ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology No. 4/2021

doi: 10.21307/ACEE-2021-032

DESIGN AND PERFORMANCE PARAMETERS OF SHEAR WALLS: A REVIEW

Abdulkadir Cüneyt AYDIN [a]*, Barış BAYRAK [b]

[a] Prof.; Engineering Faculty, Civil Engineering Department, Atatürk University, Erzurum, Turkey
*E-mail address: *acaydin@atauni.edu.tr*

[b] PhD; Engineering Faculty, Civil Engineering Department, Atatürk University, Erzurum, Turkey

Received: 27.05.2021; Revised: 14.09.2021; Accepted: 22.09.2021

Abstract

Reinforced concrete (RC) walls are used in buildings to provide lateral stiffness and strength against lateral forces like earthquake, wind etc. Shear walls are one of the most important lateral load-resisting systems in high-rise buildings. This paper provides an overview of not only reinforced concrete (RC), but also composite shear walls. The paper focuses on four inter-related review areas, namely i) conventional shear walls with rectangular cross section, ii) coupled shear walls, iii) composite shear walls, and iv) shear walls with opening(s). Behavior of shear walls which are the most damaged structural elements during earthquake and the parameters affecting this behavior are evaluated in this paper. However, this paper presents the available information about the design and performance parameters of shear walls.

Keywords: **Design; Composite shear wall; Coupled shear wall; Performance; Shear wall.**

1. INTRODUCTION

The reinforced concrete (RC) walls are used in buildings to provide lateral stiffness and strength against lateral forces like earthquake, wind, etc. Shear walls are one of the most important lateral load-resisting systems in high-rise buildings. Researchers have focused on understanding the behavior and characteristics of the shear walls over the last decades. Failure process, failure mode and deformation capacities of the shear walls have been the focus of many researchers. The investigations on the shear walls started in the early 70s and 80s [1–5]. Moreover, the experimental and theoretical investigations of the behavior of RC shear walls have been conducted since 1990s [6–10].

This paper focuses on four inter-related review areas, namely i) conventional and usually rectangular shear walls, ii) coupling shear walls, iii) composite shear walls, and iv) shear walls with openings. Apart from the aforementioned shear wall types, there are masonry and steel shear walls, which are beyond the scope of this paper. Many experimental and numerical studies have been carried out to understand the behavior of shear walls in the last decades. Thus, a large number of test data about the shear walls exists in the literature. In this paper, some selected applications of shear walls are described.

2. CONVENTIONAL RC SHEAR WALLS

The conventional shear walls are constructed with reinforcement and concrete, which can be varying types of concrete and special concrete. Such types usually have rectangular cross section but have T, U, or C type cross sections. One of the main parameters to be provided by the shear wall is ductility. The strength of the shear walls should be controlled by flexure rather than shear, which causes brittle failure, in order to ensure the ductile behavior. To achieve this, the shear capacity of a wall that must be known should be larger than the flexural capacity.

The shear walls are detailed and designed according to the capacity-design rules at the medium and high-risk area for earthquakes [11-12]. Shear walls have an important effect on decreasing structural damage by limiting the drift ratio. The performance of shear walls has been affected by a few parameters that alter the failure mechanism such as wall aspect ratio, boundary element, construction joints, ratio and layout of horizontal and vertical reinforcement. The aspect ratio which is one of the main governing parameters of the shear wall behavior is defined as the height–length ratio (H/L). In high-rise buildings, tall shear wall types are used; however, in low buildings, squat shear walls are preferred. The squat shear walls are subjected to large flexural moments during their service life. The squat shear walls are created for flexural strength at the base of the shear wall, as a result of their shortness, which results from large shear forces that cause the brittle failure and reduce energy dissipation capacity. The boundary members are consisting of reinforcement at the end of two sides of the shear wall. These members are usually presented to a low effective anchorage of transverse beams. According to the codes, the minimum horizontal and vertical reinforcement ratio should be provided, to prevent the crack pattern and reducing the crack width. The negative influence of low reinforcement and ductility properties of longitudinal reinforcement on the displacement capacity of shear walls, further revealed that the mechanical properties of the web reinforcement should be careful about the same concentration at the boundary members, when targeting for a ductile behavior of the shear walls [13-15]. In addition, artificial neural network/fuzzy logic applications for damage level determination of the RC shear wall have been studied in recent years to predict the behavior of RC shear walls and to determine the parameters that affect the behavior [16-17].

The shear wall behavior is affected by the M/Vl_w ratio; where M is the bending moment at the base of shear wall, V is the shear force, and l_w is the length of the wall, apart from the shear wall aspect ratio (H/L). The shear walls are defined according to their M/Vl_w ratios. The squat, intermediate, and slender shear walls are mentioned, while this ratio is less than one, between one and two, and greater than two, respectively. The failure modes are changing from shear to flexure through this increasing M/Vl_w ratio.

The RC shear walls have been exposed to many types of forces, which results in bending and/or torsional moment(s) or combination of these during their service lives. Researchers have been investigating the strength and deformation capacity of the squat or tall shear walls under quasi-static, cyclic loading or shaking table tests. However, the researchers have concentrated on the cyclic loading, to simulate the earthquake forces with hydraulic jack(s). Most of these works focused on the shear walls with and without axial loading conditions. Furthermore, some researchers have carried out studies on the shear walls that were made of high-strength concrete instead of conventional concrete [18]. As it is known, the high-strength concrete is more brittle than conventional concrete. Thus, the designers should be more careful in the design of shear walls that are made of high-strength concrete. Farvashany et al. (18) conducted a research on the 1/3 scaled shear walls with the concrete strength (as high as 80 MPa) under constant axial and increasing horizontal loads. The horizontal reinforcement ratios were 0.47% and 0.75%, while the vertical reinforcement ratios were 0.75% and 1.26%. Researchers have reported that an increase in the vertical reinforcement ratio has a significant effect on horizontal failure load. However, the horizontal reinforcement ratio has no important effect as the vertical reinforcement. The shear strength of wall specimens made of the high-strength concrete has affected the horizontal reinforcement ratio.

