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Performance based assessment of reinforced concrete frames designed using eigenfrequency optimization

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Abstract

Reinforced concrete frames (RCF) are a widely used structural system, especially in developing countries due to its economy, its capacity to withstand seismic actions and the availability of materials and construction technologies. Traditionally, these RCF buildings are designed to satisfy drift, strength and ductility requirements given by design codes. Reflecting this ubiquity, there has been a significant interest by researchers to develop efficient seismic optimization methods for RCF. Recently, an eigenfrequency optimization method has been proposed, wherein the fundamental period of RCF structures is minimized, and which has potential to be a practical tool to improve the seismic performance of this system. In this work, performance based earthquake engineering (PBEE) is used to assess the effectiveness of this optimization method for a ten story building. For this purpose, a fiber model of this building is subjected to nonlinear dynamic analyses at different seismic intensity levels, and its results are used to perform a time-based assessment to evaluate the building performance over time. The building's collapse risk, expected annual losses and the expected number of casualties are calculated. Additionally, the design characteristics of this building are investigated, including column-to-beam strength ratios and column shear and moment capacities over the height of the building. The findings show that the method produces buildings that have a more uniform drift distribution along its height, with important reductions in the bottom stories and an increase in the top stories. In addition, it reduces the buildings' susceptibility to collapse and the expected number of casualties. In terms of structural changes, it produces distributions of strength and stiffness more suitable to withstand seismic forces, specifically with stronger columns and beams, and a higher ratio of column moment strength to beam moment strength at the base of the building. All in all, results show that a design approach based on period minimization can produce important impacts on seismic design and performance by increasing stiffness – and strength – at the lower stories, particularly in columns, and distributing damage more uniformly over the height of the building.

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1. Introduction

Reinforced concrete (RC) moment frame buildings (MFB) are widely used in the world due to its economy, their ability to withstand gravitational and seismic forces and the availability of the materials and technologies required for their construction. Due to this ubiquity, researchers have used different optimization frameworks [1] to propose seismic design optimization methods [2-5], which are effective providing solutions to the design problem. Nonetheless, most of these methods are computationally expensive and although significant efforts have been made to improve this [6], [7], they still need considerable time to solve simple problems in consumer-level computers [7]. Additionally, they require knowledge and expertise in areas such as nonlinear modeling of structures which are not common in the professional environment where the design is carried out. Consequently, the adoption of these methods by practicing engineers has been limited, most of which still use the traditional procedure for the design of buildings, where several iterations are performed until code requirements are satisfied.

Recently, the authors have proposed a design approach that aims to provide improvements of seismic performance in RCMFB [8]. This approach uses eigenfrequency optimization and it allows a computationally-efficient and straightforward implementation that can integrate in the workflow of structural design offices. Despite these advantages, this design approach does not explicitly include the seismic performance as a problem constraint, hence its effectiveness cannot be ensured. In this paper, performance based earthquake engineering is used to evaluate this approach. A 10-story building is considered, whose collapse fragility and annualized losses are compared to a traditional design to evaluate the effectiveness of the eigenfrequency optimization approach. Additionally, the effects of using this approach on the design characteristics are investigated, including column-to-beam strength ratios and column shear and moment capacities over the height of the building.

2. Methodology to evaluate the design approach

The effectiveness of the proposed optimization approach is evaluated using a 10-story RC moment frame. The buildings' structural system consists of spatial moment frames, wherein multiple frame lines are designed to resist lateral loads in each direction, with no irregularities in elevation or plan. The story height is 3m, with 6 bays of 5m in the X direction and 3 in the Y direction. The optimized building is compared against a traditionally-designed structure using performance based earthquake engineering (PBEE). PBEE, as developed by the Pacific Earthquake Engineering Research Center [9,10], is a framework for the probabilistic seismic performance assessment of buildings, which has seen several applications for RCMFB in recent years [11-14]

For this purpose, first a "traditional" building is designed using Response Spectrum Analysis for a location in California (37.38ºN, 121.88ºW) with soil type D conditions, with a spectral design acceleration Sa = 0.37g and for residential live load. The building satisfies all requirements of current codes [15] [16] and it is used as a baseline comparison for the optimized counterpart. After that, the building is redesigned following the method proposed in [8]. Finally, the seismic response required for the PBEE evaluation is obtained based on a 2D model created in OpenSees [17], which is used to gather the information required to perform the PBEE evaluation. Beam and columns are modeled using fiber elements with rebar, confined and unconfined concrete. To avoid localization issues, the Constant Fracture Energy Criterion [18] is used with G_{fc} = 180N/mm and with concrete properties f_c = 28MPa, f_{cc} = 33.6MPa, e_c = 0.0019, in the modified Kent-Scott-Park model. Reinforcing steel is modeled using E_s = 210GPa, f_y = 420MPa and an ultimate strain e_u = 0.14 and the hysteretic material in OpenSees. The foundation is modeled as rigid, and gravity loads are calculated based on the expected loads and using the combination 1.05D + 0.25L. P-Delta effects are included with gravity loads are calculated based on the tributary area of the beams. Rayleigh damping is applied to the structure with 3% damping in the first and third modes.

