Seismic Response Optimization of RC Slabs: Influence of Opening Location, Size, and Geometry on Structural Performance

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Abstract

In this research, the influence of the location, area and shape of the openings on the seismic behavior and performance of the concrete slab roof was evaluated and studied using the finite element numerical method, and recommendations were given for the optimal design. In order to model and analyze slab samples and perform parametric studies, ABAQUS software was used in this research. Studies were carried out based on different parameters such as different positions of the opening in the slab, the placement of the opening in the corner-side-center of the slab, different ratios of the area of the opening to the area of the slab, to be less than and more than 50% and finally different forms of the opening. In order to evaluate the seismic behavior of the slab, the time history dynamic analysis method was used based on the Tabas (Iran) earthquake record. The results of the analysis showed that for the opening located in the corner and on the side of the slab, the conditions were critical, and for the opening located on the edge of the slab (side of the slab), the conditions were more critical. Also, the results showed that the presence of an opening on the side of the slab increased the energy, force and shear caused by the earthquake to at least 40% compared to other positions of the opening in the slab, and as a result, the most critical conditions related to the placement of the opening in the slab It is considered the edge of the slab. Also, the results of the analysis showed that in the case where the opening surface is more than 50% (slab with a large opening), the condition of the slab's vulnerability is lower, but the maximum energy of the slab with a larger opening is always up to 60% more than the slab with a small opening. Of course, this energy level is related to the early times of the earthquake, and finally, the high ductility of the slab with a larger opening can include better seismic behavior and performance of the slab. Finally, the results of the analysis showed that circular and oval openings and, in general, openings with curved and non-sharp corners have better seismic conditions and performance and experience lower energy values. Trapezoidal opening has better conditions in irregular trapezoidal slabs and square opening has the highest amount of energy among different opening shapes, which is not desirable.

Keywords- concrete slab, seismic performance, finite element method, ABAQUS software, dynamic time history analysis.

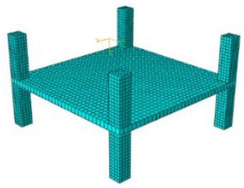
I. INTRODUCTION

In a simple way, a concrete slab roof is a type of building roof that is made using materials such as concrete and steel. These roofs are usually used in the floors of different buildings, and their thickness can vary from 10 to 50 cm [1]. Today, the construction industry has developed significantly due to the rapid development of technologies and has become much more advanced compared to the past. In building construction, it is possible to use all kinds of concrete slab roofs, block beams, steel decks, chromite beams, waffles, Uboot, movable, false, composite, Tierdal, Kubiax, pre-tensioned, impact arch, Rufix, Siak, etc. [2]. Each of these roofs can have its own advantages and disadvantages and can be used in different projects. The concrete slab roof is one of the most popular and practical building roofs, which has received special attention and has many advantages [3]. As mentioned, the concrete slab roof is a type of building roof that is made using materials such as concrete and steel. These roofs are usually used in the floors of different buildings and their thickness can vary from 10 to 50 cm. In recent years, concrete slabs have received a lot of attention, and it is even possible to create curved concrete slabs, which can be particularly beautiful and attractive. One of the most important applications of concrete slabs is building roof and floor, foundation construction, balcony construction, tunnel construction, bridge deck construction, road paving, sidewalk and pavement construction, etc. [4]. Concrete slab roofs can be divided into one-sided and two-sided categories based on the type of function. If the ratio of the length to the width of the slab is less than 2, then the slab is double-sided, and if this ratio is greater than 2, the slab will be one-sided. Each type of concrete slab roof can have special features and be used in different projects. Based on the execution method, concrete slab can be divided into 6 categories, including simple flat slab, tiered system, mushroom flat slab, mesh flat slab, hollow flat slab and pre-tensioned flat slab [5]. Concrete slabs in terms of economy and final cost - rigidity and resistance to incoming loads, especially earthquake loads - integration with the structure and proper connection with it and as a result appropriate seismic behavior and performance [6] as the best option especially for the building medium and high, but unfortunately, it is less noticed and used, the main reason of which is the traditional and incorrect attitude of the public and employers regarding economic issues and implementation challenges, reinforcement and molding of concrete slabs, which are professionally and engineering wise It is not justified in any way and it is always recommended to use a concrete slab roof as the best option for all buildings with any number of floors, as we see in developed countries [7]. The design and implementation of concrete slabs is a kind of specialized and so-called completely engineering work and requires high experience and knowledge both in terms of design and implementation and supervision, and perhaps one of the reasons for the lack of acceptance of this roof system is that It is considered a weakness in the country, and most employers and builders in the private and personal sector tend to use beam and block roofs, while in most developed countries, the use of beam and block roofs is somehow rejected [8]. It is considered that the issue of openings (staircases, elevators, patios, etc.) is inevitable in roofs, and their position, number, dimensions, as well as their shape, both regular and irregular, and in general, the percentage of the area of the openings The total area of the slab has a very important role on the strength of the concrete slab, which is especially important in terms of seismic and safety and seismic resistance [9]. Unfortunately, despite the very high quality of performance and seismic behavior of concrete slabs, the seismic analysis and design of slabs are not specially considered in the designs, and even with the existence of specialized software such as SAFE, the slab design is still correctly and completely The dimensions and conditions governing the plan are not evaluated, which will lead to very unfavorable consequences in the future, and will cause the need for retrofitting and spending high costs. which otherwise will result in loss of life and adverse and irreparable consequences [10]. What is considered in this research is to evaluate the effect of the position, surface, shape and dimensions of the openings on the seismic behavior and performance of the concrete slab roof and to determine the optimal design based on which the effect of different parameters on the position of the opening - the ratio of the dimensions of the opening to the dimensions of the slab (or the ratio of the area of the opening to the total area of the slab) and the shape of the opening will be considered. For this purpose, for a slab sample with specific dimensions and for different positions of the opening in the corner - middle - side of the slab and different percentages up to more than 50% of the slab including the opening and different geometric shapes of the opening under the lateral load of the earthquake based on the finite element numerical method And by using ABAQUS software, it is studied parametrically so that in addition to investigating the effect of the mentioned parameters on the seismic behavior and performance of the slab, the conditions and optimal design among the studied designs can be evaluated and determined.