The seismic performance of the shear wall is critical to assess for investigating the response of the structure at laboratory conditions. The loading conditions at the laboratory must represent the real earthquake and the response of the shear wall and/or structure by observing experimental data [19].

The researchers are referred to the shaking table tests instead of quasi-static ones, as the most applicable experiment for reproducing the real dynamic effect of the earthquake to the structures. The dynamic effects are applied more realistically to shear walls, by using shaking tables. The displacement of the shear wall is the function of basic structural properties, due to the dynamic conditions [20–21]. However, there are a few disadvantages of the shaking table tests. Firstly, the shaking table system for full-scale testing of shear walls is very costly. Thus, the size of tested shear walls can be limited. Secondly, the controlling movements associated with the interaction of shaking table tests and with overturning moment that has an important effect on the tested shear walls is difficult [22]. In the quasi-static test method, the load and the deformation are increased and decreased, monolithically and cyclically. Despite the shaking-table tests, the quasi-static (QS) one is less costly and simple. During the QS

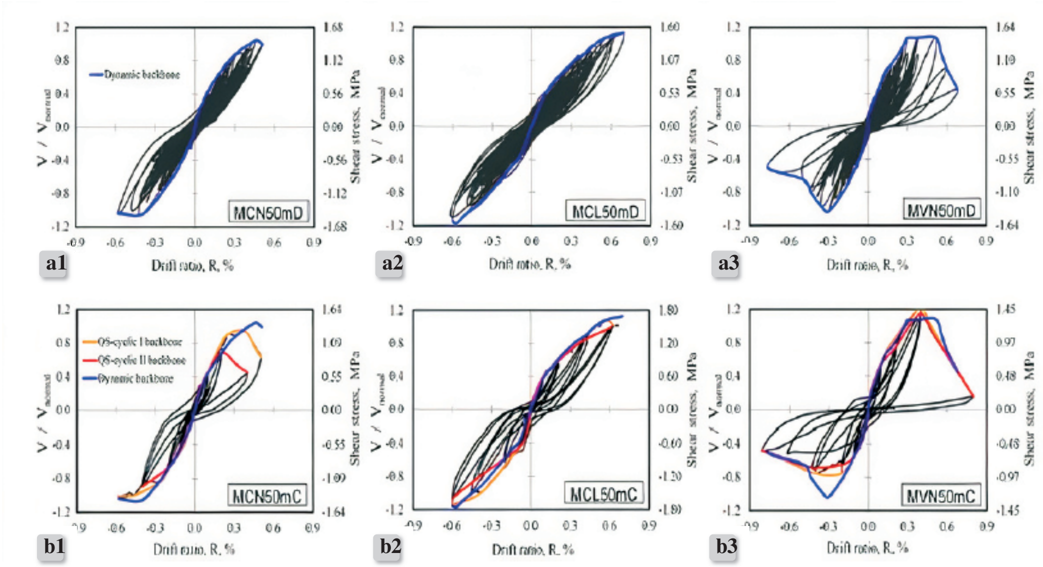
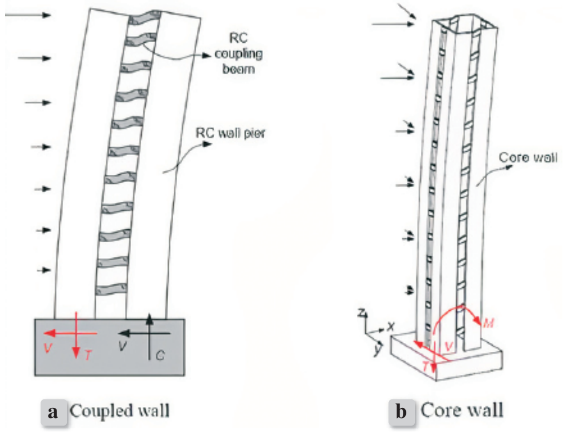


Figure 1.
Hysteresis curves of walls that failed diagonal tension a) shaking table tests b) QS-cyclic tests [22]