3. Evaluation results for a 10 story RC frame building

The traditional building is designed in ETABS v13.1.2. Columns of 55cmx75cm and beam sections of 35 x 40cm with reinforcement ratios of 1.2% (columns) and 0.93% (beams) satisfy the requirements of the design code at the building site. This design is assumed to be uniform along the building height. For the optimized building, the dimensions are allowed to be in the [35,50] cm and [50,85] cm range for beams and columns, respectively. Further details of the optimization result of this building can be found in [8].

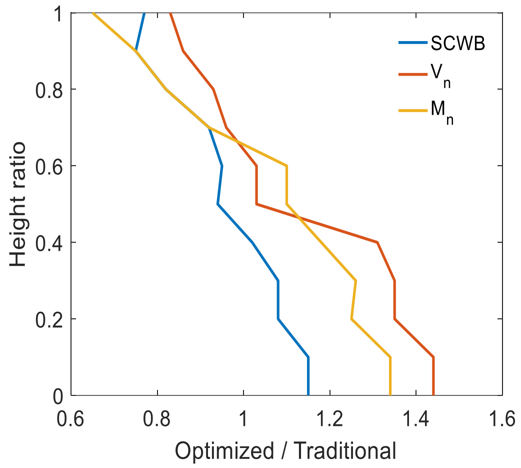

Fig. 1. Impact of optimization on (a) column moment strength, (b) ratio of column moment to beam moment strength and (c) column shear strength over the height of the building. X axis represents the ratio of the parameter between the optimized and traditional buildings

Figure 1 shows how the design changes between the traditional and optimized building over the height of the building, considering column moment strength, column-to-beam moment strength ratio, and column shear strength. A trend is observed for these parameters, wherein the ratio is larger than 1.0 for the bottom stories and it decreases along the building height. Hence, columns in the optimized building have higher ductility and a larger capacity, both in moment and shear strength than its traditional counterparts. Based on these findings, it is expected that the optimized building will have better seismic performance.

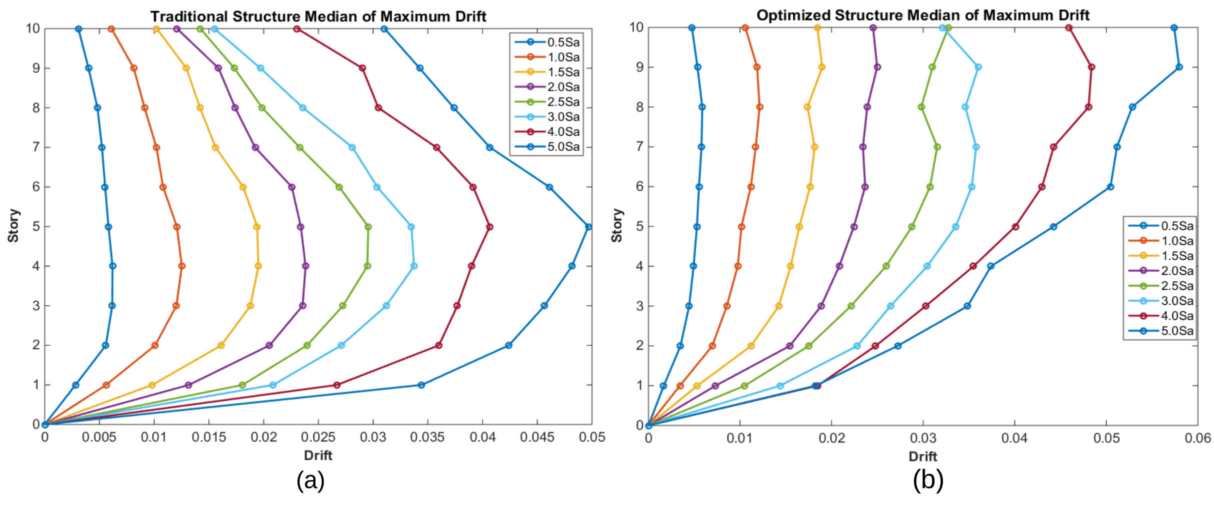

Fig. 2. Median of maximum story drift for (a) traditional building in X direction; (b) optimized building in X direction

The performance evaluation is carried on using the results of nonlinear analysis at eight different intensity levels, multiples of the spectral design acceleration (Sa) and using a set of 22 pairs of ground motions of the FEMA P-695 [19]. The intensity is quantified by Sa(T1=1.7s) where a period of 1.7s is approximately between the period for the traditional building (1.80s) and the optimized building (1.58s).

Figure 2 shows the median of the maximum drift at each story for those ground motions were no building collapse was observed. A more uniform distribution of drift along its height is observed for the optimized building, while in the traditional building, the drift is concentrated in the lower stories. The behavior of the optimized building is preferable, since the bottom play an important role in the structural stability.

