Seismic performance of thin RC wall buildings reinforced with welded-wire mesh: a case study in Bogotá, Colombia

O. Arroyo(1), J. Carrillo(2), D. Feliciano(3), M. Hube(4)

(1) *Associate Professor, Departmento de Infraestructura y Sostenibilidad, Universidad de La Sabana, orlando.arroyo@unisabana.edu.co*
(2) *Full Professor, Department of Civil Engineering, Universidad Militar Nueva Granada, Colombia, julian.carrillo@unimilitar.edu.co*
(3) *Research Assistant, Departmento de Infraestructura y Sostenibilidad, Universidad de La Sabana, dirsafeag@unisabana.edu.co*
(4) *Associate Professor, Departamento de Ingeniería Estructural y Geotécnica, Pontificia Universidad Católica de Chile, Chile, mhube@ing.puc.cl*

Abstract

The increasing demand of housing in urban areas in Latin America has driven the construction of a significant number of buildings using thin and slender reinforced concrete (RC) walls, with single layer of reinforcement provided by a welded-wire mesh (WWM). Studies in Colombia have found buildings using walls as thin as 80 mm and being as height as 7 stories. Experimental studies also have demonstrated that the WWM currently available in Bogotá should not be used for reinforcement of concrete structures requiring intermediate or special energy dissipation. Main concerns are related to the lack of ductility, scarce evidence about their behavior during earthquakes, and the lack of clarity of design guidelines in modern earthquake-resistant codes.

This research aims at providing evidence by calculating the seismic fragility functions for a thin RC wall building constructed in Bogotá, Colombia. This building has six stories with 100 mm walls with web reinforcement made of WWM, which is representative of the design and construction practices that emerged using thin RC wall buildings. After gathering relevant information from the building structural drawings, a nonlinear model was created in *OpenSees* using the shear-flexure interaction multiple vertical line element (SFI-MVLEM). As a benchmark, a second model was created using reinforcement made of deformed bars (DB). Incremental dynamic analyses (IDA) were conducted on the models using the ground motion suite provided by the FEMA P-695, which served as input for the development of fragility functions for the building. The results show that the fracture of steel in the WWM is the dominant failure mode of the building, with failures occurring in several walls simultaneously. In contrast, the building with DB experience a different type of failure characterized by….. The findings also show that the probability of failure of the building with WWM is 84% when the ground motions are scaled to the maximum credible earthquake and 34% when ground motions are scaled to the design earthquake. Overall, this study supports the idea that the use of WWM for construction of thin RC wall buildings leads to probability of failures that exceed significantly design code targets, providing evidence to limit the use of WWM for residential buildings located in high hazard seismic regions.

1. Introduction

Housing demand in Latin America has increased considerably in recent years. To supply this demand, an important number of low- and mid-rise buildings with thin reinforced concrete (RC) walls have been constructed in seismic prone countries like Colombia, Mexico, Peru, Venezuela, and Chile [1–5]. The advantage of this structural system relies on its economy and its speed of construction. In Colombia, RC walls as thin as 80 mm have been used [6], using one layer of web reinforcement made of deformed bars (DB) or welded-wire mesh (WWM). The latter type of reinforcement is the preferred option by constructors because it allows a higher construction speed. However, ductility capacity of WWM is limited or nonexistent [7] and are currently being using for projects in major cities like Bogotá and Medellín.

Many of the described buildings do not fulfill seismic requirements of widely-used design codes like the ACI 318 [8], but reflecting on the awareness of housing demands, local codes in some countries have included special provisions for buildings with thin RC walls. As an example, the Mexico City Building Code [9] allows structural walls with 100 mm thickness for houses of up to two stories. Similarly, the Chilean code [10] allows the use of ordinary RC walls for buildings up to five stories if they are designed with a strength reduction factor equivalent to that of masonry structures. For such walls, the minimum wall thickness is 100 mm and single or double layer of web reinforcement may be used. In other countries like Colombia, whose code for concrete structures includes many similarities with the ACI 318 [11] does not include specific clauses for these type of particular buildings, and designers are wrongly following the RC wall building provisions.

Different concerns emerge about the seismic performance of buildings with thin RC walls, particularly for those reinforced with WWM. These relate to the possible lack of ductility, the scarcity of information about their behavior during earthquakes, and the absence of design guidelines supported by experimental research. Reflecting these needs, researchers have investigated the behavior of thin RC walls by both experimental and analytical means.