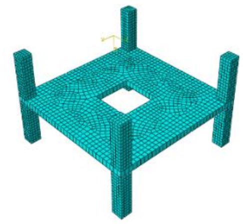
II. RESEARCH METHOD

The research methodology was developed to systematically examine how variations in opening location, opening-to-slab area ratio, and geometric shape influence the seismic behaviour of reinforced concrete slabs under strong ground motion. The numerical modelling framework was established in ABAQUS, where a representative flat slab system measuring 5 m × 5 m with a thickness of 200 mm was constructed. The 400 mm reinforced concrete column stubs above and below the slab plane supported this slab, which is a typical half-story arrangement found in multi-story RC buildings. Three-dimensional solid continuum elements were used to describe the structural components, which allowed the simulation to more accurately represent shear deformation, localized cracking, and through-thickness stresses than shell-based idealizations. Figure 1 displays the whole set of slab configurations that were investigated in this work, including slabs with openings in various positions, slabs without openings, and slabs with openings of different shapes and surface ratios. This list of geometrical changes serves as the basis for the parametric analysis carried out in this study [11].

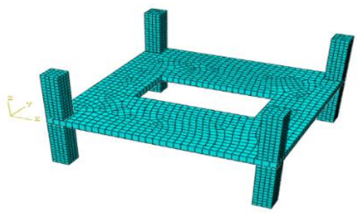
The damage-plasticity constitutive model was utilized to define concrete material behavior, which represents tensile cracking, compressive crushing, stiffness degradation, and nonlinear softening during seismic loading. The bases of the column stubs were fixed in order to avoid artificial boundary stiffness, while the slab edges were left unrestrained to develop realistic deformation patterns under lateral excitation. The analysis involved sequentially applying two load stages: first, the application of gravity loads consisting of slab self-weight and superimposed dead load, allowing a stable initial state, and second, imposing seismic loading through the use of the Tabas (Iran) ground-motion record as indicated in figure 2, known for strong long-period content and capable of mobilizing both flexural and shear mechanisms. The seismic input is imposed in a nonlinear time-history analysis format to track the entire evolution of stress redistribution, stiffness degradation, and dynamic amplification effects.



