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.

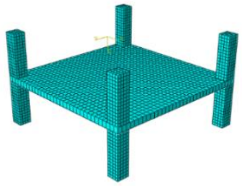
I. Introduction

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.

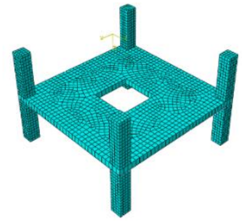
II. RESEARCH METHOD

The experimental design was formulated with the intention of systematic investigation of influence of variations in the location of an opening, the ratio of areas between opening and slab, and geometry on the seismic response of reinforced concrete slabs exposed to strong ground shaking. The numerical modeling approach was designed in ABAQUS environment, where a representative flat slab of dimensions 5 m × 5 m with a thickness of 200 mm was constructed. This slab was supported by 400 mm reinforced concrete column stubs both above and below slab plane; such a flat slab configuration corresponds to the common half story design of multi-story RC buildings. Three dimensional solid continuum elements were chosen as the most suitable choice to describe structural components because of their ability to capture the phenomenon of shear deformations, localization of cracks and through-thickness stress distribution. Figure 1 shows the full list of slab configurations considered in this study that includes slabs with openings in different locations, slabs without openings, and slabs with openings of different shapes and surface ratios. This list of geometrical variations forms the basis of the parametric study conducted in this paper [11].

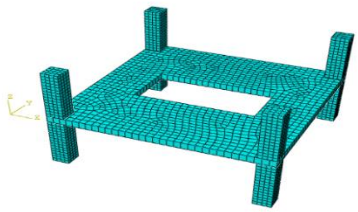
Constitutive model of damage-plasticity type was chosen to describe material behavior of concrete that accounts for phenomena of tensile cracking, compressive crushing, stiffness reduction, and nonlinear softening in the process of seismic loading. The bases of the column stubs were fixed to avoid the effect of artificial boundary stiffness, while the edges of the slab remained free to allow realistic pattern of deformations under lateral loading. The analysis included sequential consideration of two load stages: first stage, when the load of gravity nature that consists of the slab self-weight and superimposed dead load is applied and allows achieving the state of stability, and second one when the load of seismic origin is applied using the ground-motion record of Tabas (Iran) as shown in figure 2, which is characterized by the presence of strong long period content and ability to activate both flexural and shear mechanisms of seismic response. 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.



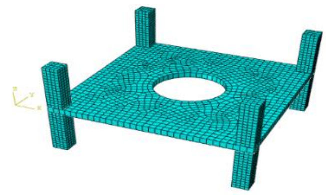
Slab without opening



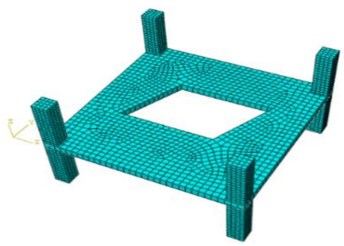
A slab with a square opening in the center of the slab



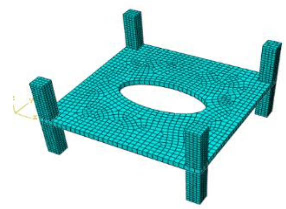
A slab with a rectangular opening in the center of the slab



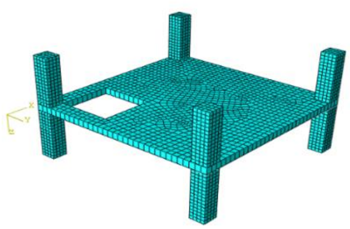
A slab with a circular opening in the center of the slab



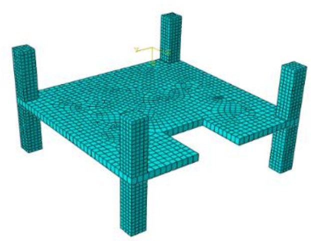
A slab with a parallelogram opening in the center of the slab



