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Improving Seismic Vulnerability of Irregular Reinforced Concrete Moment-Resisting Frames using Shear Walls

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ABSTRACT

Vertical geometric irregular reinforced concrete (RC) buildings are widely used in structural engineering due to their aesthetic appearance and functional characteristics. Indeed, improving their reliability and seismic performance is of crucial interest and has even become a necessity. This research study underlines the importance of using shear walls (SW) as a fundamental means of reinforcement for this type of structure. Twenty models, including ten with SW and ten without SW, of mid-rise buildings with setback irregularity were considered for this purpose, and fragility analyses were carried out, using a non-linear procedure, to highlight the potential usefulness of shear walls for irregular structures. The results of this work clearly indicate that the dynamic behavior and response of buildings have been improved by the use of shear walls. The fragility study reveals that for some cases the damage probability is reduced, with the difference exceeding 13% for the majority of models, and for some cases the differences are highly significant, ranging from 30% to 60%. This shows the benefits of incorporating shear walls into the design phase of irregular buildings.

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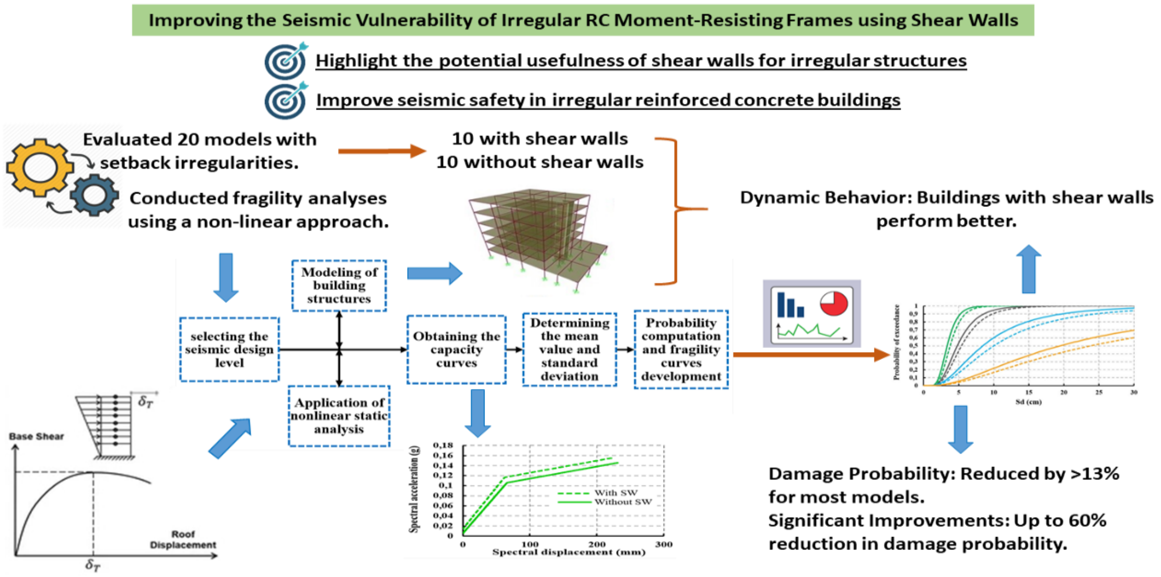
Graphical Abstract



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1. INTRODUCTION

Recently, in the field of structural engineering, the use of irregular building structures has become increasingly common, due to their functional characteristics and aesthetic appearance (1-3). Despite scientific and technical progress in the fields of geotechnics and earthquake engineering, this type of structure has shown a mysterious behavior when subjected to seismic shocks. The earthquakes that have shaken many countries around the world have confirmed that the majority of economic and human losses due to seismic activity result mainly from the defective behavior of building structures.

Structural vulnerability assessment is a fundamental element of modern performance-based seismic design and assessment procedures. Major advances in the development and implementation of fragility functions have taken place over the last three decades. Structural seismic fragility refers to the probability of a structure experiencing failure or reaching a specific failure state during an earthquake (4-7). Understanding the structural seismic vulnerability of structures is crucial for designing and constructing resilient buildings that can withstand seismic events. It helps engineers identify potential weaknesses and implement appropriate measures to mitigate the risk of failure, ensure occupant safety, and minimize damage during earthquakes. Methods for assessing seismic fragility curves differ in complexity, accuracy, and purpose. The choice of method for assessing seismic vulnerability will depend on the quality and quantity of data available, and on the objective, which may be to estimate the seismic vulnerability of a single building or a group of buildings (8). This extensive work reflects, on the one hand, the importance attached by researchers to estimating the damage to different systems and, on the other, the multiplicity of approaches developed. Among the methods listed, the large majority are analytical. Empirical methods also featured prominently in these studies.

In this context, empirical seismic vulnerability has been widely applied worldwide to assess seismic vulnerability and risk for different structural systems. Li and Gardoni (9) have studied the impact of multidirectional seismic sequences, updated the instrument intensity calculation model, and proposed a quantitative method taking into account hybrid intensity measurements to assess the vulnerability of building groups. Also, research studies conducted by Li and his coworkers (5-7, 10-12) have shown the importance and interest of assessing the vulnerability and resilience of structures on the basis of empirical studies.

Ultimately, it can be contended that the choice of the most appropriate procedure depends on the resources available for data collection, the computational expertise available, and finally the scale and objective of the study. In this research work, to estimate the seismic vulnerability of irregular building structures, the analytical approach was chosen to determine the seismic response of the structure through a non-linear static analysis.

The seismic reliability of buildings under seismic actions is greatly affected and the vulnerability of the building to damage caused by ground motions becomes more significant, particularly for building systems with structural irregularities. Therefore, it is interesting to focus on the response and behavior of these structures in seismic conditions. This need has aroused the interest of scientists in this field, and for decades there has been a steady stream of research aimed at developing seismic design methodologies to better understand the dynamic behavior of irregular buildings and to reduce their consequences. Over the past few years, many researchers have studied the influence of setback irregularity on the dynamic response of RC building. They have used the concept of fragility analysis to carry out both static and dynamic analyses. Among these studies, Ruggieri (13), Praveen and Gopikrishna (14) Azad et al. (15), Shojaei and Behnam (16), Ruggieri et al. (17, 18) focused on investigating the local and global performance of setback RC buildings designed according to different international standards. According to the researchers, the geometric irregularity of structures obviously influences the seismic response of building structures, which has a remarkable effect on the probability of damage of buildings. Likewise, research works conducted by Men et al. (19), Kassem et al. (20), Nazri et al. (21), Kumar et al. (22), Ayub et al. (23), Mouhine and Hilali (24, 25), El Janous and El Ghouloubzouri (26), Hashim and Ali (27) show that the presence of irregularities in the structural configuration affect significantly the performance and the dynamic response of reinforced concrete buildings during the seismic excitation. In construction engineering, the use of shear walls is a highly functional alternative for improving the resistance of structures to lateral and gravity loads. Shear walls are essential for achieving very good performance under extreme load conditions (28). Also, shear wall systems offer greater lateral rigidity to effectively reduce displacement and maintain the structural integrity during earthquake events (29).

This work's main purpose is to investigate the contribution of shear wall-resisting systems to enhance the seismic reliability of vertical geometric irregular buildings. Storey displacement, an important indicator of structural performance, is used to assess how this solution works to minimize the storey displacement and limit building drift ratio. Moreover, structural capacity and fragility curves will be investigated to determine how successfully the shear wall system dissipates energy and resists to seismic consequences.