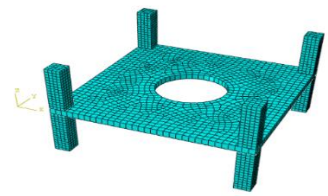
Slab without opening



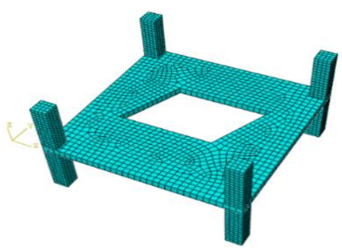
A slab with a square opening in the center of the slab



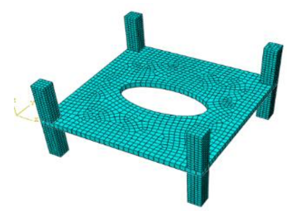
A slab with a rectangular opening in the center of the slab



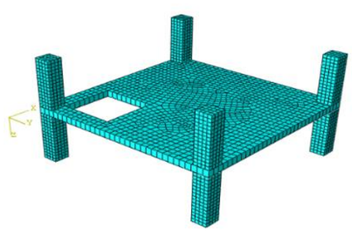
A slab with a circular opening in the center of the slab



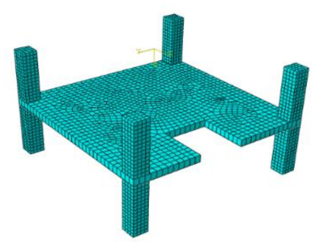
A slab with a parallelogram opening in the center of the slab



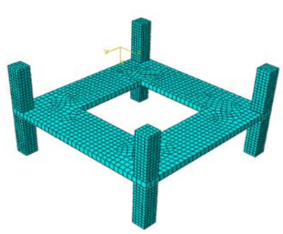
Slab with an oval opening in the center of the slab



Slab with an opening in the corner of the slab



Slab with an opening at the edge of the slab



Slab model with a central opening with a surface ratio of more than 50% of the total surface of the slab

Figure 1. Numerical models and different states of the slab studied in this research

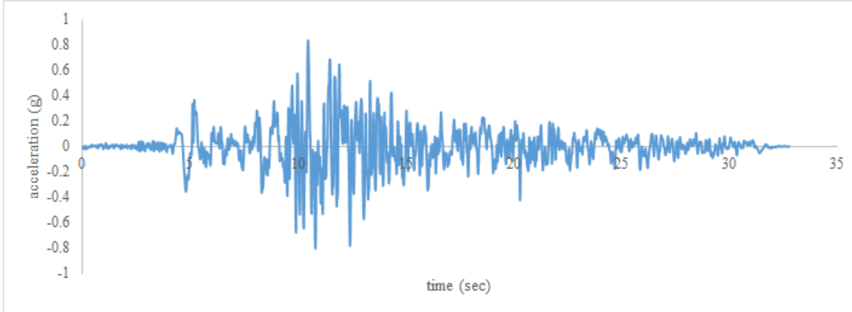


Figure 2. Time acceleration curve of Tabas earthquake to perform dynamic analysis of time history

A refined meshing strategy was used in order to increase solution accuracy. Local mesh density was increased around openings, at slab edges, and at the slab-column interfaces to capture strain localization and stress gradients due to punching. To make sure the chosen mesh size generated a stable solution without incurring undue computing costs, mesh convergence checks were carried out. This study's technique includes a structured parametric investigation in which each of the three major variables is changed separately. The opening site changed between the slab's edge, corner, and center, allowing for the evaluation of structural continuity in each instance. Openings below 50% of the slab area and openings beyond that amount were the two groups in which the opening-to-slab area ratio was examined. Square, rectangular, circular, oval, parallelogram, and trapezoidal opening shapes were among the geometric shapes. To give a consistent comparison, all of the designs in Figure 1 were examined under the same loading and boundary assumptions.

The relevant geometric and material properties of the numerical model are compiled in Table 1. The vast range of opening configurations shown in Figure 2 corresponds to the total number of parametric variants considered in this work, which is summarized in Table 2. These tabular inputs establish the modeling space and provide the basis for estimating the independent influence of each opening parameter in the dynamic response evaluation. Data outputs, such as stress distributions, acceleration profiles, shear concentrations, and energy-time histories, were computed for each of the several slab designs in order to adequately illustrate the structural behavior for severe seismic activity.

