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Openings effects in reinforced concrete shear walls; a literature review on experimental and finite element studies

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Abstract— **One of the types of earthquake-resistant systems is the concrete shear wall system, which has attracted the attention of engineers due to its good performance in past earthquakes. But some architectural constraints force engineers to install openings in shear walls; thus, this will affect the behavior of the shear wall. Many researchers have conducted experimental and finite element studies for assessing the effects of openings in reinforced concrete shear walls. However, there is a lack of comprehensive comparisons between different studies. This paper reviews some most recent experimental and finite element studies available in the literature and presents a review of the main contributions. This literature review reveals that the seismic responses and the stiffness of structures are influenced by the size and location of the openings in the reinforced shear wall.**

***Index Terms*— Concrete shear wall, Seismic parameters, Literature review, Opening**

I. Introduction

The forces affecting a structure (by wind or earthquake) are dealt with in different ways, with the effect of earthquakes on buildings being quite different from those affecting them. Considering the structural members in a building, structures can deal with forces in different ways. Some of the structures, like double layer barrel vaults, utilize straight members to transfer applied loads and moments,[1]. However, the effect of the earthquake is that its forces are far more complex and effective than other forces. Generally, structural systems to resist the lateral forces include moment frame and shear wall, or a combination of these two systems. The use of the moment frame as a lateral reinforcing element, especially if earthquake-induced lateral forces, require specific details to provide sufficient framing. For example, for Special Truss Moment Frames, there are specific detailing and design approaches. Also from design perspective, resent researches proved that the geometrical parameters can play significant rolls in the behavior of these lateral-load-resistant structural systems,[2]. These details are often haphazard in execution and can be ensured that they are properly executed and that the quality of execution and supervision in the workshop is very high. Controls, while for tall frame structures alone cannot be responsive in this regard. On the other hand, it could be claimed that the safety and resistance of structures in front of various hazards are crucial for the economy, and industrial improvement and shear walls could significantly provide this aim for the structures [3].From structural material viewpoint, recent revealed that variation in material of reinforced moment frame can change the behavior of the structural system significantly,[4]. Here are some examples of shear walls [5]:

1- Steel Shear Walls: Sometimes, steel sheets are used as shear walls. To prevent local buckling of such steel shear walls, vertical and horizontal reinforcers should be used.

2- Composite shear walls: Composite shear walls include: reinforced steel sheets buried in reinforced concrete, steel sheets buried inside reinforced concrete walls, and other possible composite walls, all of which are full steel or composite frame.

3- Shear walls of building materials: Building materials have long been used as solid reinforced concrete walls, but it has been shown that these walls are weak in terms of earthquake resistance and are now replaced by shear walls such as the walls are used with hollow bricks filled with slurry.

4- Reinforced concrete shear walls: Another type of shear wall is reinforced concrete shear walls.

One of the confident ways to counter the lateral forces is to apply reinforced concrete shear walls. The shear wall acts as a large, column-resisting seismic system and is an essential member for tall reinforced concrete structures and a suitable member for medium to short structures. Generally, all kinds of shear walls significantly effect on the seismic behavior of structures. Many researchers conducted studies on these effects such as the coefficient of stiffness, ultimate deformation, added resistance coefficient, final strength level, base shear coefficient, and other seismic behavior factors were compared to various shear panels, and they proved the suitable seismic performance and behavior for this type of structures [6]. In this paper, a literature review conducted on some recent investigations that performed with finite element simulation and experimental tests for evaluating the opening effects on the behavior of reinforced concrete shear walls.

II. Reinforced concrete shear wall types [5]

There are two types of reinforced concrete shear walls:

1- In-situ shear wall: In-situ shear wall is hooked to the peripheral frame in order to maintain the uniformity of the wall bars.

2- Prefabricated shear walls: Prefabricated shear walls are made of trapezoidal kidneys along the edges of the panel or by connecting the panels to the frame by steel nails. Wall Shape Impact: Embedded wings in walls are very useful for structural stability and flexibility.

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III. The Forces That Enter the Shear Walls [5]

In general, shear walls are subject to the following forces:

1- Variable shear force whose value is maximum at the base.

2- Variable bending anchor, which is again maximum at the foot of the wall and generates traction on one edge (the edge is close to the forces and the pressure on the reciprocating edge). Due to the possibility of changing the direction of wind or earthquake in the building, the traction must be at any time Consider the two edges of the wall.

3- The axial force of compression due to the weight of the floors resting on the shear wall.

If the shear wall height is low, the shear strength will often be the design, but if the shear wall height is high, the bending anchor will be the design. However, the wall must be controlled and armed against both forces.