The outcomes of this research work provide substantial practical benefits for setback building structures design in seismic regions. This research explores very useful perspectives for the selection and improvement of building systems to assure the structural integrity and resilience of structures exposed to dynamic loads by contrasting the dynamic behavior of irregular buildings with and without shear wall systems. Understanding the benefits and drawbacks of these systems will also contribute to advancing earthquake design procedures and facilitating informed decision-making.

In summary, this research study highlights how crucial it is to consider the importance of using shear walls system to improve the dynamic behavior of irregular RC structures. Additionally, the study intends to expand knowledge of the role and performance of shear walls for irregular buildings by conducting a rigorous analysis. As such, researchers and practitioners involved in structural design and rehabilitation are likely to benefit considerably from the results of this research work.

2. MODELING AND METHODS

2. 1. Building Structures Description and Modeling

In the present study, twenty models of six-storey moment-resisting reinforced concrete frames are selected, including 10 models with shear walls, as illustrated in Figure 1. These configurations represent mid-rise residential building structures. The selected models are located in Agadir city in Morocco which is qualified as a high seismic risk region according to the Moroccan standard. The studied buildings have a total height of 18 meters, with six floors, and each floor height of 3 meters. These building models have a plan area of 300 meters square and an identical plan dimension of 20m × 15m with five bays in the longitudinal direction and three bays in the transverse direction. The dimension of the beams and columns of the structure has been taken at 200mm × 400mm and 400mm × 400mm, respectively with a reinforcement bars of 3T10 + 3T14 for beams and 8T16 for columns. The shear walls have a thickness of 200mm with T12 reinforcement bars in both directions. The slabs are 150mm thick, supposed to be rigid, and support their self-mass as well as additional loads of 2.5 KN/m² for live loads (LL) and 1.5 KN/m² for dead loads (DL). The combination (DL) + 0.2 (LL) is used to take into account the structure's weight according to RPS2000. In this work, seismic analyses were carried out using a FE program (30). The studied configurations are modeled as 3D models including the modeling of all building components such as slab, beam, column, shear

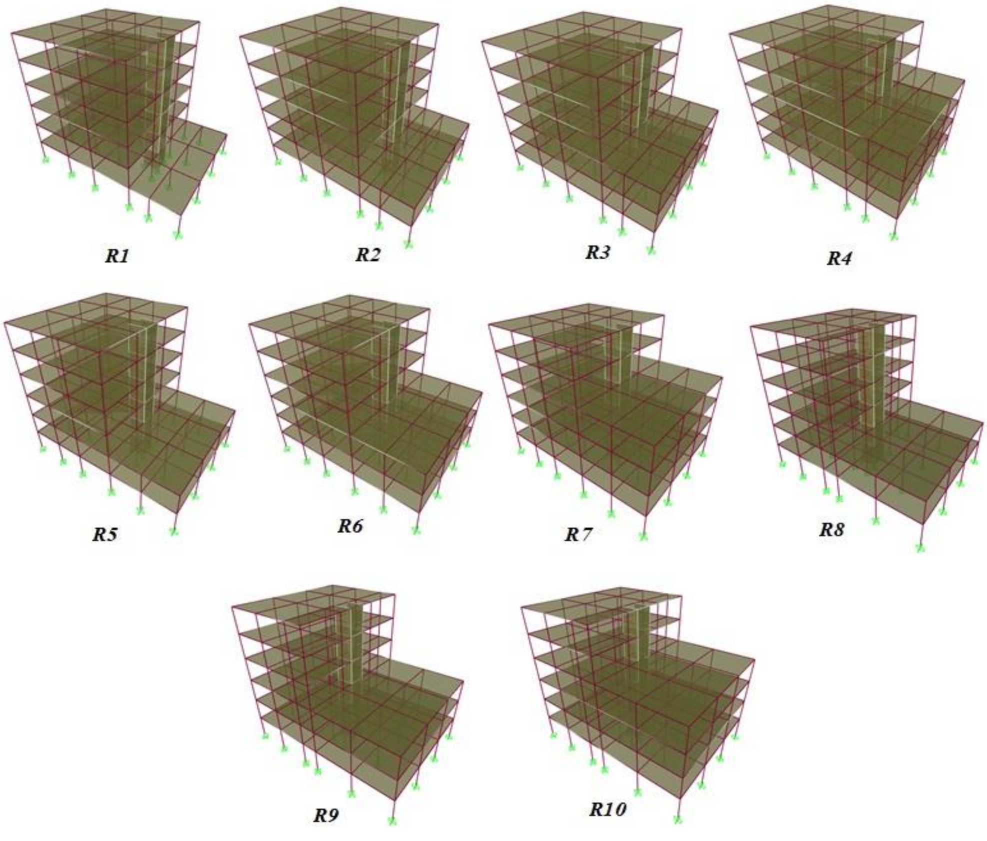


Figure 1. Configurations of building structures with shear walls

wall, and boundary conditions. Strong-column weak-beam concept is used to reduce significantly the probability of collapse (31). Nonlinearities are considered in structural elements by defining plastic hinges in beams and columns (32-34). For the materials used in the building construction, the concrete is class C25/30 with a characteristic compressive strength of 25 MPa. Tensile strength and modulus of elasticity are calculated in accordance with European standard (EC2) (35). The reinforcement bars have a yield strength of 400 MPa and a Young modulus of 210000 MPa. The bars are spaced following the constructive dispositions specified by EC8-2004 (36).

2. 2. Concept of Fragility Curves

The reliability of irregular reinforced concrete buildings under seismic shaking is an interesting topic in the field of earthquake engineering and seismic risk management. The vulnerability of building structures represents their sensitivity to the damage caused by ground motion (37-41). Many researchers used the fragility curves concept to describe the structural damage states occurred in buildings during and after seismic shaking and to assess the probability of damage to the building structures (16, 22, 24, 28). A fragility curve provides an overview of the building's behavior in response to a particular seismic activity. Fragility curves allow to calculate the probability that a structural engineering demand parameter (d) exceeds a specific damage state (ds) based on a parameter defining the seismic intensity chosen as the spectral displacement (Sd) in this study, as given in Figure 2. The curve of fragility is a cumulative lognormal distribution function with logarithmic standard deviation β and mean value γ (42-46). The mean value γ_{dsi} is defined as a function of yield D_y and ultimate D_u displacement of the structure obtained from the capacity curves of buildings. The expressions retained in this research for the calculation of damage state thresholds in accordance to Milutinovic and Trendafiloski (45) are presented in Table 1.

$$P\left[ds_i / Sd\right] = \Phi\left[\frac{1}{\beta_{ds_i}} \ln\left(\frac{Sd}{\gamma_{ds_i}}\right)\right] \tag{1}$$

Φ : normal cumulative distribution function

γ_{dsi} : mean displacement

β_{dsi} : logarithmic standard deviation computation (24, 47)

Figure 3 depicts the strategy employed in the present work to create fragility curves using nonlinear static (pushover) procedure. In this approach, after selecting the appropriate seismic design level, the building structure models considered are modeled using a FE calculation program (30). Then, these buildings sample are subjected to a seismic load to obtain the capacity and the performance of each structure.