TABLE I. TABLE 1: GEOMETRIC AND MATERIAL PROPERTIES OF THE NUMERICAL MODEL

Category	**Parameter**	**Value**
Slab Geometry	Plan Dimensions	5.0 m × 5.0 m
	Thickness	0.20 m
Column Geometry	Section	0.40 m × 0.40 m
Material Model	Concrete	Damage-Plasticity
Element Type	3D Continuum	Solid Elements
Mesh Strategy	Refinement	Increased density near openings/supports

TABLE II. TABLE 2: PARAMETRIC VARIATIONS OF OPENING CONFIGURATIONS

Parameter Group	**Variations**	**Notes**
Opening Location	Center, Corner, Edge	Edge expected most critical
Opening Area Ratio	<50%, >50%	Larger openings evaluated for ductility effects
Opening Geometry	Square, Rectangular, Circular, Oval, Parallelogram, Trapezoidal	Curved shapes expected to reduce stress risers

III. FINDINGS

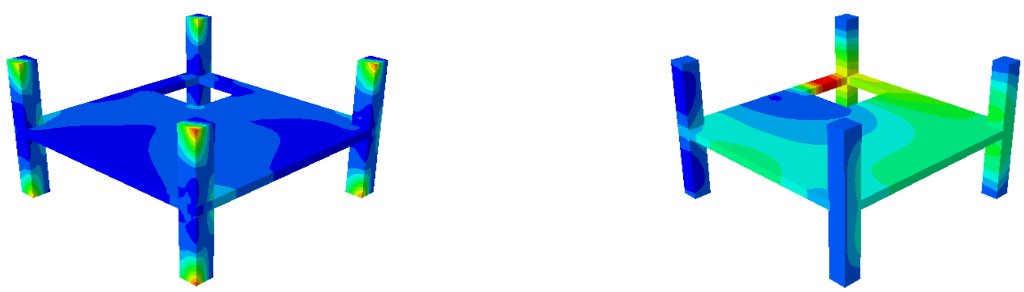
The numerical study presented here gives insight into how opening location, size, and geometry control the seismic response of reinforced concrete slabs subjected to strong ground motion. This integrated evaluation of stress fields, acceleration distributions, shear concentrations, and energy–time responses provide specific behavioral patterns that jointly determine the global and local seismic demand mechanisms. The analyses were carried out for all the slab configurations shown in Figures 3–11; the resulting trends are synthesized in the following subsections.

The reference slab with no opening shows the anticipated concentration of stresses and accelerations at the slab-column interfaces, presented in Figure 3. The behavior here is mainly controlled by the punching-shear and flexural deformation mechanisms. The same was reflected in the reported experimental observations by Grabski & Ambroziak, 2023 [12]. This model, therefore, sets the basic seismic response to be used for comparison against modified slabs. Acceleration fields are rather uniform except at support regions, due to the inherent stiffness concentration in traditional flat slab systems.

(1) (2)

Figure 3. Distribution contours 1: Stress 2: Acceleration caused by earthquake for slab without Basho

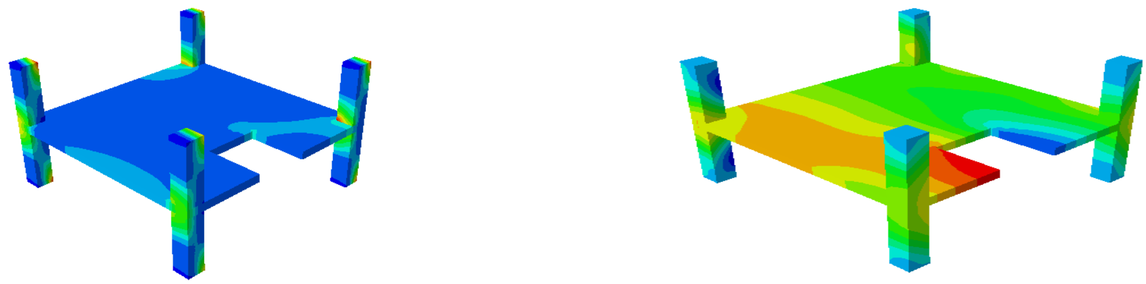
Significant deviations arise when an opening is introduced. For the corner-opening configuration, Fig. 4 shows marked asymmetry in the stress contours, with amplified stress fields near both the opening and the surrounding slab region. This increased demand results from internal stresses having to reroute around a weakened corner region due to discontinuity's disruption of natural load-transfer pathways. Similar behavior was reported by Genikomsou (2024) [13], who discovered that perforations close to a slab's boundaries caused the punching mechanism to become unstable, decreasing the slab's effective stiffness. Further evidence that corner discontinuities alter the inertial response under dynamic excitation is provided by acceleration amplification close to the opening's perimeter.