IV. Shear Wall Solution to Earthquake

The earthquake engineering of buildings began in 1950, with extensive reconstruction activities following the end of World War II. Initial attempts to retrofit buildings were based on poor assumptions about the structural response to ground vibration, which were incomplete due to a lack of proper analysis tools and sufficient earthquake information. Observing the performance of structures during earthquakes as well as analytical studies and laboratory work and collecting earthquake information of the last four decades have provided a modern way to design earthquake resistant structures. During the 1950s, the Ductile Bending System originated from the Ductile Bending System, which at the time was the only resistant system in multi-story concrete buildings, and due to the proper earthquake behavior, its application until late. The 1970s continued. During this time, newer and more efficient systems such as shear walls or trusses were introduced to tolerate lateral wind pressure in high-rise buildings, and almost the only framed construction was abandoned. Experimental and theoretical research around the world during the 60s, 70s, and 80s led to the gathering of detailed information on the response of sheer-walled building systems to earthquakes, which emphasized the importance of the flexural framework in reducing earthquake load. As structures with higher rigidity (i.e., less plasticity) are subject to much stronger forces during earthquakes, and since shear walls in buildings increase their rigidity, the use of shear walls has become inappropriate, and most buildings have been identified. They were made by the bending frame method. For example, in some countries, especially underdeveloped countries, without meeting the minimum criteria for plasticity, building frames were fragile and unable to withstand strong earthquakes without causing severe damage to the building, and as many have seen in the last four decades. The residents were trapped in "death traps." The following is a summary of the behavior of shear wall structures that have been involved in earthquake events for the past 30 years [7].

A. May 1960 Chile earthquake

The first report on the behavior of sheer-walled buildings is related to this earthquake. Experiences in the Chilean earthquake confirm the use of shear walls in severe earthquakes to reduce structural and non-structural damage. In some cases, shear walls have cracked, but the overall behavior of the building has not changed.

B. The July 1963 Yugoslav earthquake

In this earthquake, unarmed concrete walls (e.g., in or around the core of the building) were able to prevent major damage by restraining torsion between floors and only in a few exceptional cases were the lower parts of the perimeter beams separated by severe vibrations.

C. February 1971 Earthquake of San Fernando, CA

After the earthquake, the 6-story Indian Hill Medical Center building with a composite frame and shear wall system needed only to be repaired during the 8-story Holy Cross Hospital building next to it because the frame system was used only. It was badly damaged and eventually destroyed.

D. March 1977 Bucharest earthquake (Romania):

The earthquake, in which 35 multi-story buildings were destroyed, hundreds of tall buildings and apartment towers that used concrete walls along the corridors or throughout the building remained largely untouched, safe, and usable.

E. October 1985 Mexico City (Mexico) Earthquake

The devastation of this earthquake in Mexico well illustrated the consequences of not using reinforcing shear walls. In this earthquake, about 280 multi-story buildings with a single frame system were destroyed and destroyed due to the lack of shear walls.

F. December 1988 earthquake in Armenia

The 1988 Armenian earthquake is another reason for the negative results of the removal of shear walls in multi-story buildings. The earthquake devastated 72 buildings due to a lack of shear walls, and 149 buildings were severely damaged in four cities, Leninakam, Spitak, Kirovakan, and Stepomavan. However, all 21 buildings with large panels in the four cities were unharmed and survived in the wreckage of other buildings.

In recent decades, ways have been devised to build structural systems that sometimes did not have the potential to increase earthquake resistance, which in turn provided a false sense of security. At the beginning of the science of earthquake engineering, many experts mistook the concept of ductility with flexibility, and as a result, many flexible structures were built in earthquake-prone areas of the world. While some were formable, irreparable damage was caused to the buildings during the earthquake, as a result of the high tide between the floors. In today's construction, only 20% of the total cost of the structural system is spent, and the rest is spent on architectural and electrical and mechanical installations. Choosing an appropriate structural system that incorporates the safety and security of people is of particular importance, and one way to achieve such security is to use shear walls in concrete structures.

Details of the shear wall formation that have been mentioned in recent bylaws in recent studies have not yet been tested in real earthquakes. Undoubtedly, using these details will make the walls more pliable, but the exact amount of productivity of the pliability must be determined in real earthquakes or complex earthquake dynamics studies. Ductile wall design is correct when its resistance is by bending, not by shear, and the shear capacity of the wall at each section is greater than that of the section based on the bending strength of the wall. Also, not only the final shear capacity but also the behavior of the member between the cracking initiation state and the shear failure state are specified.