Several experimental campaigns have been carried to assess the seismic behavior of thin RC walls with different configurations, such as walls reinforced with welded-wire mesh [12], walls with different thickness and lap splicing [13], and walls constructed with lightweight and low-strength concrete [14]. Other tests have been conducted to compare the quasi-static and dynamic behavior of thin RC walls [15], to evaluate their out-of-plane behavior [16], and to propose shear strength and hysteretic response rules [17]. Furthermore, numerical models have been proposed to simulate their seismic behavior [18,19] and equations have been proposed to estimate their shear strength [20]. In addition, nonlinear three-dimensional analysis of typical Peruvian RC thin wall buildings have been conducted [20] and fragility function have been calculated for one-story houses reinforced with WWM in Perú [21] and for typical Chilean two-story houses [22].

Despite the described efforts, there is still need of more analytical information about the seismic behavior of thin RC walls that can provide guidance about the correct practices for their usage as a structural system. In particular, there is need for development of fragility function for mid-rise buildings, shedding light about the vulnerability of the existing constructions based on this system and looking towards its application in the seismic risk analysis of urban areas.

Contributing to these needs, this research investigates the seismic performance of a six-story thin RC wall building located in Bogotá, Colombia. This building was designed per the Colombian NSR-10 Code [23] and constructed using WWM as web reinforcement. First, this article describes the building structural configuration and then, a section of the building is selected for developing a nonlinear model in *OpenSees* [24], using the shear-flexure interaction multiple line vertical element (SFI-MVLEM) [25] model for the thin RC walls. This model is subjected to incremental dynamic analyses (IDA) [26] using the far field suite of the FEMA P-695 [27], which served as input information for the development of seismic fragility functions. The walls failure modes are identified and their height-wise behavior is described. Finally, the effect of steel reinforcement type is assessed using a second benchmark model with deformed bars (DB), which is subjected to the same seismic demand and the results compared to those of the model with WWM.

2. Description of the case study building

This study considers a six-story building constructed in Bogotá, the capital city of Colombia. This building was part of a survey conducted by the Colombian Earthquake Engineering Research network (CEER) in four major cities in Colombia.