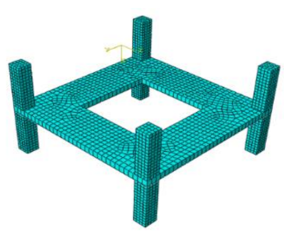
Slab with an oval opening in the center of the slab



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

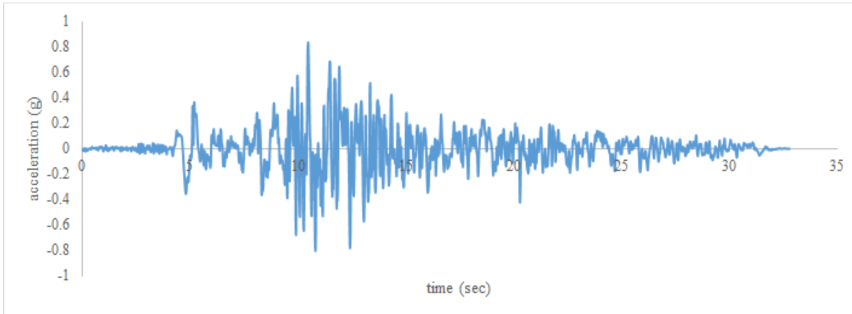


Figure 2. Time acceleration curve of Tabas earthquake to perform dynamic analysis of time history

Mesh convergence was employed in the current study as a refinement approach to improve the precision of solution. Mesh density was increased locally at openings, slab edges and slab-column connections for capturing strain localization and stress gradients caused by punching. In order to ensure that selected mesh size would produce a stable solution without high computational cost, mesh convergence tests were performed. The approach used in the current study involves a systematic parametric analysis with changes in one of three main variables separately. Opening location varied between slab edge, slab corner and slab center for examining the structural integrity for each case. Openings smaller and larger than 50% of the slab area were the two categories where the ratio of opening to slab area was studied. Geometric forms included square, rectangle, circle, oval, parallelogram and trapezoid shapes. All of the schemes in Figure 1 were tested under the same conditions of loading and boundaries for consistency.

Relevant geometric and material parameters of the numerical model are listed in Table 1. The extensive variety of opening configurations shown in Figure 2 covers the total number of parametric variations used in this study, which is provided in Table 2. These tabular data define the domain of modeling and serve as the base for estimation of the separate impact of each opening parameter on the dynamic response. Outputs of data, such as stress distributions, acceleration diagrams, shear concentrations and energy-time diagrams, were calculated for each of multiple slab schemes in order to properly demonstrate the structural response under severe seismic events.

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

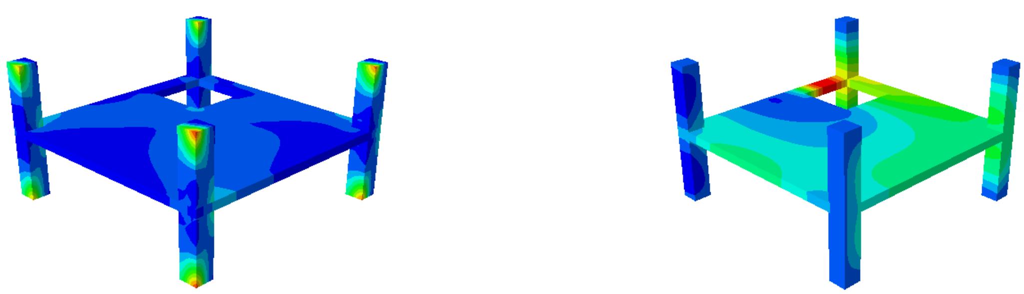
In addition, the current numerical investigation can shed light on the effect of opening location, dimensions, and geometry on the seismic performance of reinforced concrete slabs when exposed to severe ground motions. In particular, the combination of analysis of stress field, acceleration field, shear concentration, and energy-time response can reveal unique behavioral patterns, which together define the global and local seismic demand mechanism. These analyses have been conducted for all slab geometries considered as shown in Figs. 3-11; and the trends thus revealed are discussed in the following subsections.