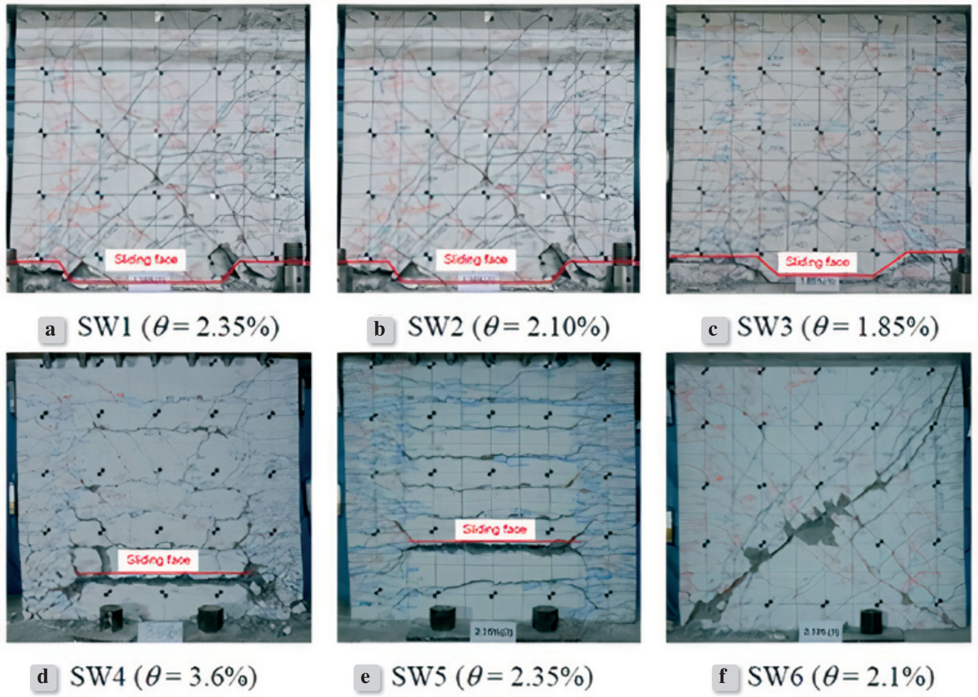
testing, to observe the crack pattern and the damage propagation is easier. Furthermore, the displacements, forces, and limit states can be measured easily. However, the seismic action of the tested shear wall models can be neglected at the quasi-static method [23]. Carrillo and Alcocer compared the seismic performance and the characteristic properties of the low-rise reinforced shear walls by using the QS-cycling loading and the shaking table tests [22]. The behaviors of the shear walls are investigated for the concrete (normal and lightweight concrete), the web steel ratio (0.125% and 0.250%), the wall geometry (solid and wall with opening), and web reinforcement type (deformed bar and welded-wire mesh), except the testing style. A comparison of the hysteresis curves is presented in Fig. 1. The results of the shaking table and QS-cyclic tests were given to compare and verify the results. The loading rate and the strength mechanism related to the failure modes were affected by the stiffness and strength parameters of the shear walls, for both shaking table and QS-cyclic tests.

On the other hand, axial loading is another point to be observed. While some of the researchers are focusing on axially loaded shear walls, the others are not. The axial load is usually applied to top of the shear walls. The researchers have shown that the shear walls may be subjected to tension force or combined shear and tension forces. These types of loadings, like the tensile or coupled tensile and shear forces frequently occur at the coupled shear walls. When the coupled shear wall has a high coupling ratio, the wall pier is subjected to the tensile force or may be subjected to the combined tensile and shear loading that is induced by lateral force(s). Due to the core wall system under bi-directional ground motion owing to overturning moment, occurred by lateral loading in the x-direction and shear force induced by lateral loading in the y-direction, the tensile stress is evaluated and is shown as in Fig. 2. The researchers [24–27] worked about the shear walls under axial tension and observed that the tensile force led to decreasing the stiffness and strength of the shear walls. If the shear walls' pier is to be subjected to an axial tensile force, more attention should be given by the designer.



a Coupled wall **b** Core wall

Figure 2.
The tensile stress at the coupled and core wall systems [27]



a SW1 ($\theta = 2.35\%$) b SW2 ($\theta = 2.10\%$) c SW3 ($\theta = 1.85\%$)

d SW4 ($\theta = 3.6\%$) e SW5 ($\theta = 2.35\%$) f SW6 ($\theta = 2.1\%$)

Figure 3.
Pictures of tested shear walls [27]

Ji et al. (27) carried out an experimental study to determine the influence of tensile forces on the rectangular cross-section of the shear walls. They suggested two empirical formulas that were defined to measure the degree of the axial tensile forces, within this study. The first one is the normalized concrete tensile stress (n_c), and the second one is the normalized reinforcement tensile stress (n_s). The researchers suggested the formulas, $n_s = T_n/(A_s f_y)$ and $n_c = T_n/((A_c + A_s E_s/E_c) f_y)$, where T_n, A_c and A_s denotes the axial tensile force of the wall, the cross-sectional area of concrete and the vertical reinforcement, respectively. E_c and E_s denote the elastic moduli of steel and concrete, and f_y and f_c denote the yield strength of steel and axial tensile strength of concrete, respectively. They have indicated that the shear strength of the tested wall decreased with an increasing axial tensile force. The shear walls are illustrated in Fig. 3. The shear walls tests, which are presented in Fig. 3, show that three failure modes. Figs. 3a-b-c and Figs. 3d-e show the RC shear wall under the axial tensile force and high axial tensile force, respectively. Fig. 3f show the diagonal tensile failure of RC shear wall.

Last decade, the researchers started to focus not only on the evaluation of the characteristic parameters of shear walls, but also on the retrofitting and strengthening of shear walls, using conventional or innovative materials, such as the steel-plate bonding, the reinforced concrete jacketing or the fiber-reinforced polymer (FRP) [28–29]. Among them, the FRP, which is used with epoxy for retrofitting and/or strengthening of existing RC members, is the most popular technique owing to its simplicity of application, high resistance to corrosion, free maintenance, and low cost. Investigation of the behavior of RC members with FRP has especially focused on the columns. One of the first applications of FRP was the repair and strengthening of RC columns in early 1990s [30]. Christidis and Trezos carried out the experimental investigation of the strengthening of shear walls [31]. They studied the behavior of medium-rise shear walls consisting of various arrangements under cyclic loading. Furthermore, Antoniades et al. investigated the behavior of 1:2.5 scale shear walls that are repaired and strengthened by using FRP sheets [32]. The test results have shown that the flexural and shear strengths of the tested shear walls were increased by using FRP. After major earthquakes, the researchers have shown that the shear walls were the most damaged structural elements because of their high lateral stiffness. Thus, it is an important issue to repair or strengthen the shear walls for improving the deformation or the energy dissipation capacities of the structure(s), after medi-