V. Shear Wall Structures

The gravity and lateral load resisting system of any buildings consist of columns, slabs, and the reinforced concrete walls. In other words, shear wall structures are the main vertical structural systems that were resisting both the lateral and gravity forces. The thickness of the concrete shear walls depends on the number of stories of a building, which varies from 140 mm to 500 mm. These shear walls usually reinforced throughout the height of the building. Nonetheless, due to permit for parking spaces or commercial purposes, some shear walls are discontinued at the basement level or street front [8].

Shear wall structures are commonly used in the plan and elevation of structures. Fig. 1 shows the efficiency of shear walls in terms of stiffness. The most efficient shear walls are the Solid shear walls, and they are highly desirable, however, for some functional necessity (e.g., doors and windows) providing openings are often required in the shear walls. In most of the buildings, lower levels of them are applied for commercial purposes. Commonly, these shear walls used for the residential buildings and from 100 to 500 inhabitants per building [8].

Couple walls are a term that called for Shear walls with openings. These shear walls applied as cantilevered shear walls connected by coupling beams (lintels or spandrel beams) for shear effects and bending. In the design of concrete shear walls, an important criterion that is using is based on providing the required stiffness and strength to avoid/limit the damage under frequent earthquakes loads while ensuring adequate wall deformation capacity [9]. These beams and connections could act as fuses and dissipate seismic energy when they designed in a ductile manner and generally it can be stated that increasing the ratio of the concrete surface conducted the greater capacity for the lateral systems [10]. Table 1 illustrates the recent studies on the effects of opening in reinforced shear walls and summarized the major finding of these studies as well.

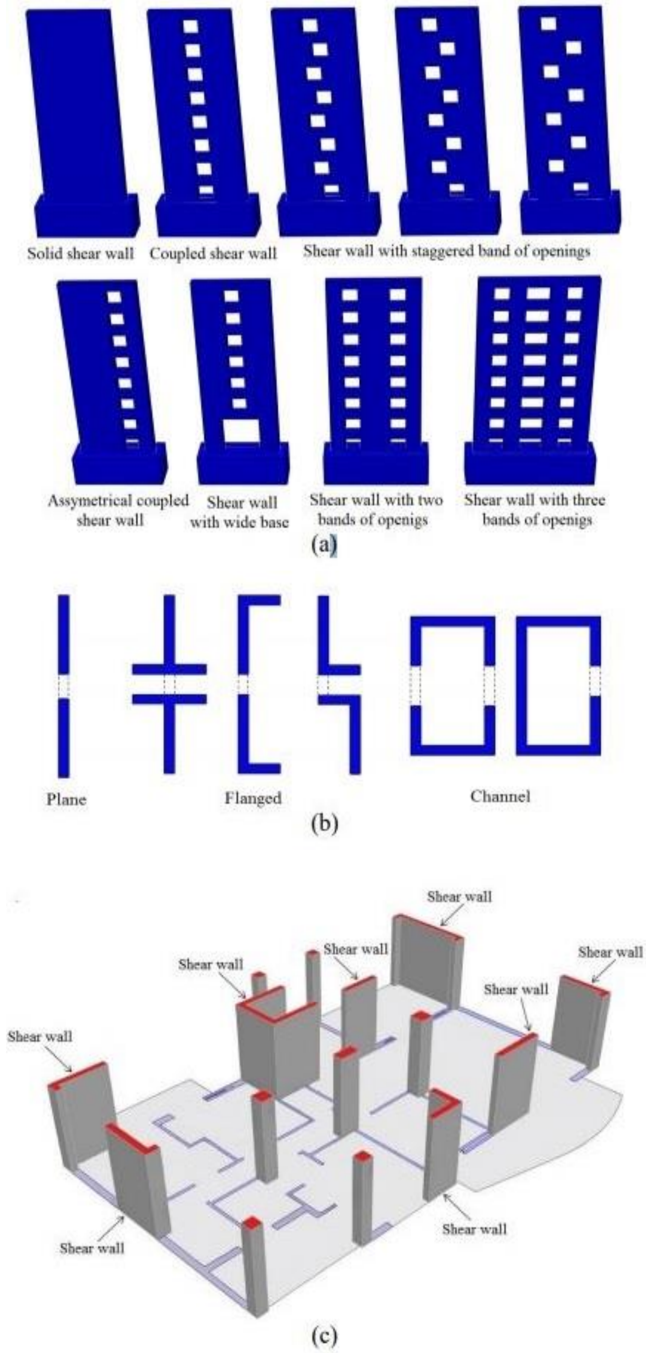

Fig. 1. a) typical shear walls b) usual plan sections for the shear walls c) the plan view of a supposed building with different types of shear wall sections [8].