The reference slab without any opening demonstrates the expected stress and acceleration concentration around the slab-column interface shown in Fig. 3. In this case, the seismic response pattern is governed mostly by the punching-shear and flexural mechanisms. Similarly, it was observed in the experimental work reported by Grabski & Ambroziak, 2023 [12]. Thus, this model defines the basic seismic response, which will be used as a basis of comparison for modified slab models. Acceleration field is fairly uniform apart from the support locations, owing to inherent stiffness concentration in traditional flat slabs.

(1) (2)

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

Important differences will occur with the introduction of the opening. As illustrated in Fig. 4 for the case of the corner opening arrangement, considerable asymmetry occurs in the stress pattern with higher stresses occurring in both the vicinity of the opening and the entire slab area. This higher requirement is attributed to the necessity of the internal stresses being routed through the corner area, which has been made weak due to the effect of the discontinuity and disrupting the natural load path. The same phenomenon has been observed by Genikomsou (2024) [13], whereby he found that openings in the vicinity of the slab boundaries would lead to instability in the punching mechanism and hence lower slab stiffness.



(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 problem becomes even more pronounced when the opening exists in the vicinity of the edge of the slab, as illustrated in Figure 5 below. In fact, this case invariably produced the highest local stress values and the highest acceleration amplifications of any of the investigated cases. The edge of the slab was always an area of lower strength and redundancy for shear transfer anyway, and its exposure to an opening made it into a critical weak spot. This fact is emphasized by the energy-time history plots presented in Figure 6, where it can be seen that the slab with the edge opening has no less than 40% higher total seismic energy transmitted compared to both the solid slab and the center opening slab. This dramatic energy amplification makes it clear that the edge opening case is the worst-case scenario and requires additional strengthening, such as perimeter beams, column collars or FRP wrapping (Abd-Elhamed et al., 2023 [14]).

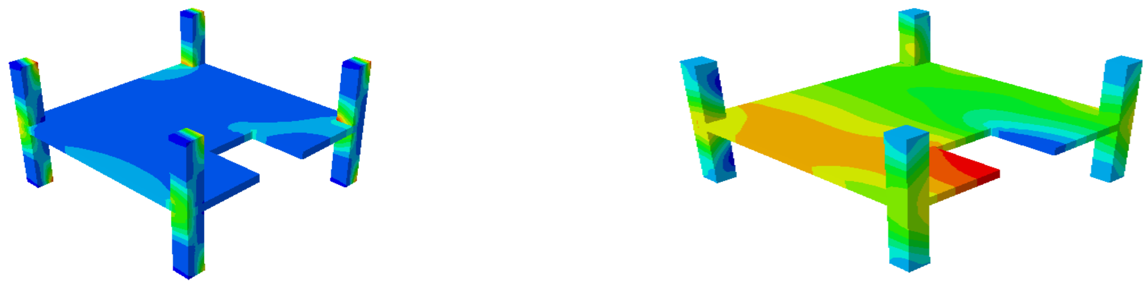


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Figure 5. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with an opening at the edge of the slab