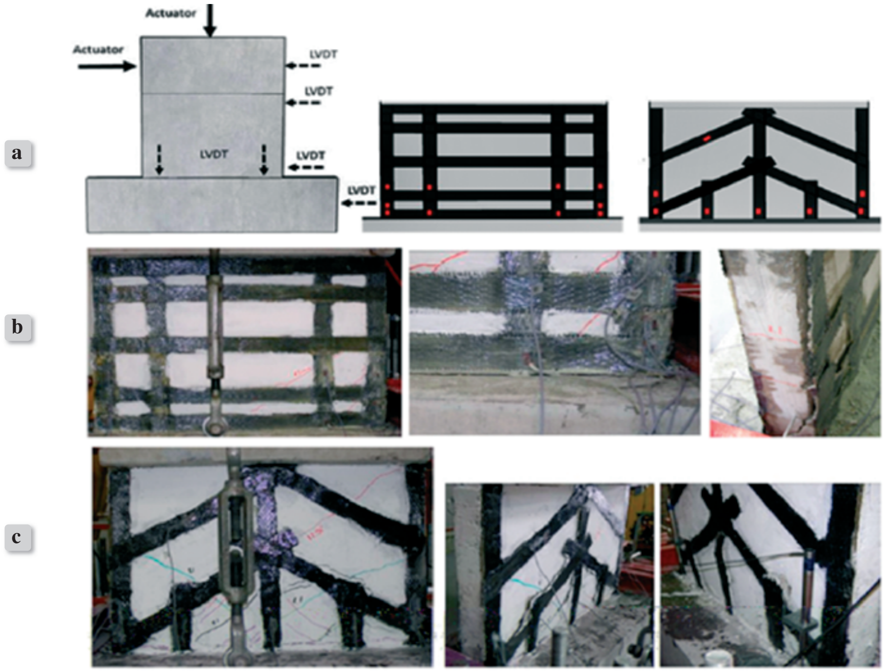


Figure 4.
a) Schematic detail of strengthened shear walls b) Failure pattern of strengthened strip shape shear wall c) Failure pattern of strengthened diagonal shape shear wall

um or high magnitude earthquakes. Some researchers have also investigated the effect of carbon fiber-reinforced polymer (CFRP) [15–33] on the seismic behavior of the shear walls, by the CFRP wrapping technique [34–36]. Furthermore, Qazi et al. [37] carried out the applicability of CFRP on the energy dissipation capacity, strength, and stiffness of the short shear walls that were susceptible to brittle shear failure, which restrain deformation capacity; and hence, decreased the seismic performance under cyclic loading with a constant axial loading at the top of the wall. They manufactured three shear walls, where one of the models was for the control, and two of them were strengthened with CFRP by bonding two different configurations, which were shaped as diagonal and strip. Two types of CFRP applications positively affected the shear strength, the stiffness, and the crack pattern of the shear walls. The diagonal cracks and the concrete splitting at the wall base were similar for two types of the shear walls (Fig. 4). Lefas and Kotsovos [7] studied the shear walls for retrofitting purposes by using two methods. In the first method, their goal was only to control the damage in the compression zone. The goal of the second method was not only to control the damage in the compression zone, but also, to control the tension and inclined cracks within the wall web by using epoxy resin. The design parameters of the shear walls were similar for the horizontal and vertical reinforcement ratios. However, the loading type and the repairing technique were different. The loading type was the pseudo equivalent of a field event which was representative of an event with greater pre-failure severity for wall. The test results showed that the repaired shear walls, displayed lower stiffness and ductility than the ones that are not repaired. Meanwhile, the crack pattern and the failure mode were similar for both the original and the repaired walls.

The lightweight concrete provides thermal and acoustic insulation, energy saving, fire-resistance, dead load reduction, which provide low lateral earthquake loads for structures, and consequent reduction of seismic base shear. Thus, lightweight concrete is preferred by the researchers instead of conventional concrete. The conventional concrete is frequently used to manufacture the shear wall at the experimental investigations. Carrillo et al. [38] have carried out an experimental work to observe the displacement, stiffness, shear strength, energy dissipation capacity of the shear walls, which were manufactured with lightweight concrete for three aspect ratios (0.5:1.0:1.5), two web reinforcement ratios (0.25% and 0.125%), two reinforcement types (mid-steel deformed bars and cold drawn welded-wire mesh), and two testing types (quasi-static cyclic and shaking table). The

Table 1.
The dimensions and reinforcement characteristics of tested shear walls [38]

