 2021). In the simplified method, these contributions are incorporated in a single value by introducing the mean tangential strength of masonry (τ_r) obtained experimentally.

$$V_{r,i} = A_i \cdot \tau_r \cdot \sqrt{1 + \frac{\sigma_{0,i}}{1.5 \cdot \tau_r}} \quad (1)$$

where:

- A_i is the area of the structural elements in one of the two main directions of the building (*x* or *y*) for the i-th floor;
- τ_r is the mean tangential strength of masonry, this value (660 kPa) was obtained from previous laboratory tests conducted on reinforced confined masonry walls (Diego A. Hidalgo-Leiva et al., 2021, Navas Carro & Cordero Segura, 2013, D. A. Hidalgo-Leiva et al., 2016)
- $\sigma_{0,i}$ is the mean compressive stress acting on the masonry panels at the i-th floor.

For the comparison with the nonlinear static analyses results, the resisting shear ($V_{r,i}$) should be computed in the two main directions of the building (*x* or *y*). Then, for each direction, the comparison between the resisting shear and the acting shear ($V_{s,i}$), the latter computed through a linear static analysis with a unitary spectral acceleration, allows to identify the weakest storey, corresponding to the minimum value of the ratio $V_{r,i}/V_{s,i}$. Furthermore, this ratio is needed for characterising the structural resistance in terms of spectral acceleration (S_a).

The simplified method also introduces a reduction coefficient (C_{rid}) to account for the possible influence of structural behaviour modifiers, not directly taken into account in the calculations. This coefficient is determined by using 10 of the 11 parameters specified in the second level GNDT form (Gruppo Nazionale per la Difesa dai Terremoti, 1994), assigning to them a class (A, B, C, D) according to their vulnerability (i.e., A: less vulnerable, D: most vulnerable), and a weight. The complete procedure is reported in Mazzotti et al., 2013. Table 1 shows the considered parameters, with the applied weights, and the reduction coefficients for each of the studied buildings. By knowing the reduction coefficient, the collapse pseudo-acceleration ($S_{a,c}$) at the Life Safety Limit State can be calculated according to Equation 2:

$$S_{a,c} = S_a \cdot C_{rid} \quad (2)$$

It is worth mentioning that, when considering the simplified method in the context of new construction, some of the GNDT parameters could become more relevant than others, differently to the case of existing unreinforced masonry buildings, especially in presence of seismic design prescribed by Building Codes. In this case, only irregularity, roof type and maximum distance between walls hold significance, indeed they are the only parameters with a class different than A in Table 1. This could indicate the need for a customised approach in assigning weights to these parameters when calculating the C_{rid} for the implementation of simplified method in new residential buildings.

On the other hand, with respect to the equivalent frame method, it is worth mentioning that a previous study conducted by Torres-Olivares et al. (2023) validated the modelling of masonry walls made of partially filled concrete blocks with vertical and horizontal reinforcement with the 3Muri software by comparing the results with those of experimental tests carried out by Hidalgo-Leiva et al. (2021). The 3Muri software is utilized to simulate the behaviour of masonry components using a bi-linear elasto-perfectly plastic model. This implies that, following the initial elastic phase, masonry elements will undergo plastic deformation until they reach their maximum drift. The criteria for failure consider two strength domains: one for bending (ultimate moment) and one for shear (Mohr-Coulomb), with both being influenced by the axial compression force acting on the element. Moreover, the type of failure in each element can change depending on the magnitude of the axial load. Consequently, the maximum drift can be due to either shear or bending, contingent on the failure mode. The software also includes the capability to simulate reinforced masonry elements and reinforced concrete ring. beams. The walls are simulated as PG-RCM, vertically and horizontally reinforced, with a reinforced concrete beam at the top. The slab and the roof, due to their construction, are considered rigid diaphragms, as commonly observed in this type of housing (Esquivel-Salas 2020).