(1) (2)

Figure 4. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with an opening in the corner of the slab

This behavior is even more severe in the case where the opening is located along the edge of the slab, as shown in Figure 5. Indeed, this case constantly yielded the highest local stresses and acceleration intensification measured in all the considered cases. The edge region of the slab, which already has lower shear transfer capacity and redundancy, became a major weakness whenever intersected by an opening. This observation is reinforced by the energy-time histories in Figure 6, where the edge-opening slab exhibits at least a 40% increase in total transmitted seismic energy relative to both the solid slab and the center-opening slab. This substantial magnification of seismic demand demonstrates that the edge opening is the most unfavorable configuration and necessitates significant reinforcement, such as perimeter beams, column collars, or FRP wrapping to prevent premature failure (Abd-Elhamed et al., 2023 [14]).



(1) (2)

Figure 5. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with an opening at the edge of the slab

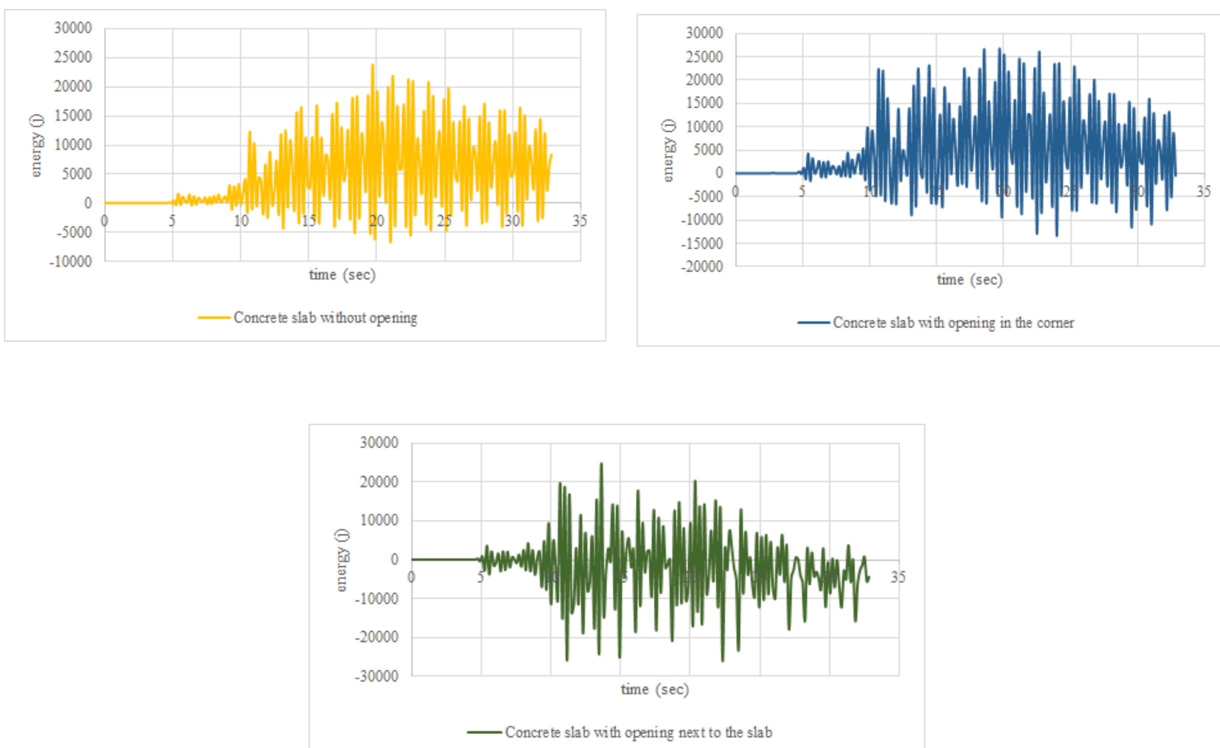


Figure 6. Energy-time curves for different positions of the opening in the slab and comparing them for the slab with and without the opening in different positions.

In contrast to the pronounced influence of opening location, the role of opening area ratio produced a more nuanced and, in some cases, counterintuitive response. For openings occupying less than 50% of the slab's surface, the local stress fields remain elevated both around the opening and the slab–column interfaces (Figure 7). The structure retains a relatively stiff global response, but stress concentrations around the opening's perimeter signal heightened vulnerability. Unexpectedly, slabs with large openings (>50%), as shown in Figure 8, demonstrated a more ductile and energy-absorptive seismic behavior. Because the stiffness reduction is distributed more uniformly in the larger opening scenario, the slab transitions into nonlinear action earlier and more smoothly. While the large-opening slab may develop up to 60% higher peak energy instantaneously, the comparative energy–time histories in Figure 9 depict more stable overall dissipation patterns and the avoidance of abrupt stiffness-loss stages. This agrees with a phenomenon identified by Xu et al. (2024) [15], where it was found that large-opening slabs subjected to impact loads may achieve desirable energy dissipation through a distributed deformation mode rather than through localized brittle failures. Such findings clearly contradict traditional assumptions, indicating that larger openings do not necessarily correspond to higher seismic vulnerability.