Concrete Type	No	Wall	t_w (mm)	l_w (mm)	h_w/l_w	Web reinforcement		Boundary element			
						Layout	$\rho_{h,v}$ (%)	Longitudinal		Stirrup(s)	
								Lay	ρ (%)	Lay	ρ (%)
Lightweight concrete	1L	MCL50M	102	2397	1.01	3Ø500 mm	0.14	8 ≠ 5	0.68	2Ø150 mm	0.42
	2L	MCL100M	101	2398	1.01	3Ø250 mm	0.28	8 ≠ 6	0.98		0.42
	3L	MCL50C	101	2398	1.01	3Ø500 mm	0.14	8 ≠ 5	0.68		0.42
	4L	MCL100C	101	2399	1.01	3Ø250 mm	0.28	8 ≠ 6	0.98		0.42
	5L	MRL100C	101	5413	0.45	3Ø250 mm	0.28	6 ≠ 6	0.32		0.42
	6L	MRL50mC	106	5415	0.44	mesh 6x6-6/6	0.12	8 ≠ 5	0.21		0.40
	7L	MLC50mC	100	2403	1.00	mesh 6x6-6/6	0.12	6 ≠ 6	0.74		0.43
	8L	MEL50mC	100	1221	1.94	mesh 6x6-6/6	0.12	4 ≠ 6	0.99		0.43
	9L	MCL50mD	82	1917	1.00	mesh 6x6-8/8	0.11	6 ≠ 5	0.79	2Ø180 mm	0.44
	10L	MCL50D	82	1912	1.00	3Ø320 mm	0.27	8 ≠ 5	1.06		0.44
Normal weight concrete	1N	MCN50M	102	2402	1.01	3Ø500 mm	0.14	8 ≠ 5	0.67	2Ø150 mm	0.42
	2N	MCN100M	101	2402	1.01	3Ø250 mm	0.28	8 ≠ 6	0.98		0.42
	3N	MCN50C	102	2399	1.01	3Ø500 mm	0.14	8 ≠ 5	0.68		0.42
	4N	MCN100C	101	2397	1.01	3Ø250 mm	0.28	8 ≠ 6	0.98		0.42
	5N	MRN100C	100	5400	0.45	3Ø250 mm	0.28	4 ≠ 6	0.22		0.43
	6N	MRN50mC	103	5396	0.45	mesh 6x6-6/6	0.12	8 ≠ 5	0.22		0.41
	7N	MCN50mC	103	2398	1.01	mesh 6x6-6/6	0.12	6 ≠ 6	0.72		0.42
	8N	MEN50mC	101	1239	1.99	mesh 6x6-6/6	0.12	4 ≠ 6	0.96		0.42
	9N	MCN50mD	83	1916	1.00	mesh 6x6-8/8	0.11	6 ≠ 5	0.78	2Ø180 mm	0.43
	10N	MCN50D	84	1921	1.00	3Ø320 mm	0.26	8 ≠ 5	1.02		0.42

dimensions and reinforcement characteristics of walls are presented in Table 1. The test results have shown that the shear strength, displacement, the stiffness and energy dissipation capacity of the shear walls with lightweight concrete were greater than that of the conventional ones.

The axial load ratio was selected by the researchers as 0.15. Many researchers have applied low levels of axial load effect on shear walls. However, some researchers have experimentally investigated the effect of high axial load on the shear wall behavior, the shear strength, deformation capacity, drift ratio, energy dissipation capacity etc. The axial load ratio (ALR) is equal to $ALR = N/\ (f_c A_g)$, where f_c is the cylinder strength of concrete at 28 days and A_g is the cross-sectional area of the wall. The axial load ratio has a significant effect on the failure mode, ductility, and stiffness of the shear walls, where these parameters provide the life safety during an earthquake [13]. Su and Wong [39] conducted an experimental work for the shear walls with high aspect ratio, high longitudinal steel ratio, and high concrete strength. They designed their experimental plan to evaluate the effect of high axial load ratio, and confinement on the performance of the shear walls, under combined axial loading, shear and moment [39]. The test results showed that, the axial load ratio has an important effect on the deformability and the failure mode of the shear walls. The maximum rotation ductility of the shear wall decreased with increasing axial load ratio. The researchers have indicated that, the axial load ratio is a significant factor for the life safety and the collapse performance criteria.

Another experimental investigation about the effect of high axial load ratio is that the shear walls with an axial load ratio of 0.25 were tested under combined axial load and shear to investigate the cracking process, failure mode, strength, deformation, and stiffness characteristics [41]. The shear walls with an axial load ratio, as 0.35, showed an undesirable out-of-plane buckling failure in the post yielding stage. Dong et al. (40) carried out a numerical investigation about how the axial load ratio affected the seismic performance; including ductility, stiffness, load-displacement responses, and energy dissipation capacity of slender shear walls. Thus, six slender shear walls under different axial load ratios (Table 2) were analyzed by nonlinear finite element method. The finite element model, geometries, and reinforcement details of analyzed shear walls are shown in Fig. 5. The increasing ALR increased the bearing capacity,

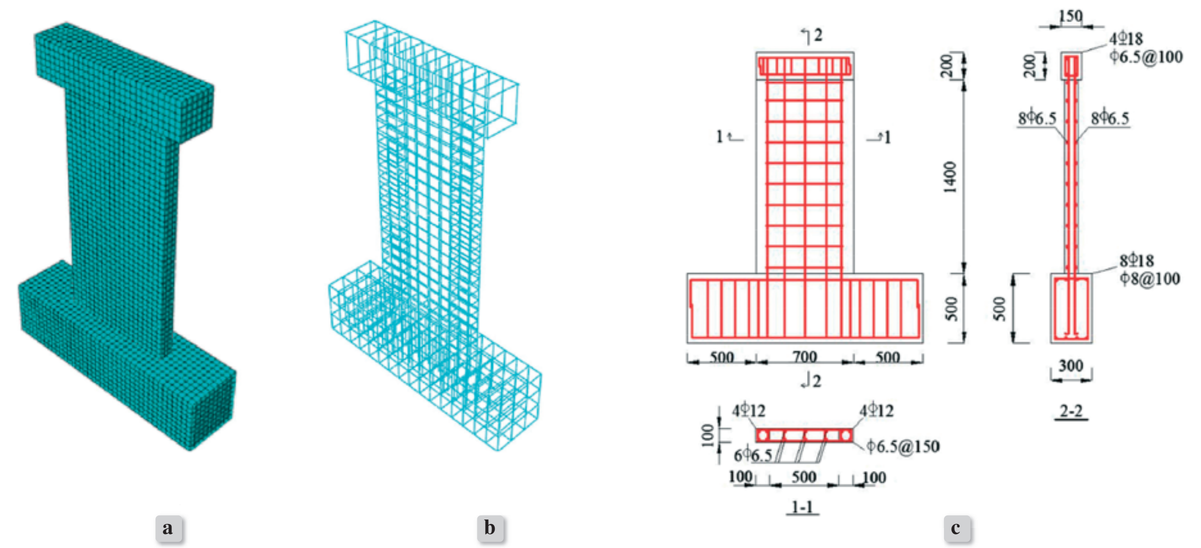


Figure 5.
The finite element model a) shear wall b) reinforcement bars c) geometries and reinforcement details of analyzed shear wall [40]