In this research, the pushover analyses of the structure are conducted in both the positive and negative X and Y directions. The applied load is distributed in accordance with the primary modes of vibration, specifically those with higher mass participation. The recorded displacement corresponds to the average displacements of the nodes on the roof.

3. Results and Discussion

In this study, 10 of the dwellings are single-storey, while 16 are two-storey, showing the increase of the medium-rise construction in modern Costa Rica (2014-2022) in contrast to the data provided by the inventory of dwellings in Central San José, indicating that more than 55% were single-storey (Esquivel-Salas 2020). Furthermore, when analysing the relationship between the resistant masonry wall area (A_r) and the total built area (A_{total}) of the weakest floor in both directions (Figure 1) it was observed that this relationship is higher in single-storey dwellings compared to two-storey ones. This difference is attributed to the layout of the spaces in two-storey dwellings, where the lower floor is generally characterized by a greater amount of opening, because it typically houses the living room and the kitchen. These findings emphasise the importance of considering the structure of homes in assessing seismic vulnerability.

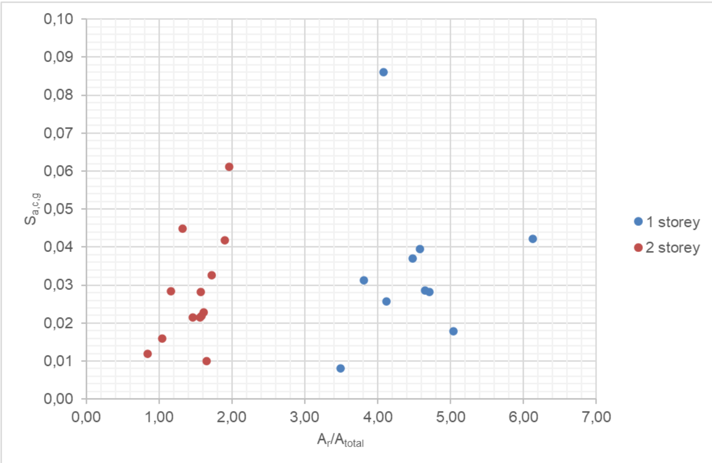


Figure 1. Relationship between wall area (A_r) and the total area (A_{total}) of the weakest storey and collapse pseudo-acceleration ($S_{a,c}$) of all the buildings under study calculated with the simplified methodology Mazzotti et al., 2013)

In the context of this study, it is important to note that only 4 out of the 10 parameters utilized to derive the reduction coefficient (C_{rid}), which is employed to reduce shear resistance (V_r), have an influence on the new PG-RCM construction projects analysed within the scope of this study (Table 1) using the simplified methodology. Within this methodology, structural irregularity is evaluated based on two of the ten parameters used to determine C_{rid}. This streamlined approach suggests that the significance of the "elevation irregularity" criterion may vary depending on the specific project, while the "plan irregularity" parameter maintains a consistent value across all samples. Although irregularity's effect is introduced through a reduction coefficient, it does not differentiate between axes to identify which one exhibits greater irregularity. Upon examining the projects, it becomes evident that in a substantial number of dwellings, irregularity varies between the x and y axes (Table 2).

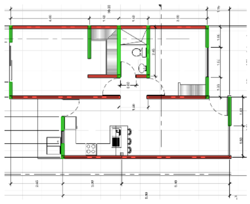
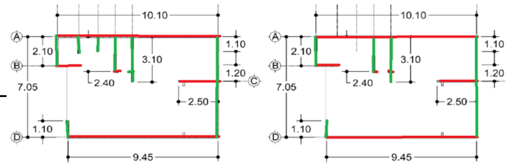
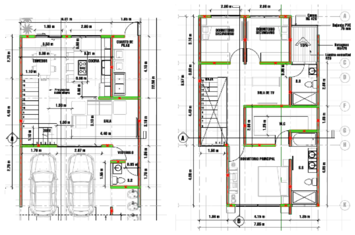
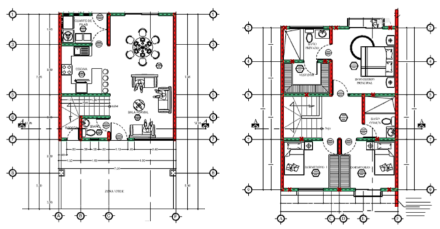
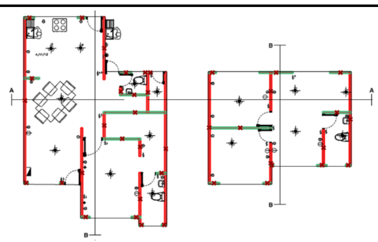
Table 1. Parameters to be considered for the determination of the reduction coefficient C_{rid}