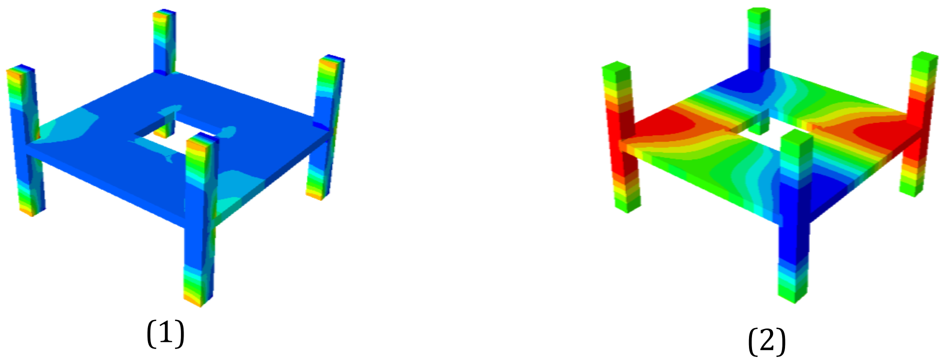


Figure 7. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with a central opening with an area ratio of less than 50%.

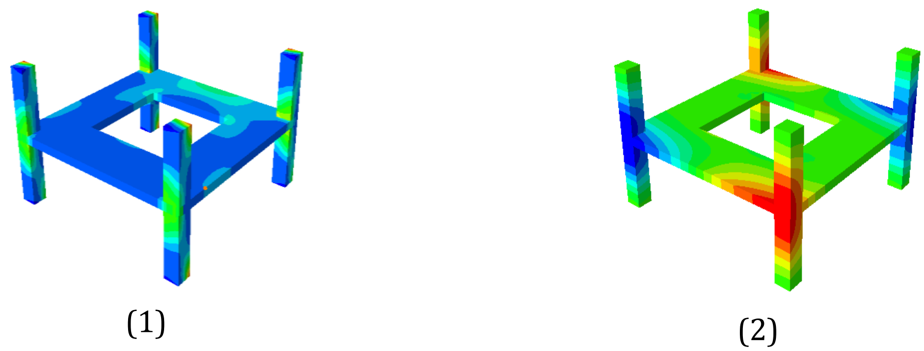


Figure 8. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with a central opening with an area ratio of more than 50%

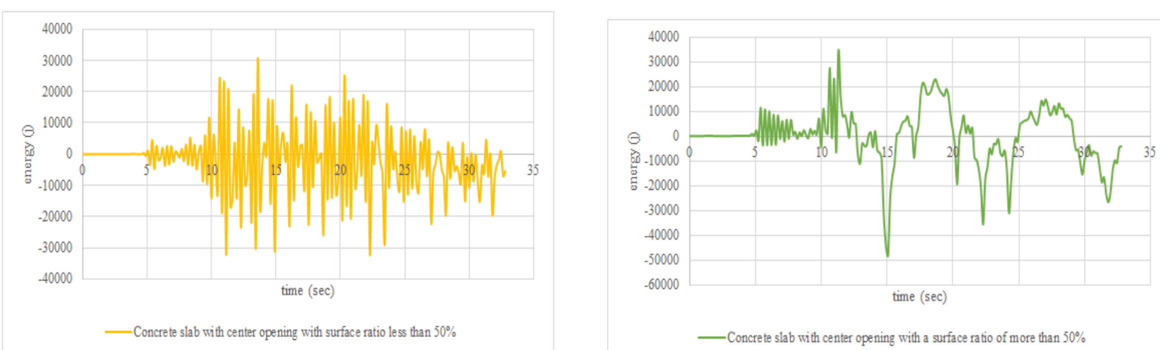


Figure 9: Comparison of energy-time curves for the slab without opening and with different opening ratios