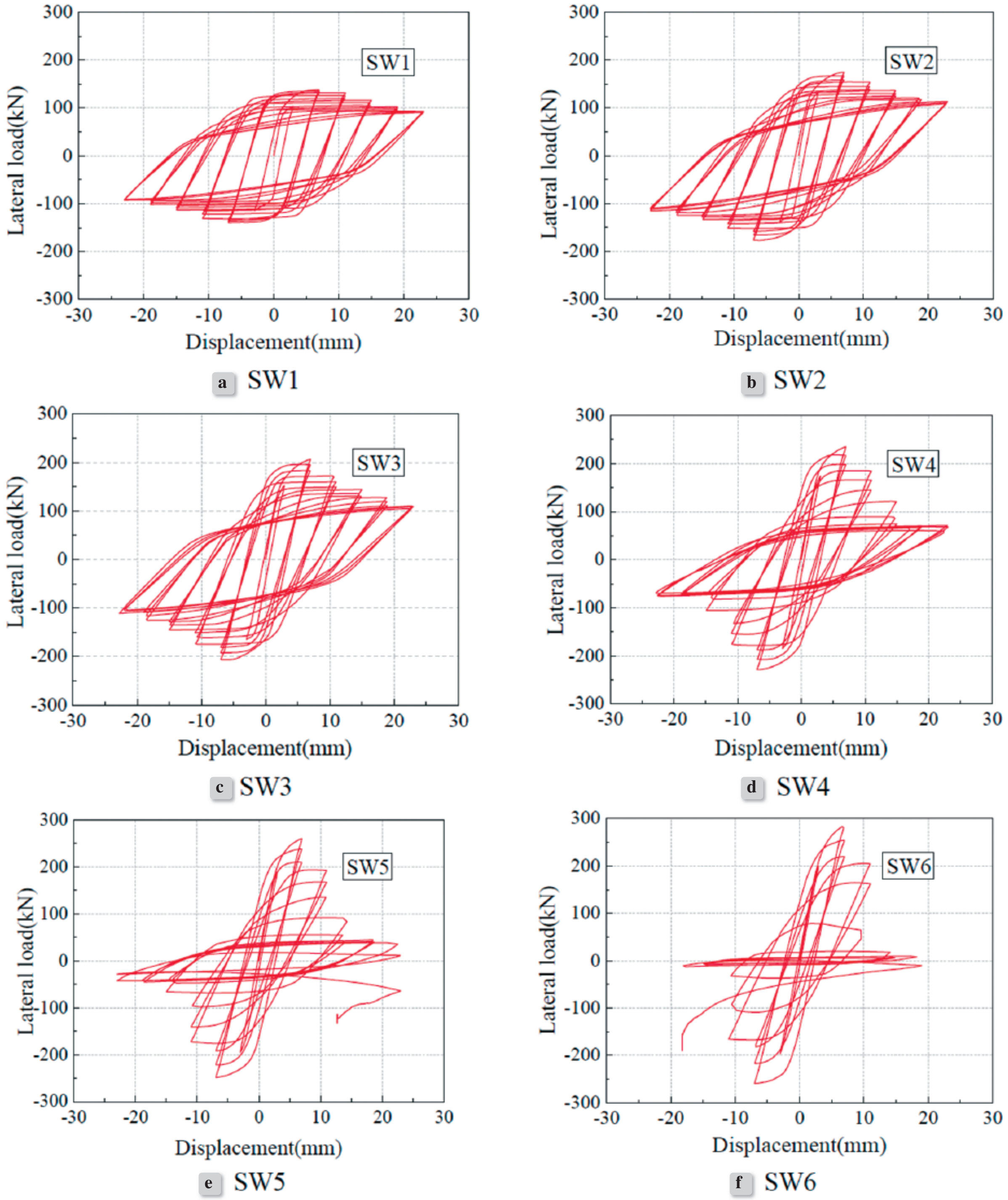
Table 2.
Axial load ratio of analyzed shear walls [40]

Shear wall	Axial load ratio	Axial load (kN)
SW1	0.1	497
SW2	0.2	994
SW3	0.3	1491
SW4	0.4	1988
SW5	0.5	2485
SW6	0.6	2982

the initial stiffness, in contrast to deformation capacity, which could be drawn from the test results. Furthermore, the maximum energy dissipation capacity is observed for the shear walls with the ALR of 0.2. When the ALR is more than 0.3, the ductility and the energy dissipation capacity decreased significantly. However, when the ALR is more than 0.4, stiffness degradation increases significantly. Fig. 6 shows lateral load-displacement curves of the modeled shear walls.

Another factor affecting the behavior of the shear walls is the reinforcement layout and also the first study used the diagonal reinforcement layout was conducted by [42]. They have remarked that the failure of the shear walls was due to the diagonal cracking, whereas in the shear wall manufactured with diagonal reinforcement, the failure mode was mainly flexural. Salonikios [43] compared the diagonally reinforced shear walls with the vertically and/or horizontally reinforced ones; for varying aspect ratios, axial load ratios, reinforcements at the edge columns, and the web reinforcements (Fig. 7). The presented study has shown that the diagonal reinforcement layout was affected to improve the strength against sliding shear as well as the flexural strength.