	Weight	**MCR2**		**MCR0**		**MCR22**		**MCR13**		**MCR12**	
1. Typology and organisation of the resisting system	**1,50**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
2. Quality of the resisting system	**0,25**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
4. Building location and foundation	**0,75**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
5. Horizontal structural elements	**0,50**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
6. Plan configuration	**0,50**	D	0,96	A	1,00	C	0,98	A	1,00	D	0,92
7. Configuration in elevation	**1,00**	B	0,99	A	1,00	D	0,92	D	0,92	D	0,98
8. Maximum distance between masonry walls	**0,25**	D	0,98	D	0,98	D	0,98	D	0,98	D	0,98
9. Roof	**0,75**	B	0,98	B	0,98	A	1,00	B	0,98	A	1,00
10. Non structural elements	**0,25**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
11. State of the conservation of the building	**1,00**	A	1,00	A	1,00	A	1,00	A	1,00	A	1,00
C_{rid}		**0,92**		**0,96**		**0,89**		**0,89**		**0,87**	

Table 2 and Figure 2 provide visual insights into the impact of plan and elevation irregularities on seismic behaviour. In Table 2, the level of plan irregularity in dwellings is showed. It can be observed that the more symmetric dwellings, such as those in Project MCR0, exhibit closer values of resisting shear between the simplified method and the results obtained through equivalent frames with 3Muri. On the other hand, in the MCR12 project, which exhibits a more pronounced irregularity in elevation and plan, the simplified approach overestimates the resisting shear, presumably due to the improper weighting of the irregularity in this case.

Figure 2 illustrates the vibration modes of the analysed structures and the damage to the structural walls during the last load step. It is evident that flexural failure is observed, especially along the weaker axis, where the cross-sectional area of the walls is typically narrow. In slender walls, the influence of failure by flexure can become particularly important (Hidalgo-Leiva et al., 2018), and it is assumed that it should be addressed by including the contribution of steel reinforcement. The simplified method, in its current formulation, does not explicitly consider flexural failure. This could explain why, in most cases, the resisting shear on the weaker axis tends to have higher values when applying the simplified method compared to the 3Muri model (Table 2). Indeed, in this direction, the slenderest walls are commonly found. On the contrary, the results along the stronger axis show a closer match, with longer structural walls failing in shear. Therefore, to adapt the simplified method to the PG-RCM construction system, the flexural capacity of the reinforced masonry shear walls should be incorporated. Different investigations have easily introduced it with a reasonable degree of precision using beam theory (Belmouden & Lestuzzi, 2009) and the Peruvian masonry design code (Ministerio de Vivienda Construccion y Saneamiento, 2018) included a reduction in the shear strength for slender wall (H/L>1) due to the moment at the top of the wall, based on the results of a numerical study in confined masonry (Pérez Gavilán Escalante et al., 2023)

Table 2. Resisting shear values obtained by the simplified method and through the 3Muri software for partially grouted reinforced concrete masonry dwelling in Costa Rica. Red, the X axes and green, the Y axes.