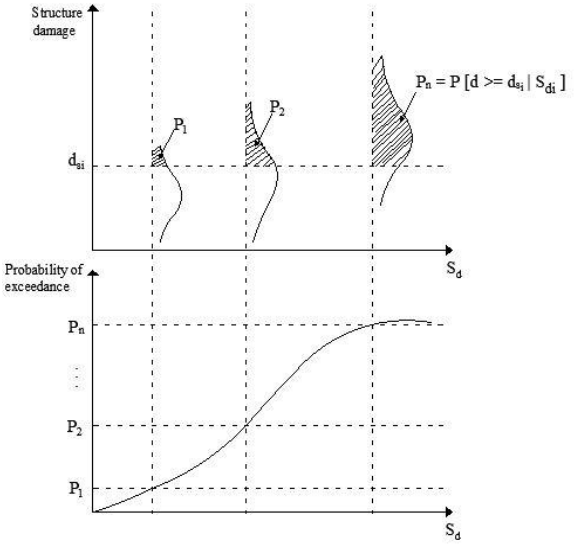


Figure 2. Probability of exceedance

TABLE 1. Mean value formulas [24]

State of Damage	State of Damage Thresholds
Slight damage	$\gamma ds_1 = 0.7 \times D_y$
Moderate damage	$\gamma ds_2 = D_y$
Severe damage	$\gamma ds_3 = D_y + 0.25\left(D_u - D_y\right)$
Complete damage	$\gamma ds_4 = D_u$

3. RESULTS AND DISCUSSION

3. 1. Storey Displacement Analysis

To emphasize the importance of using shear walls, at the design level, on the structural behavior of irregular buildings, Figure 4 illustrates the results obtained in terms of the displacement, corresponding to the different levels of the building, registered from non-linear static loading. The results clearly indicate that shear walls have a significant influence on structural response in terms of storey displacement. In general, story drift is reduced for the case of buildings with shear walls compared with those without, and this trend is almost the same for all the cases considered in this work. Furthermore, for buildings with vertical geometric irregularity at levels 1 and 2 with a percentage setback of 30%, it is interesting to note that the effect of shear walls is minimal, and the maximum

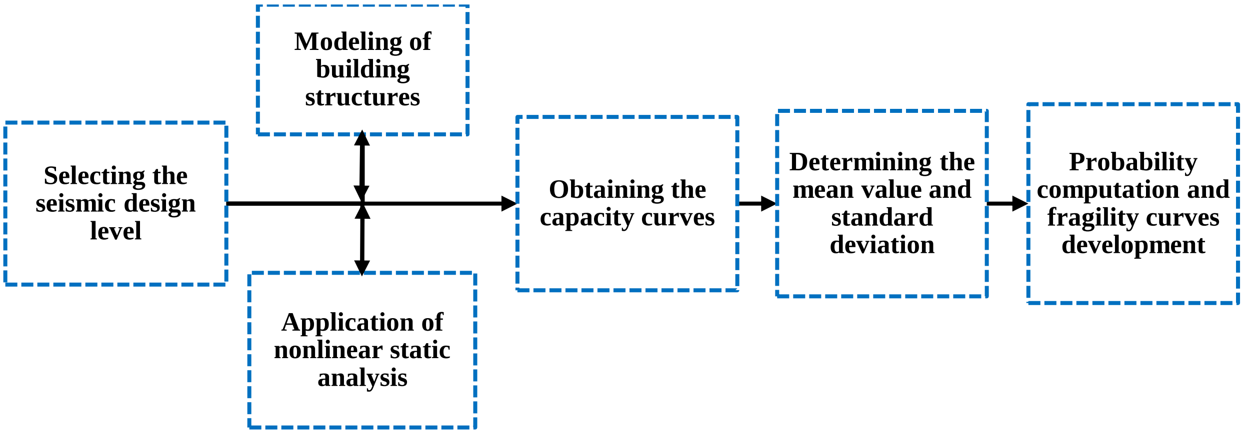
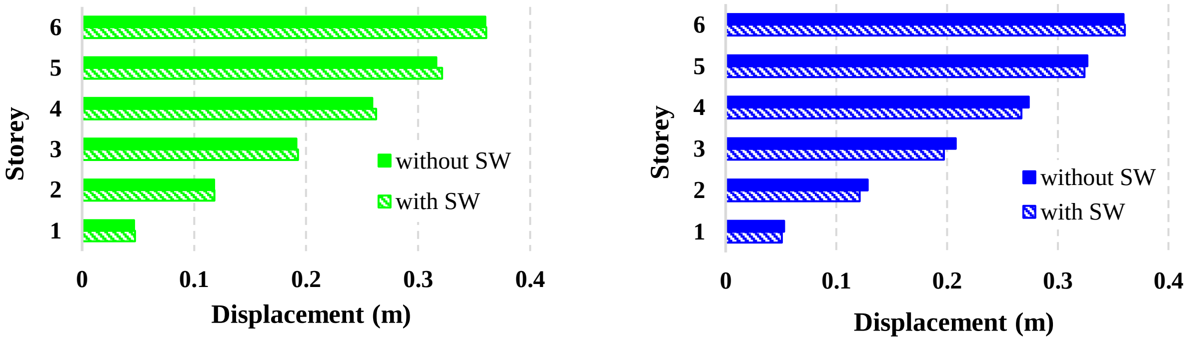
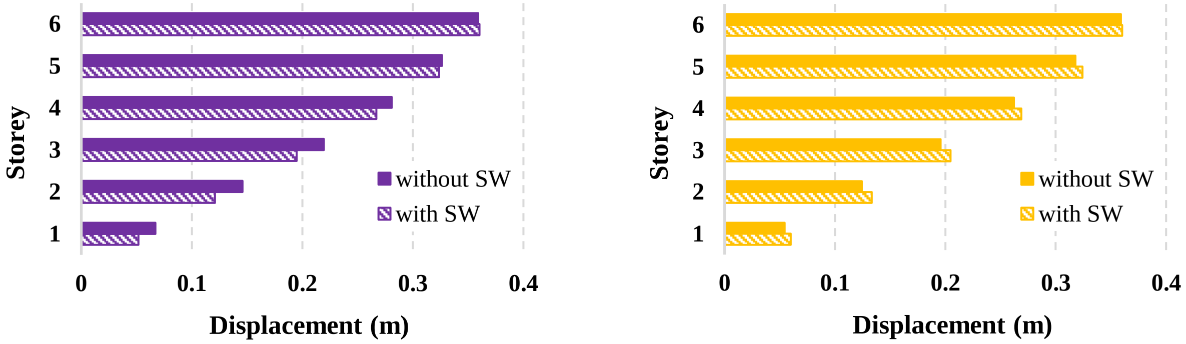