The researchers recently have tended to use innovative materials to reinforce the shear walls to improve their seismic performance for stiffness, strength, energy dissipation capacity, etc. Especially, Tolou Kian and Cruz-Noguez have studied the seismic performance of slender shear walls (aspect ratio of 2.0), which were manufactured with three different innovative reinforcing schemes. They have used mild steel and self-centering reinforcements; shape memory alloys, glass fiber reinforced polymers, and high-strength steel strands [44]. The details are presented in Fig. 8. Furthermore, the fiber-reinforced cementitious composites were used to manufacture for the shear walls to be more damage resilient. The experimental results showed that, the innovative walls reached high levels of energy dissipation and ductility capacity. Although, the innovatively reinforced shear walls had smaller drift ratio and moderated damage compared with the control shear wall. The 10 M steel bars were used together 4 NiTi bars, 5 GFRP bars, and 13 mm strand at the same shear walls since they required nearly the same amount of tensile force to attain yielding (Fig. 8).



a SW1

b SW2

c SW3

d SW4

e SW5

f SW6

Figure 6.
Load-displacement hysteresis curves of the shear walls [40]

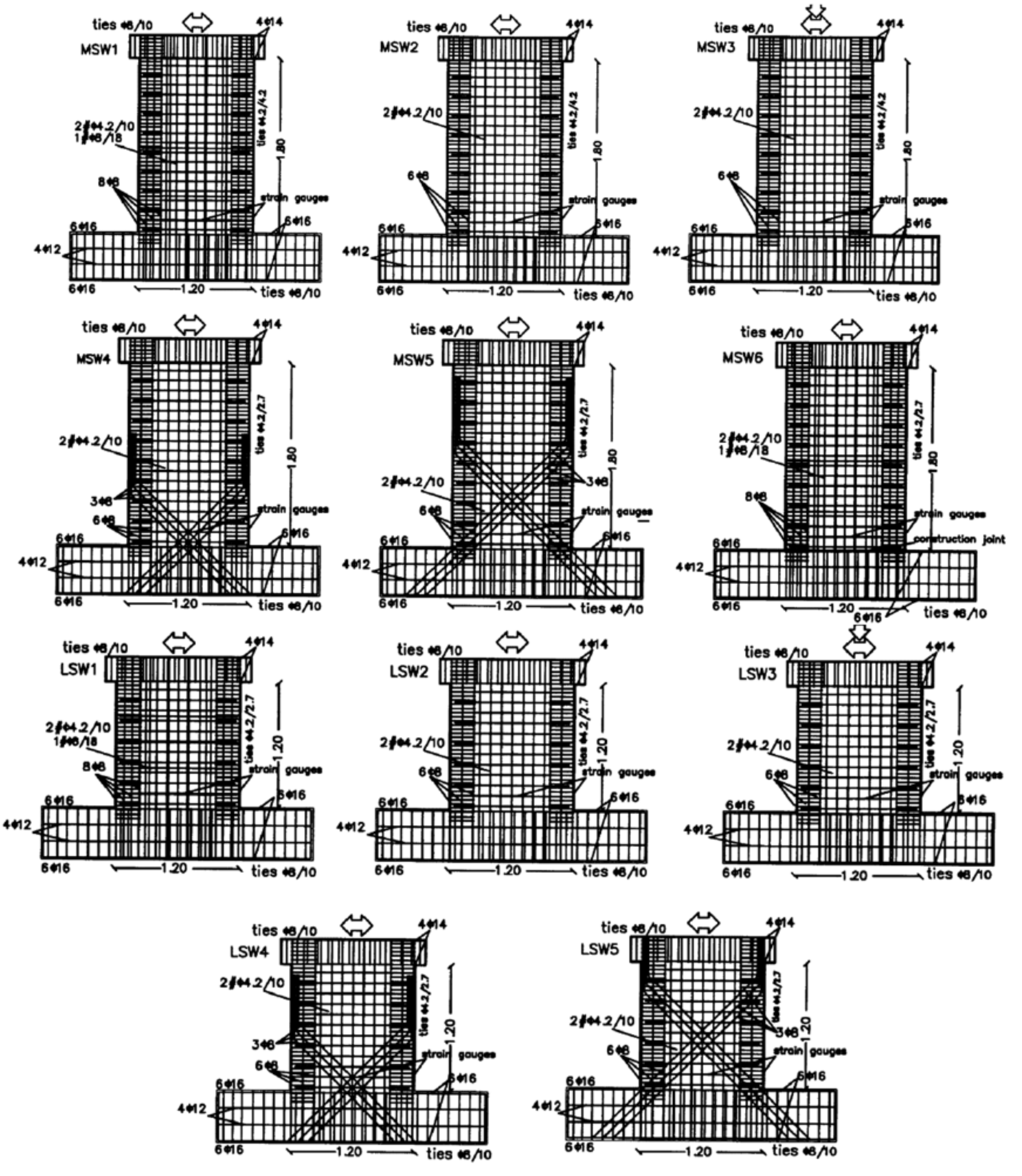


Figure 7.
Reinforcement layouts of shear walls [43]

Mohamed, Farghaly et al. [45] carried out an experimental investigation to evaluate the behavior of shear walls reinforced with glass fiber-reinforced polymer (GFRP) bars. The four shear walls as control specimens and three shear walls, designed for varying aspect ratios with GFRP bars were tested under cyclic lateral loading. According to their results, the shear walls with GFRP bars exhibited greater flexural strength with no strength decrease in accordance with the control ones. Furthermore, the shear, sliding shear, and anchor failures were not observed and could be effectually restricted. In addition to this, the aspect ratio had a significant effect on both inelastic flexural and shear deformation. The researchers indicated that the most important advantage of shear walls with steel reinforcement was the energy dissipa-