			RESISTO		3 MURI	RESISTO_3MURI	DWELLINGS SCHEME (NOT TO SCALE)
			V_R (kN)	$V_R x C_{rid}$ (kN)	Vmax (kN)	$V_R x C_{rid}/V_{max}$ (%)	
MRC2	min	Ground y	1373,8	1259,8	925,0	137%	
	max	Ground x	3045,4	2792,6	2573,3	109%	
MRC0	min	Ground y	1072,0	1031,2	925,0	111%	
	max	Ground x	1886,0	1814,2	1861,0	97%	
MRC22	min	Ground y	1297,9	1149,9	851,0	135%	
	max	Ground x	2952,4	2615,8	2617,0	100%	
MRC13	min	Ground y	1366,7	1213,5	946,0	128%	
	max	Ground x	2050,1	1820,3	1617,0	113%	
MRC12	min	Ground y	1132,0	985,4	679,0	145%	
	max	Ground x	2992,0	2604,6	2622,0	99%	

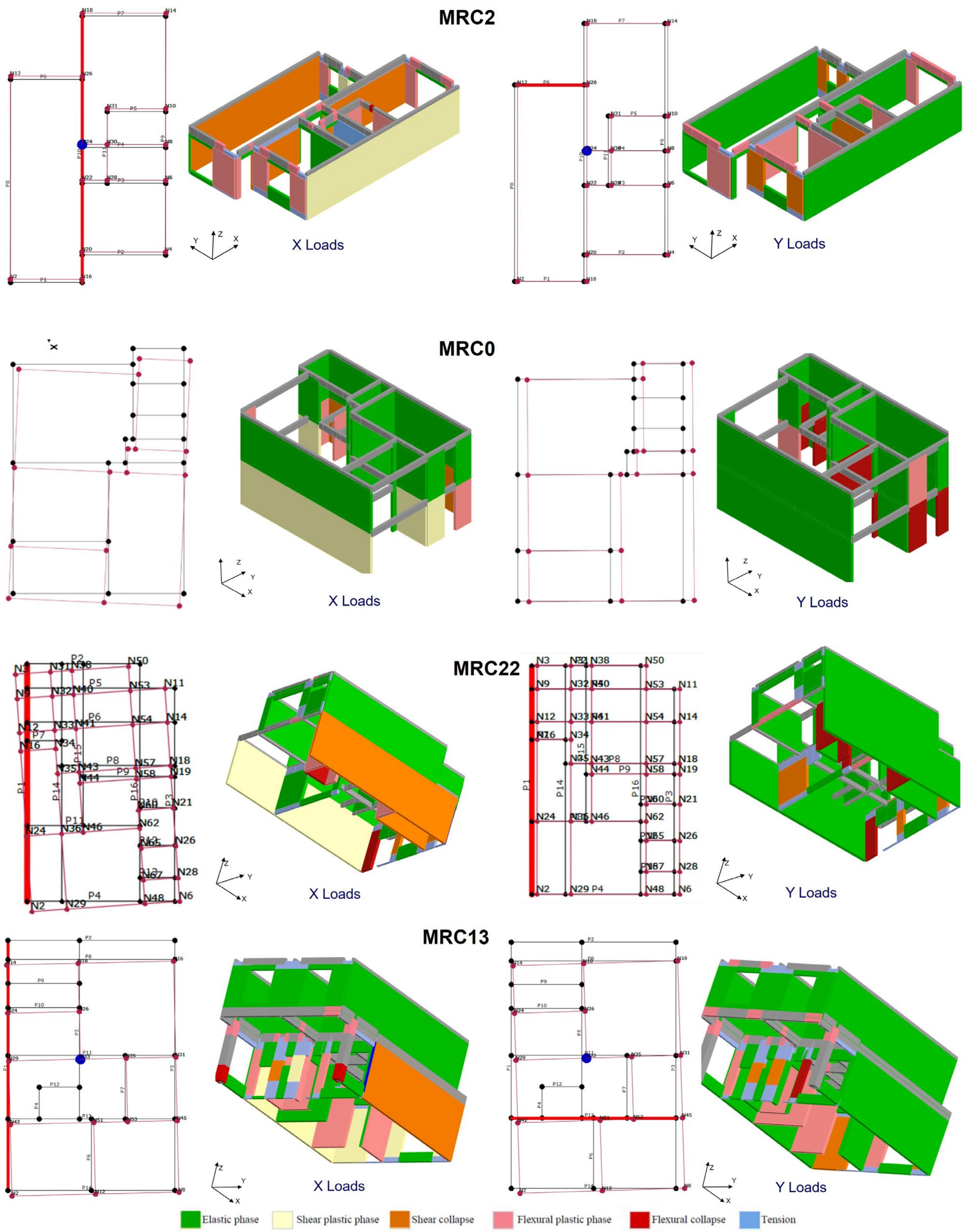


Figure 2. Failure mechanisms for loads in the positive X and Y direction and shape of the main modes of vibration (cont)

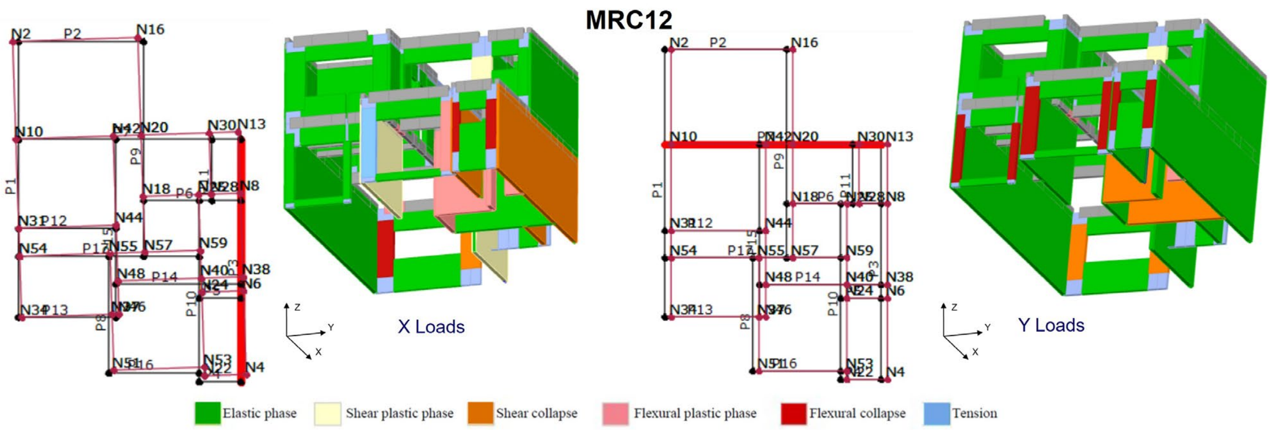


Figure 2. Failure mechanisms for loads in the positive X and Y direction and shape of the main modes of vibration

4. Conclusions

In this study 26 PG-RCM dwelling projects approved by the Federated College of Technical Engineers and Architects of Costa Rica (CFIA) between 2014 and 2022 were randomly selected and their seismic vulnerability was estimated with a simplified methodology. Five of these projects were simultaneously simulated according to the equivalent frame approach within the 3Muri software. The results of this study underscore the potential of the simplified methodology as a valid tool for decision-making in the design stages of PG-RCM projects in Costa Rica. This would allow for a more thorough consideration of construction factors that enhance seismic vulnerability in such projects. However, this study has identified room for improvement in the methodology by taking into account relevant factors for the Costa Rican building typologies, such as the weight of irregularities and the influence of flexural failure. In conclusion, further research should target the impact of irregularity parameters on seismic vulnerability and the weights that should be assigned to these parameters. Furthermore, the need to explicitly address flexural failure, which becomes significant in the slenderer walls commonly found in Costa Rican construction, is emphasized. To achieve this, it is essential to incorporate the contribution of steel reinforcement in the masonry walls.

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