Figure 3. Diagram of fragility curves development strategy



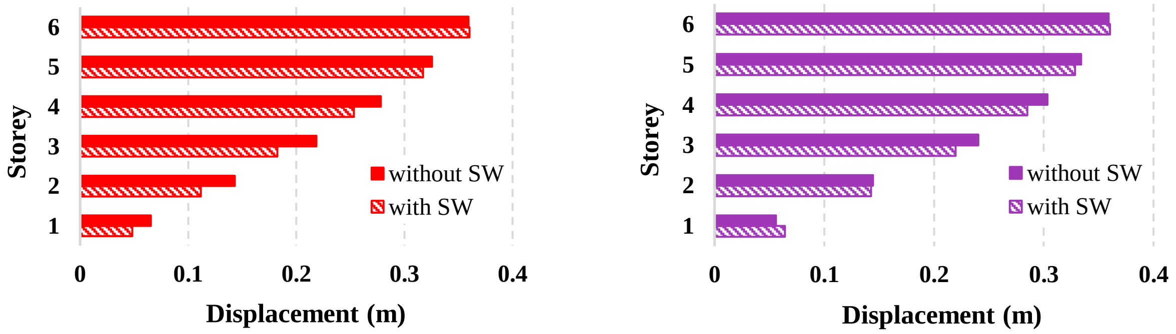
(a) for R1 model

(b) for R2 model



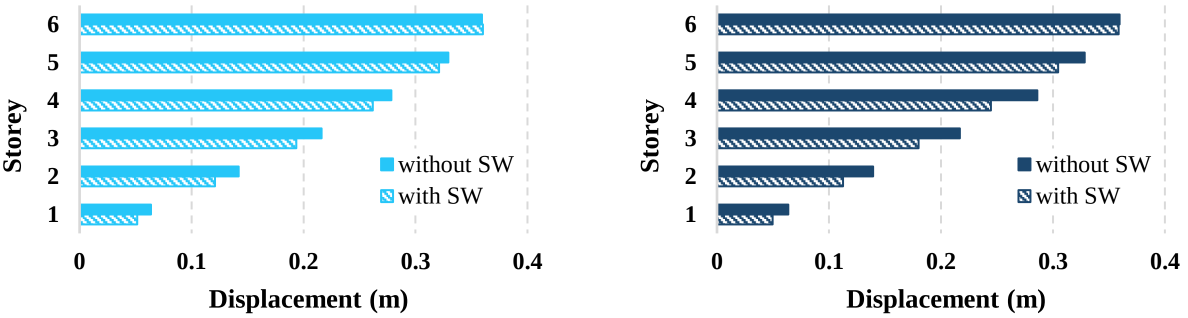
(c) for R3 model

(d) for R4 model



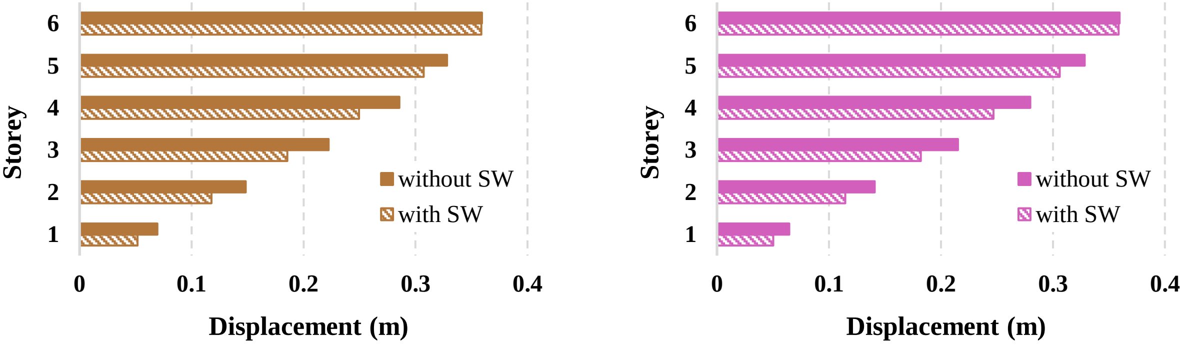
(e) for R5 model

(f) for R6 model



(g) for R7 model

(h) for R8 model



(i) for R9 model

(j) for R10 model

Figure 4. Storey displacement of building structures

deviation does not exceed 2.32% and 3.75% recorded for the case of models R1 and R2, respectively. For the other cases studied, the analysis indicates that the improvement in building response is significant and the influence of shear walls is remarkable, particularly for building models with relatively large setback values, between 40% and 50%, where the deviation can reach values of 15% to 25%, as in the case of R5, R7, R8, R9 and R10 models.

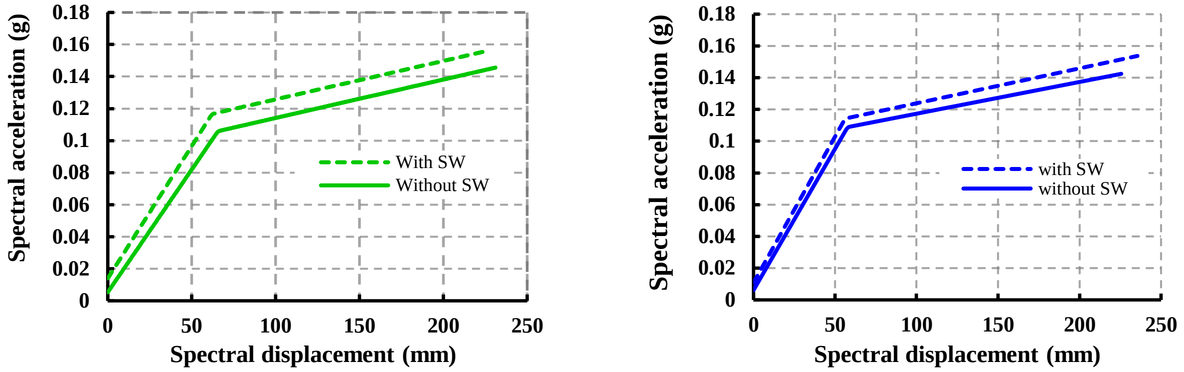
3. 2. Analysis of Building Structure Capacity

The analysis of the dynamic behavior, using a non-linear static approach, of the building structures considered in this work has highlighted the importance and the effect of using shear walls as an effective means of strengthening and improving the response of irregular buildings under seismic actions. Figure 5 shows the capacity curves, in bilinear form, obtained for all the building models considered in this study. It is clear from these figures that the use of shear walls enhances the response of buildings. This consequence can be explained by the fact that shear walls provide stiffness and strength to irregular structures, thus compensating for the stiffness losses experienced in the case of setback structures due to the reduction in structural elements. The results show that for models R8, R9, and R10, the use of shear walls significantly improved the ultimate capacity of the buildings. The differences registered are about 18.36%, 17%, and 14.36%, respectively. This incidence encourages engineers and professionals to build more resilient buildings while retaining the architectural appearance of the structures. For the other models, the difference remains a little less expressive, with a value not exceeding 9.66% observed in the case of the R4 model.

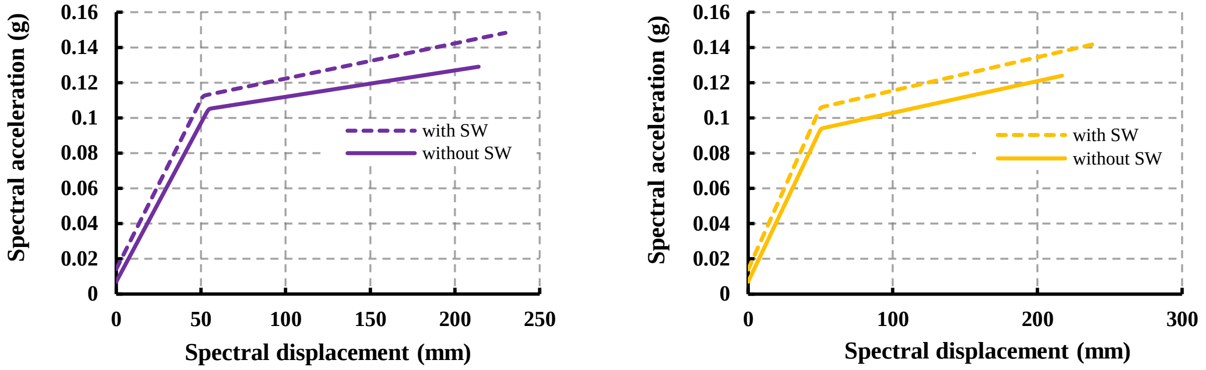
3. 3. Seismic Vulnerability Analysis

In this section, the main aim is to investigate the impact of shear walls on the seismic vulnerability of building structures in the presence of vertical geometric irregularity (setback). For this purpose, seismic reliability analysis of mid-rise buildings is carried out, and fragility curves are generated and compared as shown in Figure 6. The probability of exceeding a particular state of damage is then computed for each building model, and the results are summarized in the histograms shown in Figure 7.