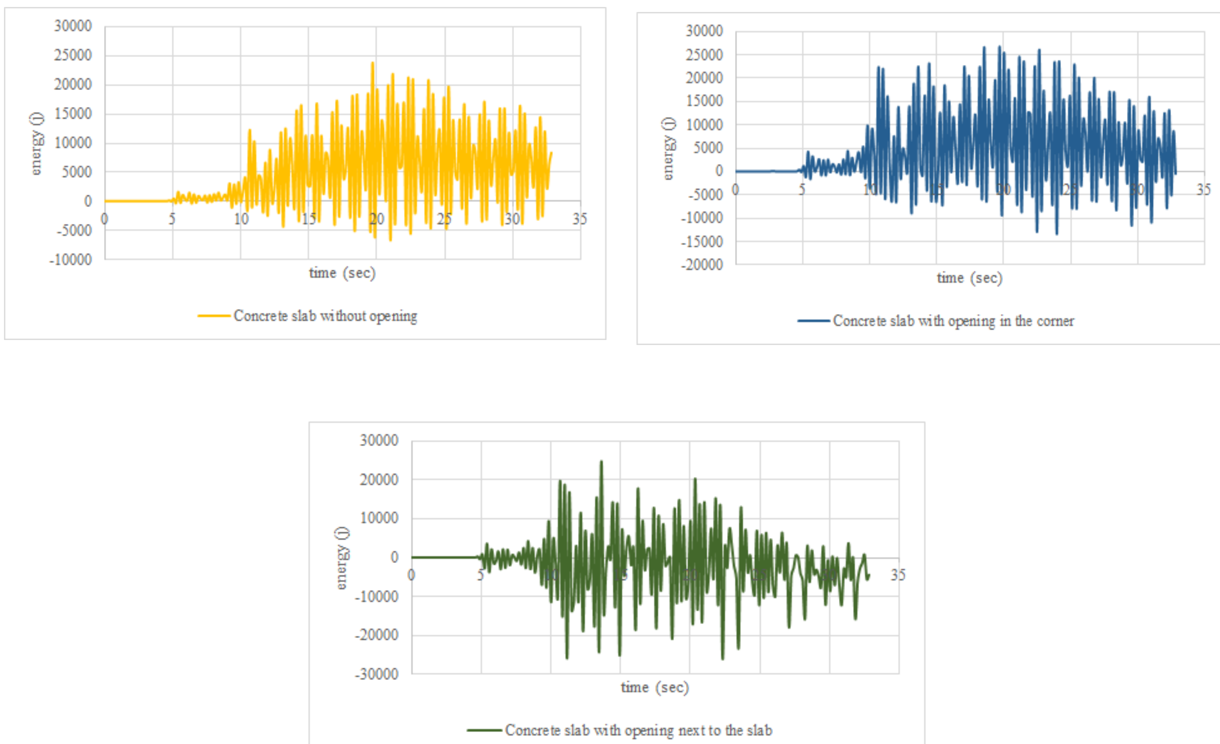

Figure 6. Energy-time curves for different positions of the opening in the slab and comparing them for the slab with and without the opening in different positions.

Contrary to the clear impact of opening location, the effect of opening area ratio caused a rather sophisticated and sometimes contradictory reaction from the structure. In case of small openings that occupy less than 50% of the slab surface, the stresses near the opening and slab-column boundaries stay high (Figure 7). In spite of its high stiffness, the structure responds to the earthquake more flexibly. The high concentration of stress at the boundary of the opening indicates increased sensitivity of the structure. However, as surprising as it may seem, large openings (>50%) lead to more flexible and energy-absorbing seismic behavior of the slab, as is demonstrated in Figure 8. As the stiffness loss is more evenly distributed in this case, the slab starts acting in nonlinear mode sooner and easier. Even though the large opening slab has the ability to absorb up to 60% higher peak energy instantly, the comparative energy-time diagrams in Figure 9 show a more stable dissipating pattern of energy without any sudden stiffness loss stages. This is consistent with the finding obtained by Xu et al. (2024) [15] according to which the large openings slabs under impact loads could have a desirable energy dissipation due to distributed deformations instead of brittle failure.

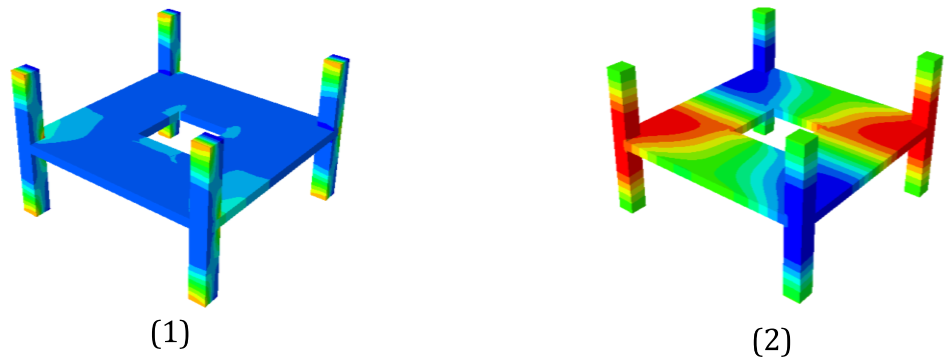

Figure 7. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with a central opening with an area ratio of less than 50%.