Seismic performance is further governed by the geometry of the opening and gives a decisive indication of design favorability. The various shapes of stress and acceleration contours, reproduced in Figure 10, show that the curved geometries, or more specifically, the circular and oval openings, have produced the most favorable stress distributions. These geometries avoid sharp discontinuities and allow the flow of stresses to reorient smoothly around the opening perimeter, reducing the intensification of stresses and delaying crack initiation. Such behavior corroborates findings by Attallah 2023 [16], who demonstrated the superiority of curved boundaries in promoting uniformity in the transfer of stresses in reinforced slabs. In contrast, severe stress concentrations at the corners of square and rectangular openings were consistently obtained; such corners are well-known initiators of natural cracks. Acceleration fields also peak more intensely near these sharp edges, corroborating their inferior dynamic performance. Parallelogram and trapezoidal openings showed an intermediate response, performing adequately only when their alignment was compatible with the global geometry of the slab.

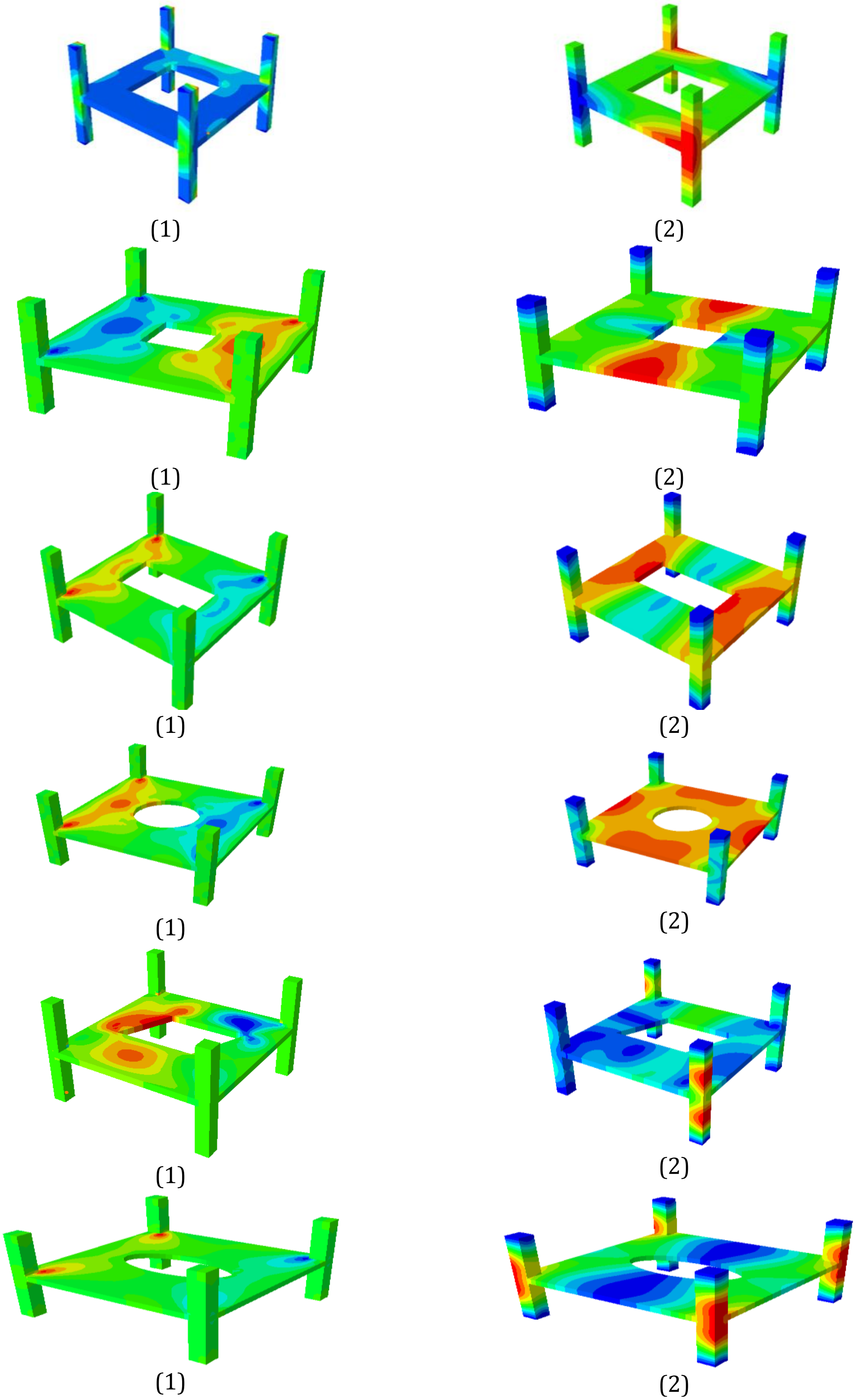


Figure 10: Distribution contours 1: Shear stress 2: Acceleration caused by an earthquake for a slab with a series of openings with different shapes