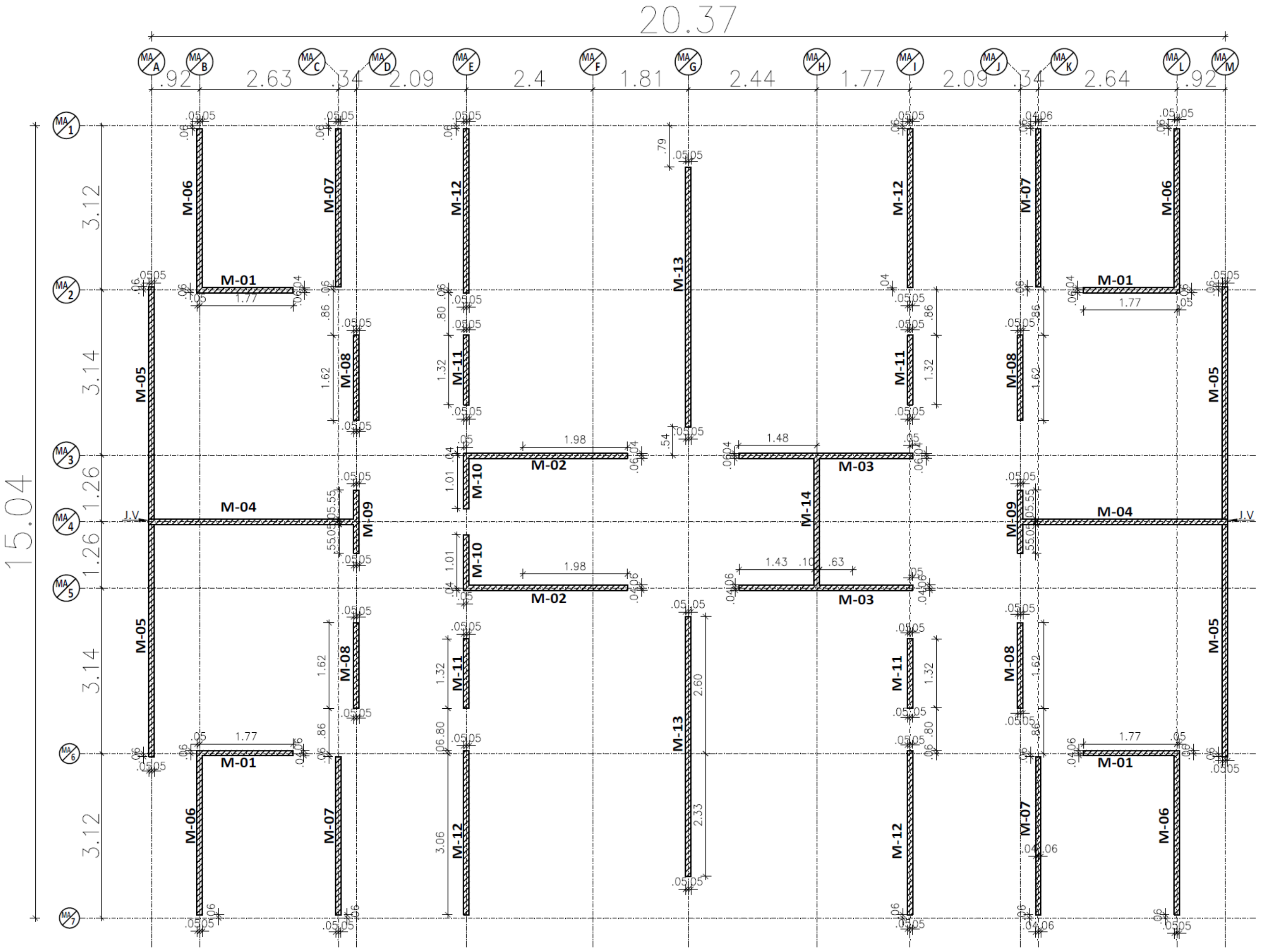

Fig. 1 - Plan configuration of a six-story building located in Bogotá, Colombia. Dimensions are in m

The building has six identical stories, which have a plan configuration (Fig.1) with a 4:3 aspect ratio and a free inter-story height of 2.45 m. The building was designed according to the Colombian design code (NSR-10) for a spectral acceleration Sa = 0.56g, with a structural system that uses 100 mm walls reinforced with a single WWM in the center of the wall. These walls also serve architecturally to separate habitational spaces. According to the structural drawings, the wire diameter of WWM used for wall reinforcement is 6.5 mm with a spacing of 150 mm in both directions, which are equivalent to a vertical and horizontal reinforcement ratio $\rho = 0.0023$. The specified concrete compressive strength is 21 MPa.

2.1 Description of the nonlinear models

The seismic performance of this building is evaluated considering a section of the X direction (Fig.2). This section is comprised of four walls, which characterize a major part of the building lateral force resisting system in the X direction.