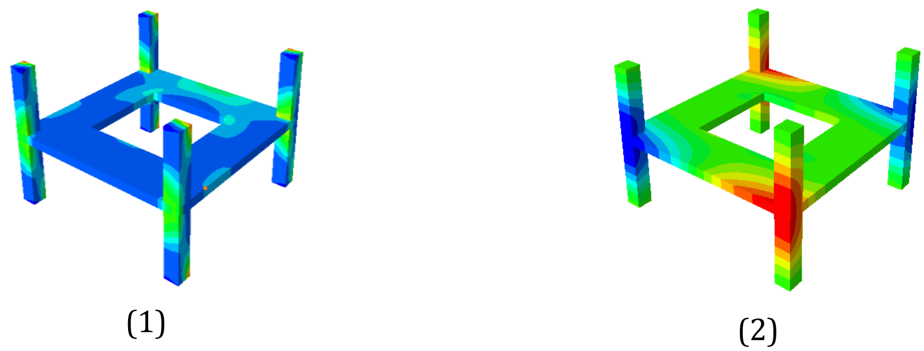

Figure 8. Distribution contours 1: Stress 2: Acceleration caused by an earthquake for a slab with a central opening with an area ratio of more than 50%

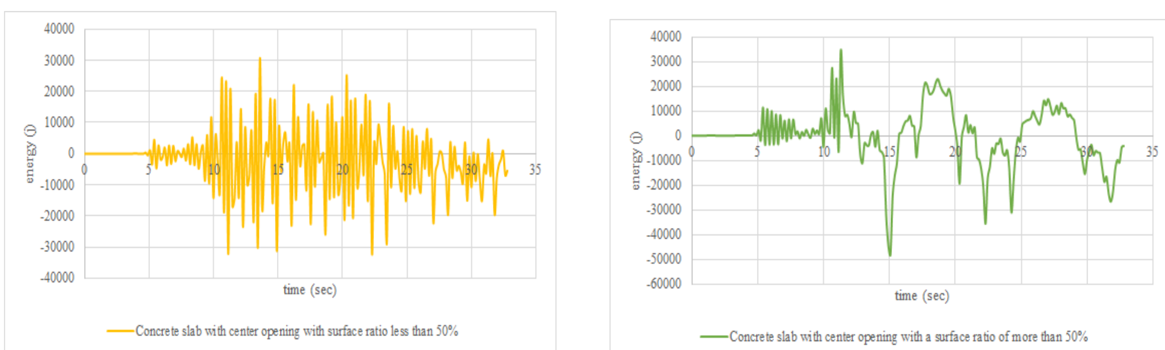

Figure 9: Comparison of energy-time curves for the slab without opening and with different opening ratios

The seismic performance is still influenced by the geometry of the opening and indicates clearly the extent to which the design is favorable. The different types of stress and acceleration contour shapes in Figure 10 reveal that the curved shapes, that is, the circular and oval openings, provide the best stress distribution patterns. This is because they lack any kind of discontinuity and enable the redirection of stress flow around the opening circumference without the intensification of the stresses to delay the formation of any cracks. This is in accordance with the findings of Attallah 2023 [16] which reveals that curved boundaries provide better stress distribution due to their superior performance in the uniform transfer of stresses on reinforced slabs. On the other hand, stress concentration around the corner regions of square and rectangular openings were observed. These corners are known to be responsible for forming natural cracks in the slab. The acceleration fields also exhibit intense peaks around these corners due to the inferior dynamic behavior of theses openings.