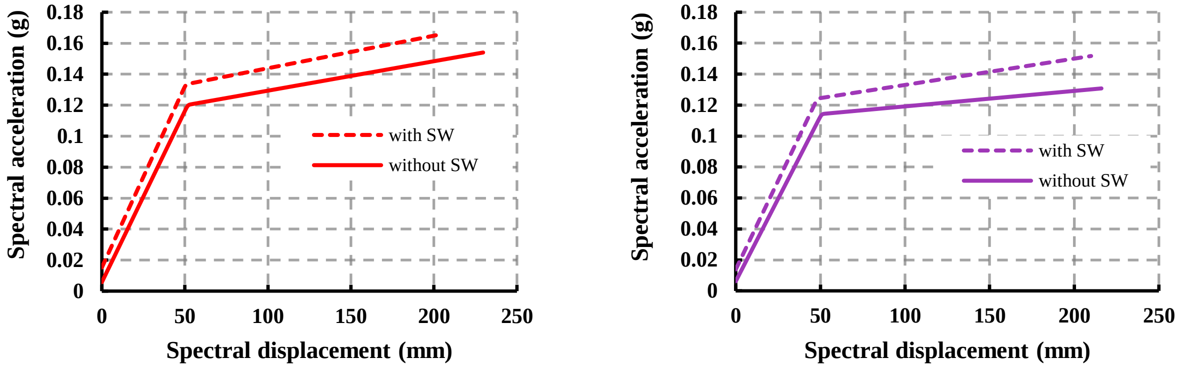
For all the cases studied, it is remarkable that the use of shear walls improves the seismic reliability of buildings, as can be seen in Figure 7. The probability that certain columns and beams near or within the joints suffer cracks due to bending or shear stresses is reduced by 12.19%. This improvement in dynamic behavior of buildings is more pronounced in the case of models R8, R9 and R10, where the percentage rises to 30.72%, 18.07% and 20.66%, respectively. For a moderate damage state, the influence of shear walls on the seismic