For both buildings, collapse was considered to occur when the story drift exceeded 10% [20] and it is calculated at each intensity level as the ratio between collapse records and the total number (i.e. 44). For both buildings, a lognormal distribution is fitted using the maximum likelihood method, as described in [21]. The results in Figure 3 show that for values up to 0.55g both buildings perform similarly, which is expected since both are designed to satisfy code requirements and they should perform well at these levels. For intermediate intensity levels, the optimized building is less susceptible to collapse as a consequence of the more distributed deformations (and damage) along the building height. For high intensity levels, both buildings perform similarly, however, these levels of intensity are very rare and have a low probability of occurrence.

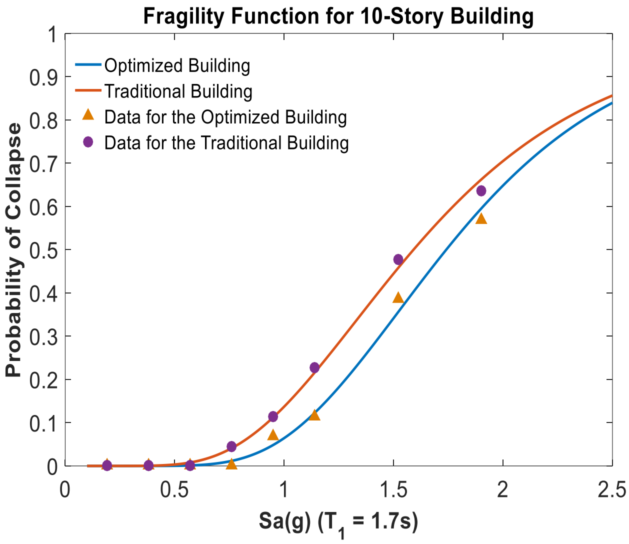

Fig. 3. Collapse fragility functions for the optimized and traditional buildings

For both buildings, the expected annual losses are calculated according to the FEMA P-58 [22] methodology using the SP3 tool [23]. The losses for the optimized and traditional building are US$ 50801 and US$ 51716. Although similar, their disaggregation (Table 1) shows that in the traditional building, collapse and residual drift accounts for 36% of the total loss, whereas in the optimized building this contribution is 27%. In contrast, damage of structural components and partition walls represent 55% of the total loss of the traditional building, and 63% in the optimized one. This is a consequence of the uniform distribution of the drift in the optimized building, which results in an overall greater number of components being damaged in exchange of being less susceptible to collapse.

Table 1. Contributions to expected annual losses for 10-story buildings

	Traditional	Optimized
Collapse	13%	9%
Residual drift	23%	18%
Structural components	25%	28%

Partition walls	30%	35%
Other	9%	10%

The expected number of casualties is summarized in Table 2. A significantly lower number of expected casualties is observed for the optimized building, especially for those intensity levels which are more relevant from a practice perspective. Moreover, the difference is larger for those intensity levels with a larger probability of occurrence and which are more relevant from a practical perspective. These results show that the design approach is effective to produce buildings are better at safeguarding people's lives.

Table 2. Expected casualties for the 10-story buildings

IM level	Traditional	Optimized
0.5Sa	0	0
1.0Sa	0	0
1.5Sa	0.4	0.1
2.0Sa	2.2	0.6
2.5Sa	5.8	2.3
3.0Sa	11.1	5.9
4.0Sa	23	16.6
5.0Sa	32.5	27.1

4. Conclusions

In this study, the PBEE framework has been used assess the effectiveness of a seismic design approach that uses an eigenfrequency framework and minimizes the fundamental period of buildings. A 10-story RC moment frame building is optimized and it is compared to traditional (non-optimized) one in terms of the seismic behavior and its consequences. Additionally, the effects of this design method on the structural design were investigated.

Compared to a traditional building, which in the customary practice has the same beam and column dimensions for all stories, structural design is changed as a result of the optimization. In the optimized building, the bottom floors have column dimensions up to 20% larger in the cross section area, with beam height being also slightly increased. Owing to these changes, beam-column strength ratios are increased at these stories. These dimensions are gradually reduced with the building height and in the topmost stories, the optimized building have columns with 25% smaller cross-sections and beam height is reduced by 5 cm compared to the traditional building.

The seismic response of the optimized building has a more uniform distribution of the interstory drift along the building height. In contrast, for the traditional building, major concentrations of drift are observed in the bottom stories. As a result of this, the collapse fragility of the optimized building is improved compared to the traditional buildings. The annual expected losses from seismic damage are similar for both buildings. However, due to the uniformity in the interstory drift, a higher contribution to losses comes from the structural components and partition walls in the optimized building. As a consequence of having a larger collapse fragility, the traditional building has bigger losses associated to the building collapse.

All things considered, the proposed design approach brings significant benefits over the traditional buildings, demonstrating the potential advantages of minimizing the fundamental period of reinforced concrete frame buildings in the design process.

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