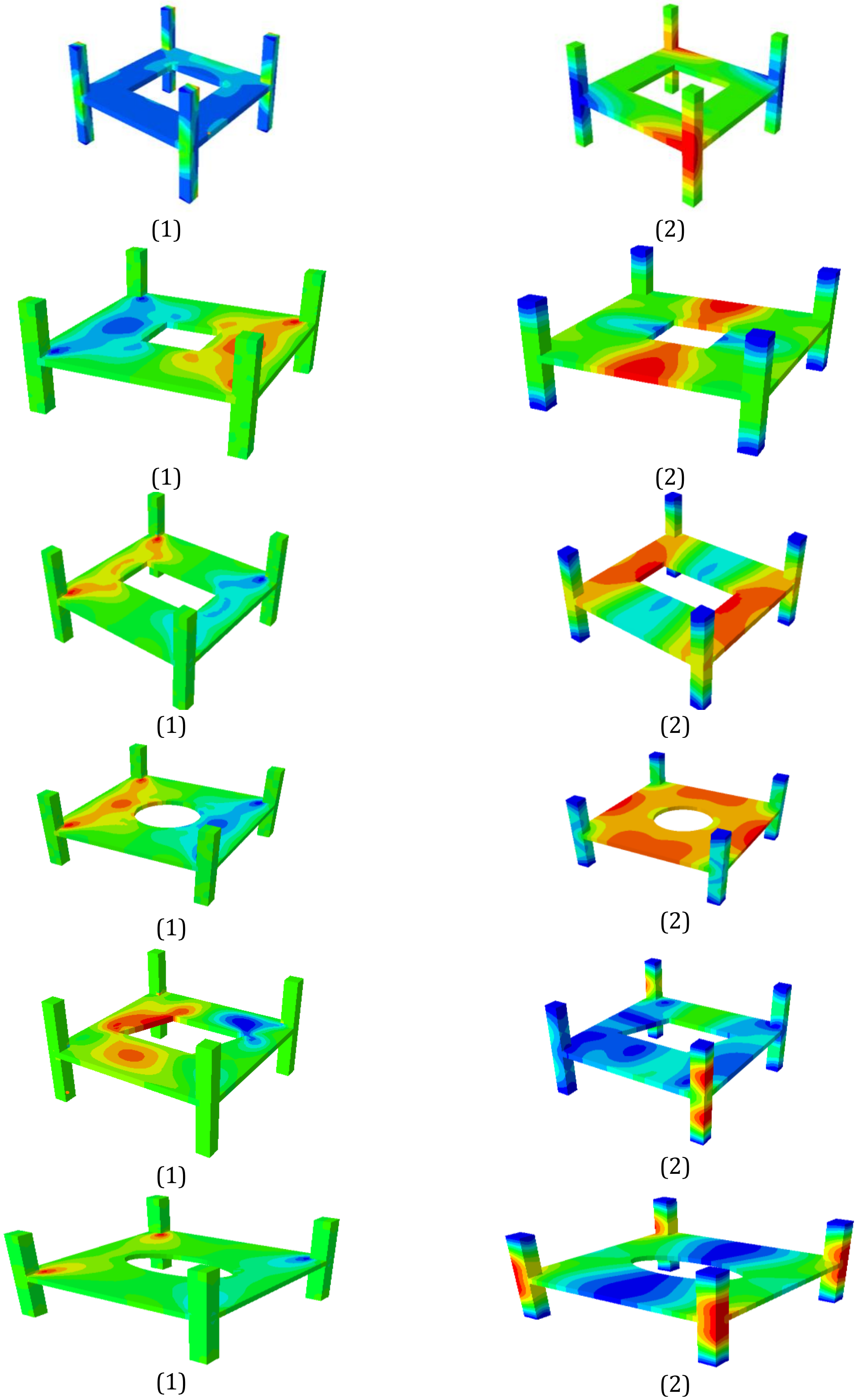

Figure 10: Distribution contours 1: Shear stress 2: Acceleration caused by an earthquake for a slab with a series of openings with different shapes

The global trends of seismic behavior of the structures with various geometric shapes, as depicted in Figure 11, are quite evident, and the circles and ovals have been found to have the minimum levels of energy accumulation. The square opening was found to have the maximum level of energy generated, and thereby, its designation as the worst possible shape for the construction of seismic buildings is fully justified. There are clear implications for design; if possible, curved openings should be chosen in seismic areas, whereas square and rectangular openings need strengthened edges [18].