As shown in Figure 11, the global seismic performance trends for all geometric configurations are clearly demonstrated, with the circular and oval openings having the lowest and most uniform energy accumulation. The square opening had the highest total energy level developed, further substantiating its classification as the least desirable shape for seismic applications. These results have direct design implications: when feasible, curved openings should be favored in seismic zones, while square and rectangular openings must have strengthened perimeters or additional confinement in place to offset their inherent tendencies for stress intensification [18].

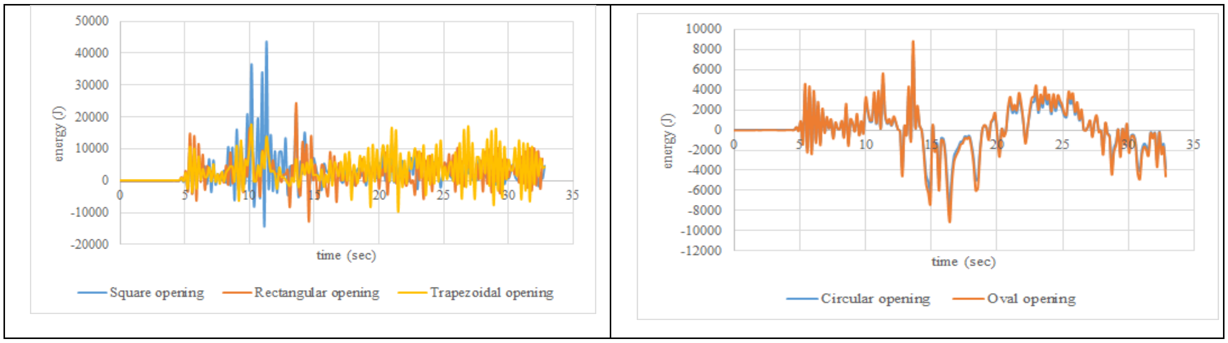


Figure 11: Comparison of energy-time curves for slab without opening and slab with different opening shapes

The analysis, which summarizes the results of Figures 3–11, concludes that the main element affecting seismic vulnerability is opening position, with edge openings displaying the most critical behavior and center openings generating the most stable dynamic response. Due to the nonlinear effect of the opening area ratio, large apertures may increase peak energy consumption while simultaneously promoting global ductility. The opening design modifies the distribution of stress, with curved geometries clearly offering superior seismic performance. All things considered, these findings offer a thorough framework that advances our understanding of the behavior of slab discontinuities under strong ground motion and offers important insights into improving design strategies and retrofitting RC slab systems in performance-based seismic design contexts.

IV. CONCLUSION

This study delivers a focused assessment of how opening position, size, and geometry govern the seismic behavior of reinforced concrete slabs under strong ground motion. The nonlinear FE simulations reveal that the opening location is the dominant factor affecting vulnerability. Openings placed near slab edges generate the most severe stress concentrations, sharp acceleration spikes, and elevated energy demand, identifying them as the most critical configuration and highlighting the necessity of stronger perimeter detailing. In contrast, centrally positioned openings promote smoother stress trajectories and more stable deformation patterns, making them the most favorable for seismic applications.

In terms of opening area ratio, a noteworthy and surprising result is revealed: slabs with wide openings greater than 50% of the surface showed improved global ductility and a smoother transition into nonlinear response, although experiencing larger instantaneous energy peaks. This suggests that while small holes typically result in localized stress intensification, general stiffness decrease might occasionally enhance energy dissipation.

These tendencies are further explained by opening geometry. While rectangular or square holes with sharp corners result in heightened tensile zones that become crack-initiation sites, round and elliptical forms function better by maintaining continuous stress flow and avoiding stress raisers. These results highlight the importance of curved, smooth borders in reducing dynamic stress amplification. The combined findings from Figures 3–11 offer a logical comprehension of the relationship between slab discontinuities and seismic demand. The study provides precise recommendations: apertures should be positioned close to the slab's center, have rounded edges, and, if big holes are needed, be supported by suitable detailing to improve ductility rather than brittleness. For RC floor systems in seismically active areas, these insights support performance-based design and retrofit techniques.

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