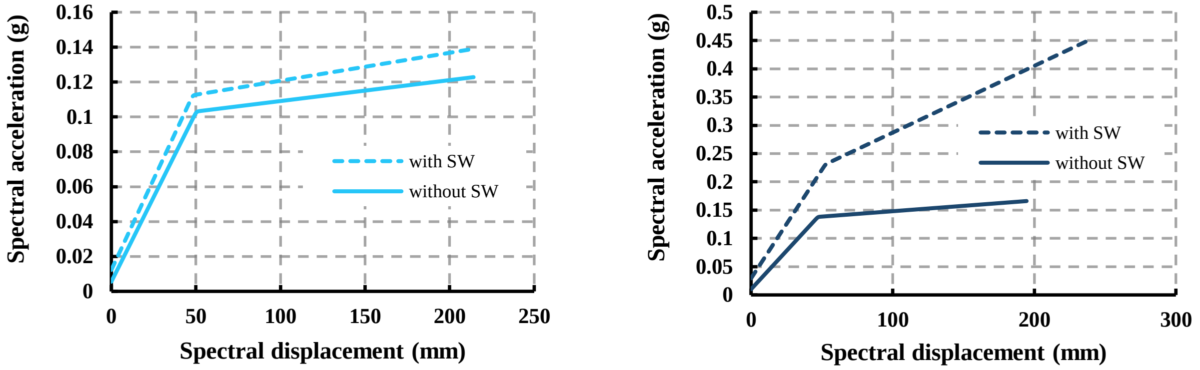
(a) for R1 model (b) for R2 model



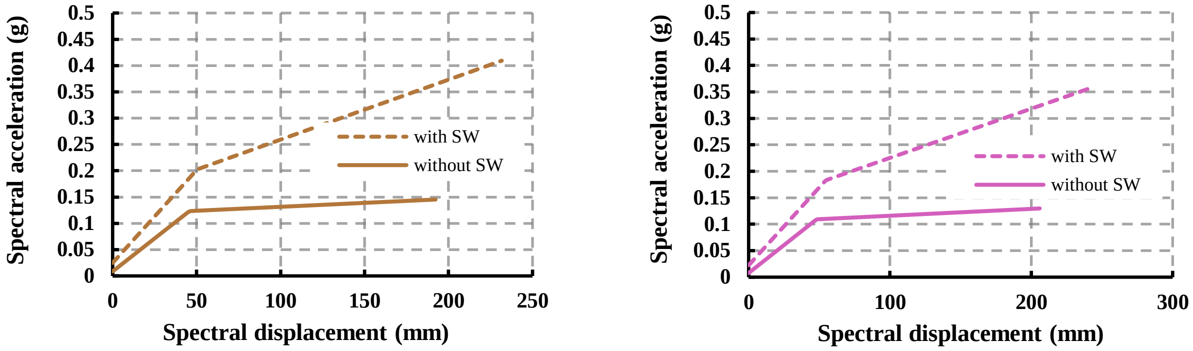
(c) for R3 model (d) for R4 model



(e) for R5 model (f) for R6 model



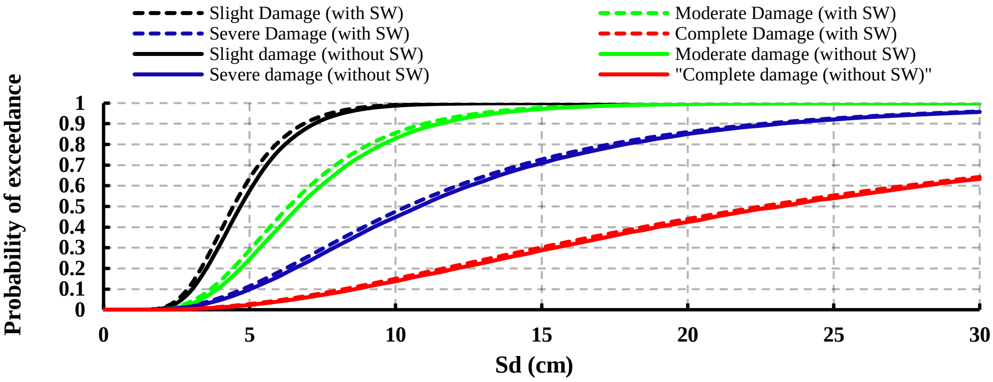
(g) for R7 model (h) for R8 model



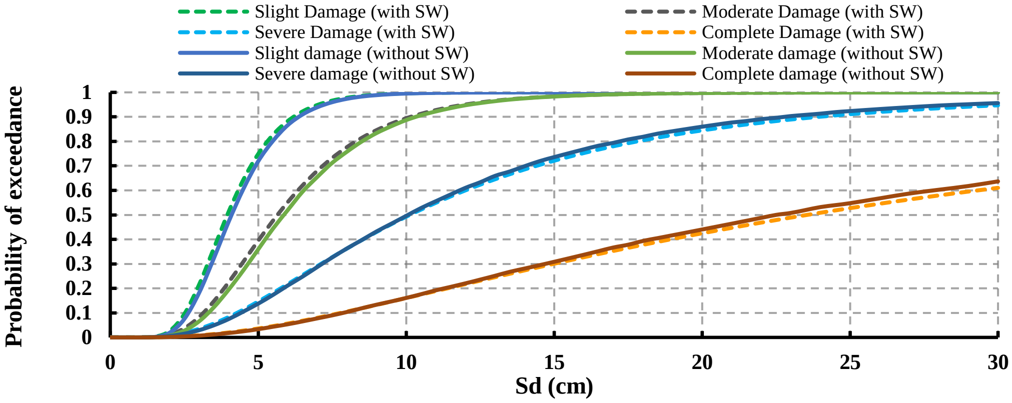
(i) for R9 model

(j) for R10 model

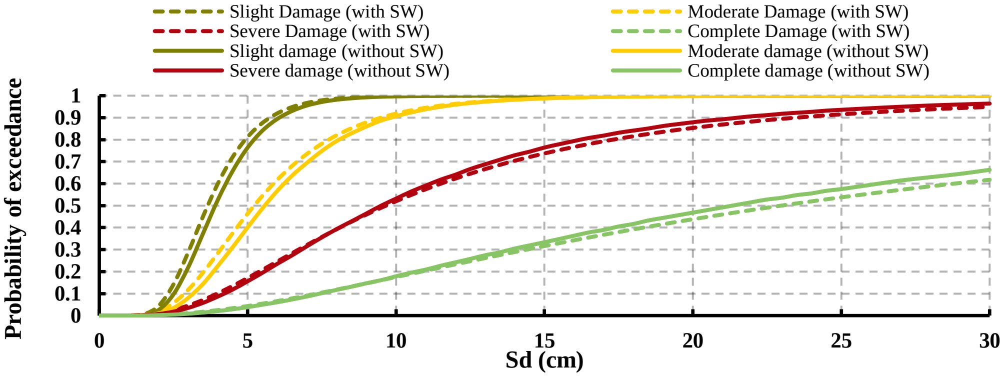
Figure 5. Capacity curves of building structures under consideration