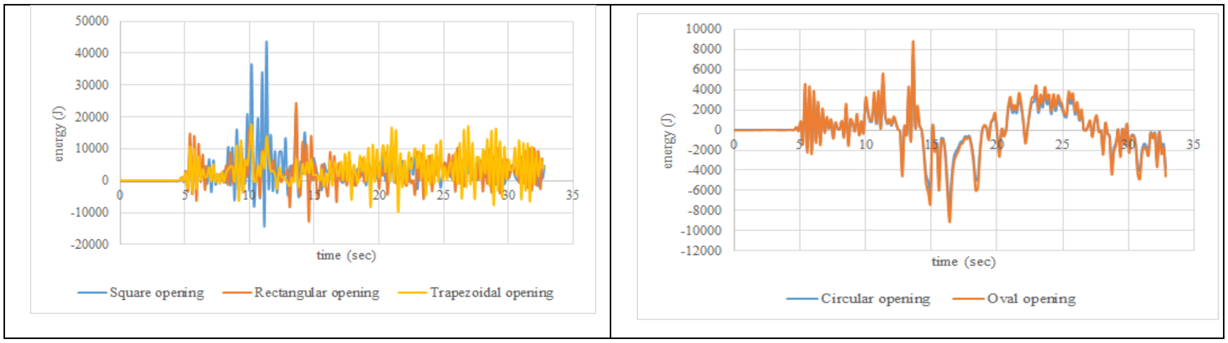

Figure 11: Comparison of energy-time curves for slab without opening and slab with different opening shapes

This analysis, which provides a summary of the outcomes of Figures 3 through 11, shows that the primary factor responsible for the seismic vulnerability is opening location, whereby edge openings are shown to be the worst-case scenario, whereas center openings produce the most stable dynamic response. Because of the nonlinearity of the influence of the ratio of the opening area, the presence of large openings can both increase the peak value of energy dissipation and enhance the global ductility of the system. Opening shape influences the pattern of the stress distribution, and curved shapes perform better than the others. Taking everything into account, this research provides a complete set of information that significantly contributes to the understanding of the behavior of slab discontinuities subjected to ground shaking.

IV. CONCLUSION

The current paper provides a clear understanding of the influence of opening position, size, and shape on the seismic response of RC slabs exposed to earthquake excitation. The nonlinear finite-element analysis shows that the position of an opening plays a key role in determining the vulnerability. Slabs with openings in their peripheral regions are the most vulnerable in terms of stress concentration, instantaneous acceleration and energy requirement. Central placement of openings provides less pronounced stress concentrations and ensures a more stable mode of deformation. Thus, they represent the most advantageous configuration, since they ensure the most appropriate performance under earthquakes.

Regarding the opening area ratio, a surprising and important discovery is made. Slabs having wide openings occupying the area more than 50% of the surface exhibit higher ductility characteristics and better transition to the nonlinear regime despite the occurrence of higher energy peaks. Hence, it could be concluded that small openings lead to local stresses concentration, but sometimes the stiffness reduction might provide more efficient energy dissipation.

These tendencies are confirmed by the opening geometry. Specifically, square or rectangular holes with sharp corners cause higher tensions and, as a result, initiation of cracks. Round and elliptical shapes are more preferable since they provide more uniform stress distribution and eliminate the stress concentrators.
The conclusions drawn from Figures 3 to 11 make it possible to gain the rational understanding of the influence of slab discontinuities on the seismic performance. The research offers quite specific recommendations concerning the placement, shape and size of apertures: the apertures should be located near the middle point of the slab and have curved boundaries, and large holes should be provided with special detailing to ensure ductility rather than brittleness.

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