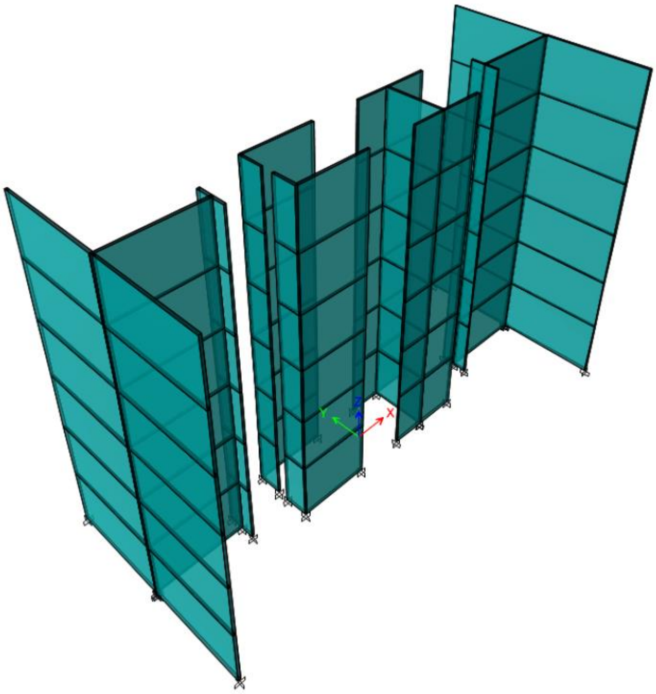

Fig. 2 - Building section used for nonlinear analyses

An *OpenSees* model is used to assess the nonlinear response of this section. The walls are modelled using the shear-flexure interaction multiple vertical line element (SFI-MVLEM) [25], with eight panels for the outer walls and six panels for the inner walls. Since the walls are reinforced with a single layer of reinforcement without any confinement, the concrete is modeled as unconfined using the ConcreteCM material, with $f_c' = 21$ MPa, and a strain at peak concrete strength $e_c = 0.002$. For the model with welded-wire mesh, the steel properties are obtained from the tests conducted on local material by Carrillo *et al*. [7], which report an elastic modulus $E = 210GPa$, a yielding stress $f_y = 621MPa$, an ultimate stress $f_u = 687MPa$ and an ultimate strain $e_u = 0.0155$. This last property is the cause of major concerns about the potential lack of ductility of these walls, as well as their seismic performance [7]. For the model with deformed bars, material properties $E_s = 210GPa$, $f_y = 420MPa$, $f_u = 630MPa$ and an ultimate strain $e_u = 0.15$ (10 times higher than that of WWM). Both steel types are modelled using a hysteretic material in *OpenSees*, in combination with the *MinMax* material to account for the fracture after exceeding the ultimate strain. For both models, the foundation is modeled as rigid, and the gravity loads for the model are calculated based on the expected loads and using the combination 1.05 D + 0.25 L. Rayleigh damping was applied to the model, with 2.5% damping to the first and third mode of the structure

These models were subjected to the 44 ground motions of the FEMA P-695 suite [27], which were scaled to 0.25, 0.5, 1.0, 1.5 and 2.0 times the design acceleration for the model with WWM. Two additional factors of 3.0 and 3.5 were included for the model with DB. The inter-story drifts, roof drift, concrete stress and steel strain were recorded during the dynamic analyses. Several failure modes were considered based on these results. Steel failure was considered due to fracture when the recorded strain exceeded the ultimate strain. Crushing of the unconfined concrete was assumed to occur at a strain e = 0.004. In addition, an inter-story drift limits of 0.5% was set as failure limit for the walls in the WWM based on the findings reported by Carrillo and Alcocer [28]. This limit was set to 5% for the model with DB (10 times higher than that for walls with WWM).

3. Seismic performance results

The summary of failure events observed during the incremental dynamic analyses (IDA) for both models is summarized in Tables 1 and 2. Columns 3 to 7 of these tables show the different types of failures observed during the IDA. Column 8 indicates the number of failures observed, regardless of its type.

Table 1 - Summary of failure events for the WWM model

Scale factor	Sa (g)	Steel fracture	Concrete crushing	Drift limit exceedance	Non-convergence of the model	Number of failures
0.25	0.14	0	0	0	0	0
0.5	0.28	3	2	3	1	3
1	0.56	15	3	12	1	15
1.5	0.84	36	4	27	4	37
2	1.13	41	6	39	3	41

Table 1 allows several observations. In terms of failure modes, the results show that fracture of the steel wires is the predominant mode of failure for this building, regardless of the scale factor used for the ground motions. For instance, at the design level (scale factor 1.0), steel fracture was observed in 15 out of 44 records, while concrete crushing was present in 3 records and the drift limit was exceeded 12 times. Some of these failures occurred simultaneously, yet the total number of failures is controlled by the fracture of steel. This pattern is present in all scale factors, suggesting that the seismic behavior of thin RC wall buildings reinforced with WWM, is controlled by steel fracture. This scenario stems from the limited strain capacity of WWM, which previous experimental studies have suggested that should become critical for situations where large deformations are expected [7]. The results of this study support this hypothesis, as the number of failures observed by exceedance of the drift limit is similar to those of steel fracture.

Table 2 - Summary of failure events for the DB model

Scale factor	Sa (g)	Steel fracture	Concrete crushing	Drift limit exceedance	Non-convergence of the model	Number of failures
0.25	0.14	0	0	0	0	0
0.5	0.28	1	1	1	1	1
1	0.56	5	2	6	2	7
1.5	0.84	7	8	9	0	11
2	1.13	9	4	16	5	19
3	1.69	12	13	29	1	31
3.5	1.97	22	14	37	6	38

Table 2 shows that the behavior for the same building detailed with DB differs significantly to that of the WWM. For this building, the predominant failure mode was the exceedance of the drift limit, particularly for higher scale factors. Steel fracture was also observed for this building; however, in a lower degree compared to the WWM building, suggesting that the additional ductility provided by the DB does exert an influence on the seismic behavior. This additional ductility and the thinness walls may explain the number of concrete crushing observed for higher scale factors.