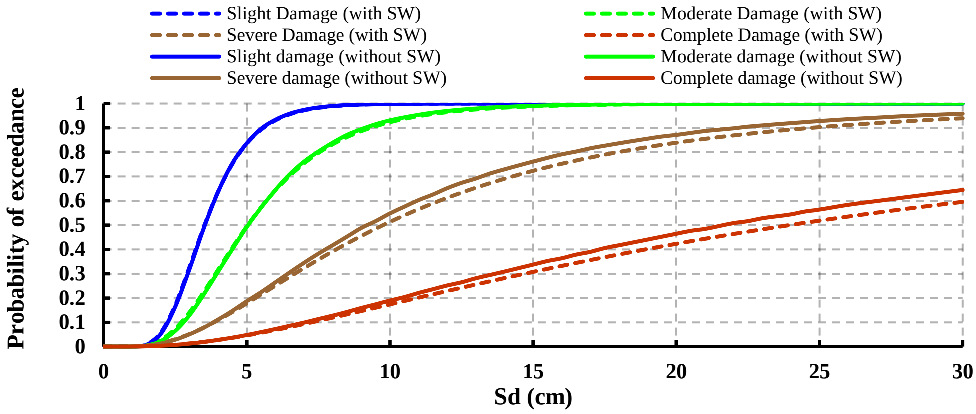
(a) for R1 model



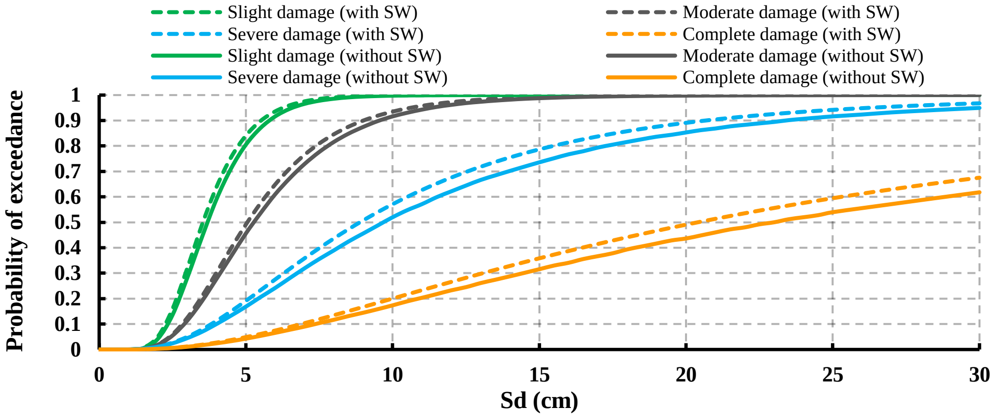
(b) for R2 model



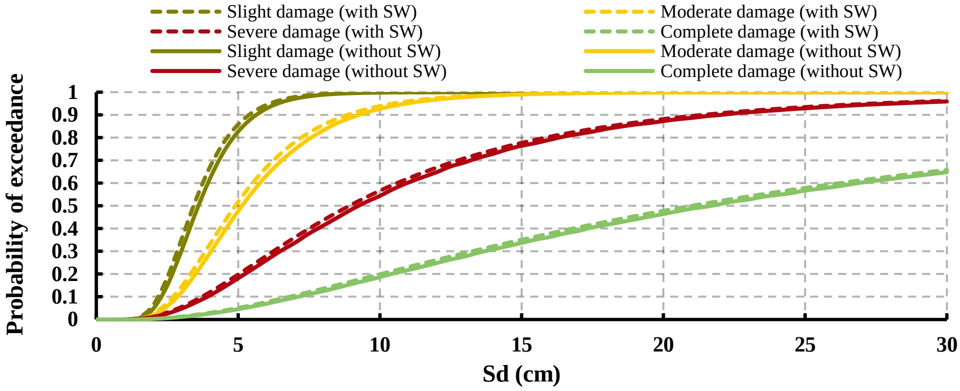
(c) for R3 model



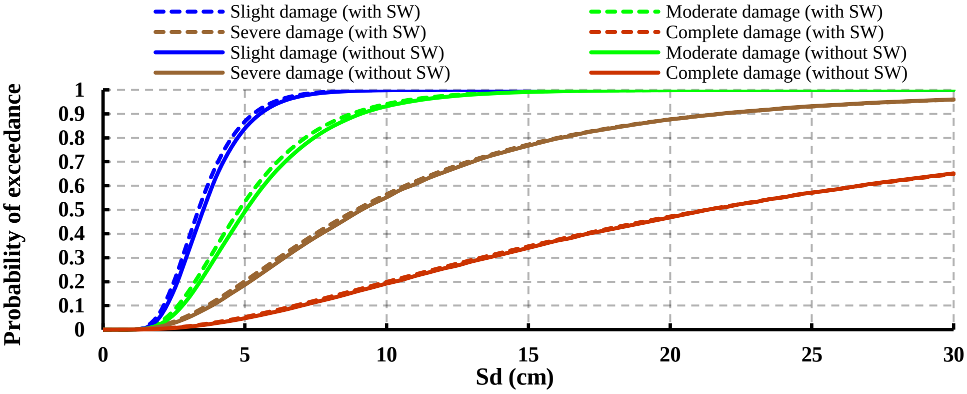
(d) for R4 model



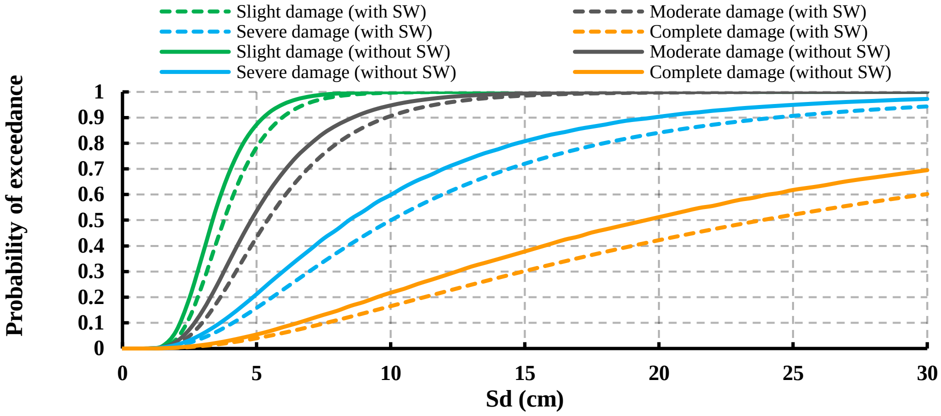
(e) for R5 model



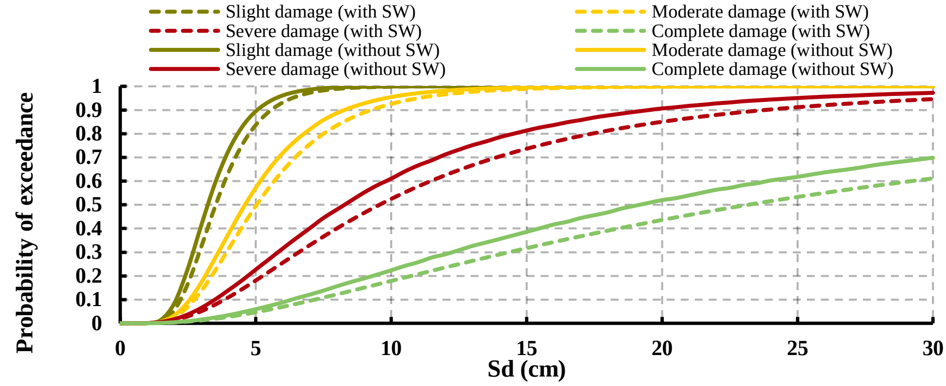
(f) for R6 model



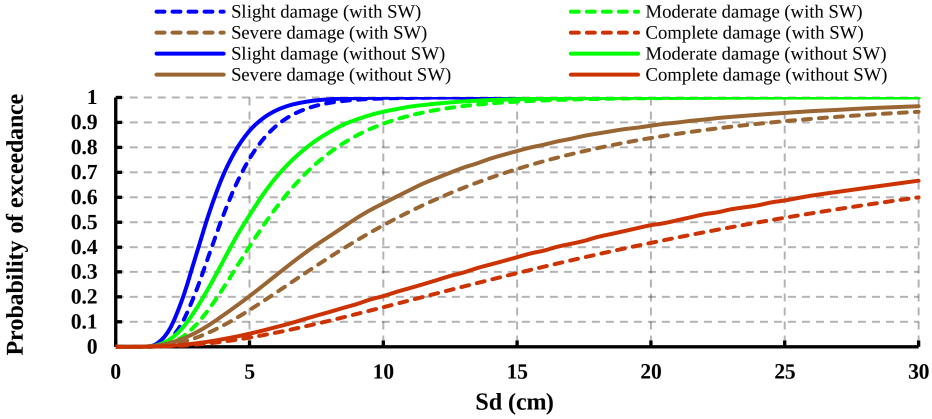
(g) for R7 model



(h) for R8 model



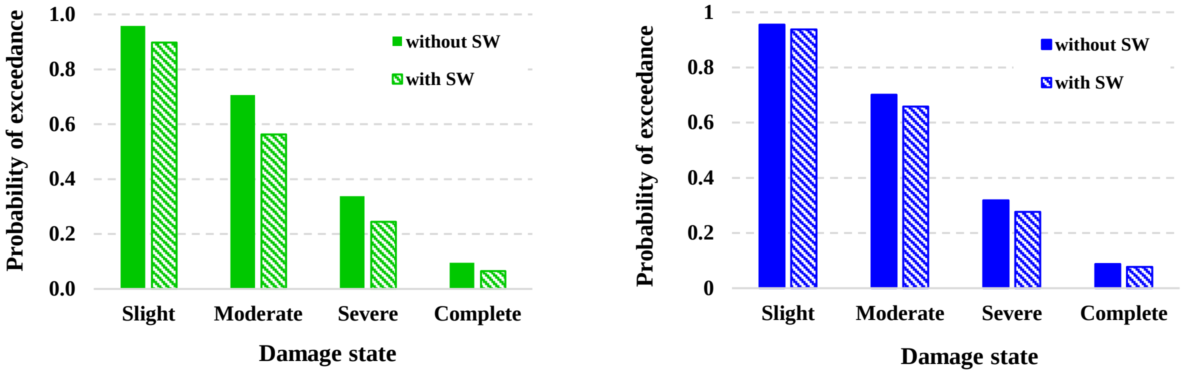
(i) for R9 model



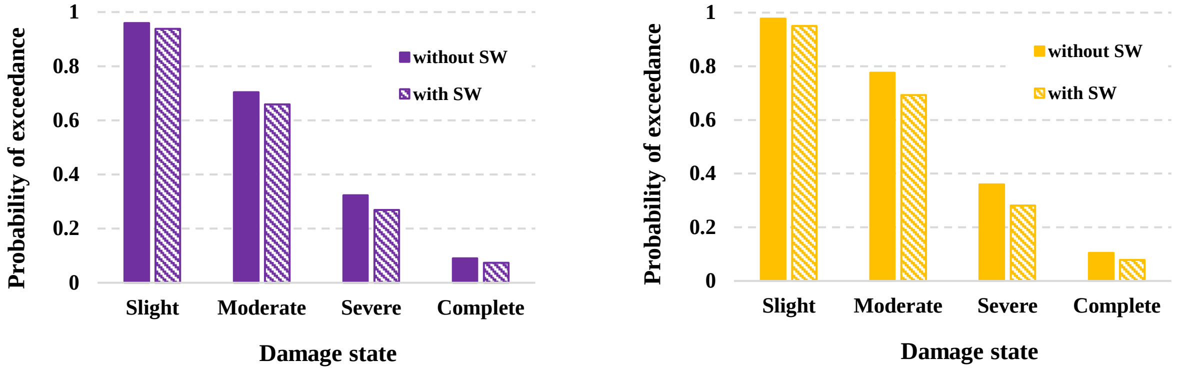
(j) for R10 model

Figure 6. Fragility curves for the studied buildings models

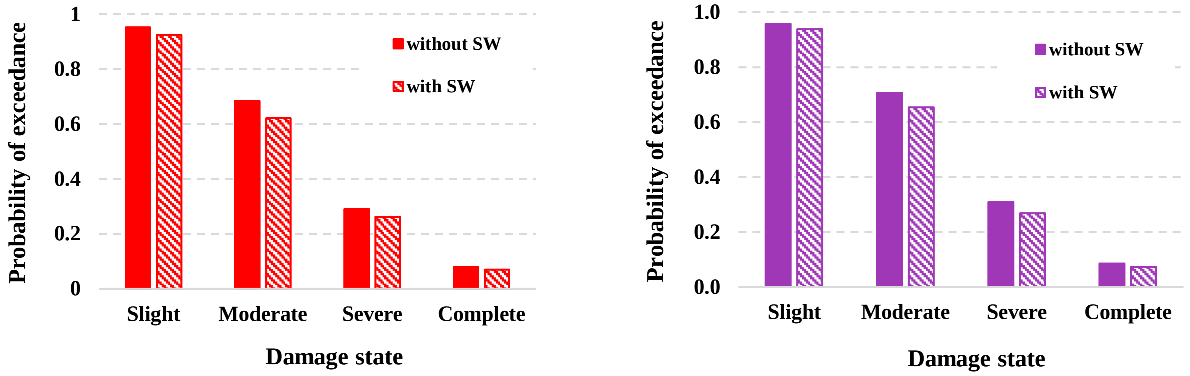
performance of building structure is more apparent. The damage probability is reduced and the difference is about 51.08%, 37.92% and 43.32% for models R8, R9 and R10, respectively. For the other configurations, the difference ranges from 6.02% to 20.26%. Similarly, for a severe damage state, the seismic risk decreases significantly, reaching a value of 58.6% for the R8 model. Considering a complete damage state, the probability of the structure collapsing or presenting a significant collapse risk because of the brittle failure of non-ductile beams and columns elements or loss of frame stability, is reduced to reach maximum values ranging from 63.48% to 54.8% for models R8, R9 and R10. For the other models studied, the differences vary between 13% and 32%. Finally, shear walls contribute, among other things, to the stability of irregular structures by improving their dynamic behavior. The probability of damage is reduced, and the differences can be significant compared to structures without shear walls.



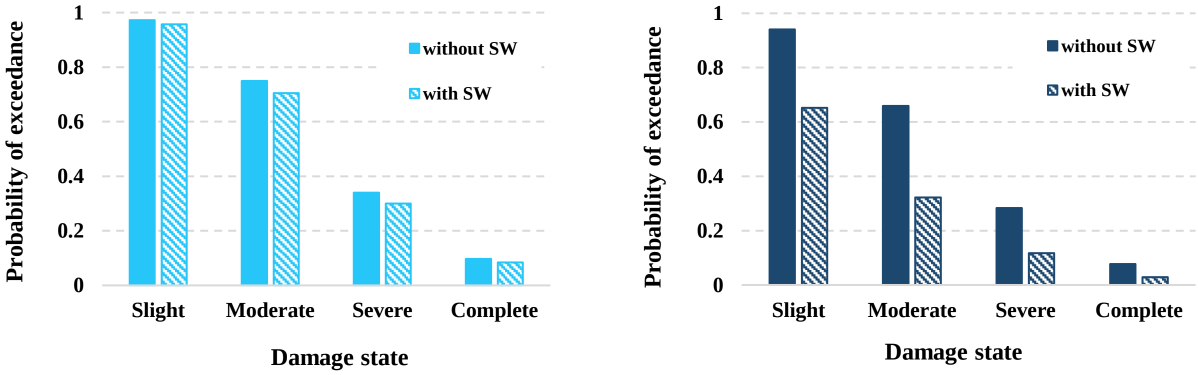
(a) for R1 model (b) for R2 model



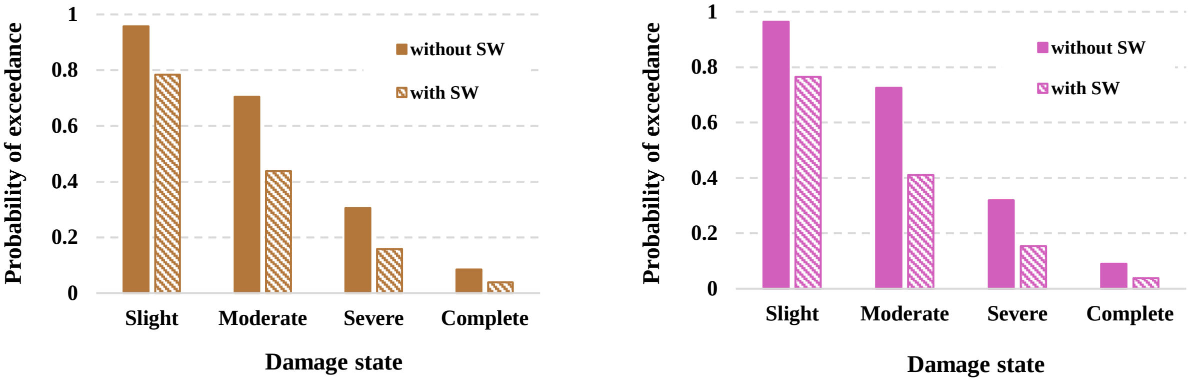
(c) for R3 model (d) for R4 model



(e) for R5 model (f) for R6 model



(g) for R7 model (h) for R8 model



(i) for R9 model (j) for R10 model

Figure 7. Damage probabilities of building structures