Table 1. Studies, variables, and major finding of the investigations

Author	Study	variables of the research	main findings
Hossein Alimohammadi et al. (2019) [11]	Finite Element simulation	The opening with different shapes (circle, square, rectangular shapes) and constant cross-section (the area of openings is equal to 1.3 of total the wall area)	1- Openings with various forms effect on the resistance/hardening of the samples 2- The closer the openings are to the edge of the wall the more decrease strength 3- Opening in the shear walls could reduce seismic properties of the shear wall up to 50 percent on the stiffness, ultimate load, and energy absorption, but the strength and ductility of the reduction is variable depending on the type and form of openings
Bhrguguli H. Gandhi (2015) [12]	Finite Element simulation	Location and size of openings in the shear wall for 6-story frame-shear wall buildings under earthquake loads	1- Stiffness and seismic responses of structures are affected by the size and location of the opening in shear wall 2-Top lateral displacement of the system could be reduced the thickness of the element in the model around the opening of shear wall
Seyed M. Khatami et al. (2012) [13]	Finite Element simulation	A time history study for tall concrete buildings, addressing the effects of openings in concrete shear walls under near-fault earthquake ground motions (a ten-story building with three types of lateral resisting systems including complete shear walls, the shear wall with an opening at right end side, and shear walls with a square opening in the center)	1- A considerable decrease in terms of the strength of the wall could be identified for shear walls with openings 2- specific behavior of the openings observed when compared with the complete wall case and causes an raise in the time history of displacements 3- large lateral displacements and ductility verified for shear walls with openings in comparison with complete shear wall
Ashok Kankuntla et al. (2016) [14]	Finite Element simulation	The behavior of shear wall, including an opening under seismic load on member forces. Hence present study aims to compare the seismic performance of 15-Storey with openings in shear wall situated in earthquake zone V and Position of the shear wall by changing the sizes and shape of openings in shear wall for all building's models	1- changing the position of the shear wall of reinforced concrete structures with various opening sizes in buildings openings are economical, 2- The external, as well as internal shear wall, reduces column moment and axial force as compared to core and core with internal shear wall
Amitkumar Yadav et al. (2019) [15]	Finite Element simulation	the location and types of openings in shear walls. The structural behavior in terms of	the opening in the shear wall should be avoided, or it should be of minimum size and number as the height of structure goes on increasing for tall structures

		deflections, bending moment and shear force for 70 stories of the building, located in seismic zone III as per IS 1893-2016	
Yinglong Zhang (2018) [16]	Experimental and Finite Element simulation	Different openings size/location on the performance of the wall panels with out-of-plane bending, axial loading, and push-over conditions	It is recommended to keep the locations of the openings closer to the neutral axis to designing the walls with circular openings. The spacing between the flexural and shear reinforcements could be decreased to improve the moment and shear capacities of the wall. Plus, a higher strength concrete could be used to provide the wall with a higher axial loading capacity
Hadi Hosseini (2017) [17]	Finite Element simulation	20 story building is analyzed for with and without opening	1- Shear walls could decrease the shear force and increase the moments in the columns. 2- No significant difference in shear force and moment provision of 20 % opening in the shear wall
Vishal A. Itware et al. (2015) [18]	Finite Element simulation	6 and 12 storied buildings with the typical floor plan and floor height with different openings size/location in the shear walls	For those opening area less than 20%, the stiffness of the whole system is more influenced by the size of openings rather than the arrangement. nonetheless, for those opening area more than 20%, the stiffness of the system is influenced by openings configuration in the shear walls
C. Y. Lin et al. (1988) [19]	Experimental and Finite	The ultimate strength of shear wall	Shear strength which contributed by diagonal reinforcement around opening
	Element simulation	under lateral load with an opening	location reach up to 40 % of the yield strength, however, the shear strength that contributed by the rectangular shape reach to 20 % of the yield strength

VI. Conclusion and Discussions

Various parameters such as wall aspect ratio, boundary elements, loading type and amount, and distribution of reinforcement are effective on shear wall behavior. Other parameters that are less studied but have a significant effect on wall behavior such as location and dimension of the opening in the shear walls. This study presented a literature review that conducted on some recent investigations that performed with finite element simulation and experimental tests for evaluating the opening effects on the behavior of reinforced concrete shear walls. By comparing the major finding from these studies could be stated that the seismic responses and stiffness of structures are influenced by the size of the openings and their locations in the reinforced shear wall. The closer the openings are to the edge of the wall, the more decrease strength. Also, the opening in the shear wall should be avoided, or it should be of minimum size and number as the height of the structure goes on increasing for tall structures.

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