In terms of probabilities of failure, the performance observed for both buildings falls below the acceptable limits. Considering the maximum credible earthquake (MCE) level (scale factor 1.5), failure probability of the WWM building is 84% (37/44), and 25% (11/44) probability for the DB building. Both values are above the 20% limit which the FEMA P-695 [27] has recommended for individual archetype models, suggesting that the buildings have unacceptable seismic performance. The 84% probability for the WWM building demonstrates that the performance expected for this existing building is far from the targets set by current design codes. This is further supported by looking at the 35% probability observed at the design base level.

To further illustrate the differences between the WWM and DB, the results of Tables 1 and 2 were fitted to a lognormal distribution (Fig.3) following the procedure recommended by Baker [29].

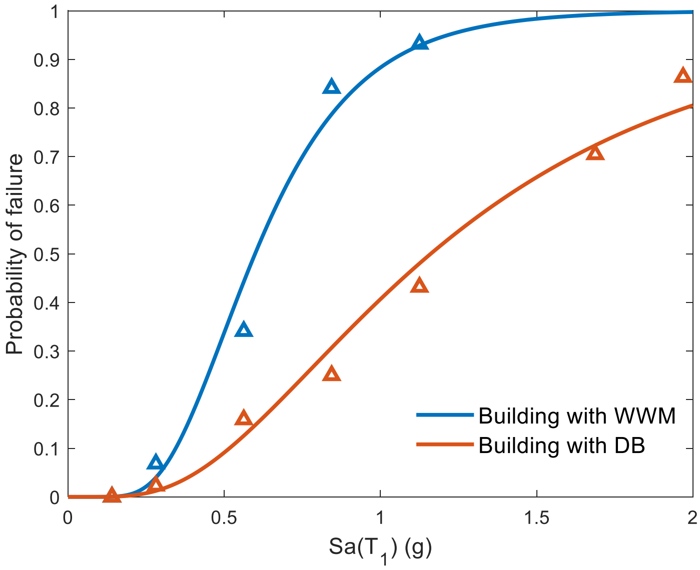

Fig. 3 - Fragility functions for the WWM and DB buildings.

It is apparent from Figure 3 that the expected seismic performance of a building detailed with DB is substantially better than that of the building detailed with WWM. The probability of failure for both buildings is similar for accelerations lower than 0.20g, which correspond to 34% of the design acceleration. Beyond this value, the failure probability for the building with DB is lower than the building with WWM, being less than half at the design level. These results corroborate that using WWM instead of DB for thin wall buildings comes at the expense of reduced seismic performance of the building.

4. Conclusions

The seismic performance of a six-story thin RC wall building reinforced with welded-wire mesh, designed and constructed in Bogotá, Colombia was investigated in this article. The building was designed according to the local design code and its structural configuration is comprised of 100 mm RC walls reinforced with a single WWM on the wall mid-thickness. The seismic performance of the building was assessed thorough Incremental Dynamic Analyses (IDA) in *OpenSees*. For comparison purposes, a benchmark model was created, where the reinforcement is modeled as deformed bars. The results of this study support the following conclusions:

- The seismic performance of the constructed building is outside the target performance of design codes, as it has an 84% probability of failure at the Maximum Credible Earthquake (MCE) level, and 34% when the ground motions are scaled to the design level.
- The dominant failure mode of the building is steel fracture, which occurs because of the limited ductility of the WWM.

- The use of deformed bars instead of WWM brings notable improvements to the seismic performance of the buildings for accelerations higher than 35% of the design earthquake. At the design and MCE levels, the failure probability of the building modeled with deformed bars is 16% and 25%, respectively. For this building, the dominant failure mode was the exceedance of the drift limit.

Overall, the findings of this study support the idea that the use of WWM for the construction of thin RC wall buildings should be limited in zones of intermediate and high seismic demand, as the limited ductility of the WWM exerts a negative influence on the seismic performance, which falls below the acceptable levels. Furthermore, the results also demonstrate that even when deformed bars are used, the expected seismic performance is not acceptable.

Future studies on this topic can be pursued in different areas. One of them is assessing the height limits which should be imposed to this type of building system. Other interesting topic is the determination of the seismic reduction factor (R) that must be used for this type of buildings. Finally, evaluating the seismic performance of a larger building set, with different structural configurations (height, plan configuration) will help to validate the results of this work.

5. References

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