4. CONCLUSIONS

This study highlights the importance of using shear walls (SW) as a means of reinforcement to enhance the seismic reliability of irregular RC buildings. The outcomes of this investigation clearly indicate that the capacity of structures is improved when shear walls are used. The difference is about 10% to 18%, which represents a significant deviation that affects the dynamic behavior of these structures. The use of shear walls provides a useful means of compensating losses in stiffness and strength due to the reduction in structural elements. Furthermore, the analysis shows that the vulnerability is highly reduced in the case of building with shear walls, the deviation in terms of fragility is interesting and exceeds 30% for several tested building models. Also, the results indicate that the storey displacement is reduced and the deviation can reach values of 15% to 25% as in the case of R5, R7, R8, R9, and R10 models.

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Persian Abstract

چکیده

ساختمان های بتنی مسلح نامنظم هندسی عمودی (RC) به دلیل ظاهر زیبایی شناختی و ویژگی های عملکردی آنها به طور گسترده ای در مهندسی سازه مورد استفاده قرار می گیرند. در واقع، بهبود قابلیت اطمینان و عملکرد لرزه ای آنها بسیار مهم است و حتی به یک ضرورت تبدیل شده است. این مطالعه بر اهمیت استفاده از دیوارهای برشی (SW) به عنوان یک وسیله اساسی برای تقویت این نوع ساختار تأکید می کند. بیست مدل، از جمله ده با SW و ده بدون SW، از ساختمان های متوسط با بی نظمی عقب افتاده برای این منظور در نظر گرفته شد، و تجزیه و تحلیل شکنندگی انجام شد، با استفاده از یک روش غیر خطی, برای برجسته کردن سودمندی بالقوه دیوارهای برشی برای ساختارهای نامنظم. نتایج این کار به وضوح نشان میدهد که رفتار و پاسخ دینامیکی ساختمانها با استفاده از دیوارهای برشی بهبود یافتهاست. مطالعه شکنندگی نشان می دهد که در برخی موارد احتمال آسیب کاهش می یابد، با تفاوت بیش از 13٪ برای اکثر مدل ها، و در برخی موارد تفاوت بسیار قابل توجه است, از 30٪ تا 60٪. این نشان دهنده مزایای ترکیب دیوارهای برشی در مرحله طراحی ساختمانهای نامنظم است.