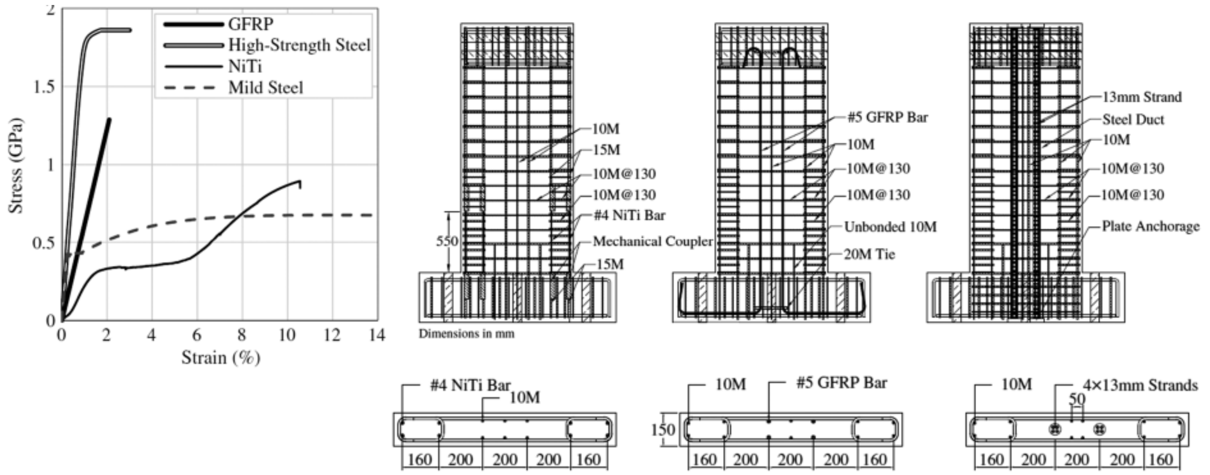


Figure 8.
Tensile stress-strain relationship of the reinforcements and reinforcement details of the shear walls [44]

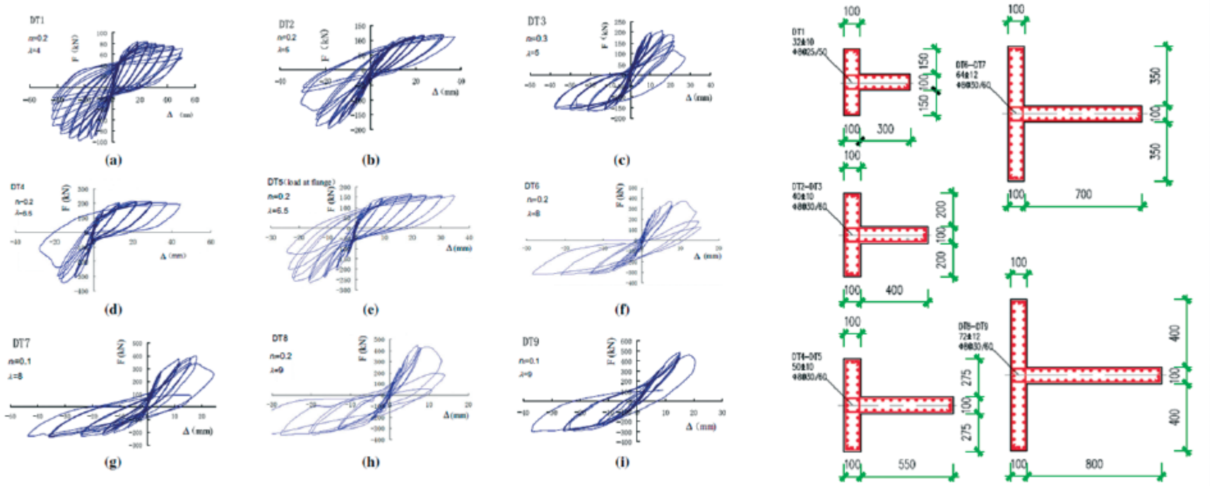


Figure 9.
Reinforcement details and hysteric loops of the specimens [7]

tion capacity. However, for the shear walls with GFRP bars, this advantage has no permanent deformation up to 80% of the ultimate capacity. Nevertheless, there are limited investigations for the shear walls with GFRP bars, either experimentally or numerically. Some more and enough investigations about the reinforcement with GFRP bars will enhance the design codes and guidelines, for their potential usage in construction industry, as a result of their striking deformation capacity, energy dissipation capacity, and strength.

Lefas and Kotsovos [7] conducted an experimental investigation on T-shape shear walls to determine the effect of the high-thickness ratio, the volumetric ratio of stirrups as well as the axial load ratio under cyclic loading. The results showed that, an increase in high thickness ratio and axial load ratio will decrease the inter-story drift and will increase the damage and the energy dissipation capacity. However, the axial load ratio doesn't affect the ductility of T-shaped shear walls, significantly. The reinforcement details and hysteric loops are illustrated in Fig. 9. The researchers suggested that the axial load ratio and the high-thickness ratio should be considered together, during the detailing of T-shape shear walls.

The plastic hinge length is calculated with a few expressions. One of these expressions is the proposed formula by Eurocode-8. The proposed formula for the plastic hinge length (L_p) in Eurocode-8 is as follows:

$$L_p = \frac{L_v}{30} + 0.2L_w + 0.11\frac{d_{Bl} f_y}{\sqrt{f_c}} \tag{1}$$

where L_v = shear span (M/V), d_{Bl} = diameter of the tension reinforcement, f_y = yield stress of the longitudinal reinforcement and f_c = compressive strength of concrete, M = bending moment, V = shear force.

Mattock [46] and Priestley, Seible et al. [47] proposed to calculate the plastic hinge length for RC members by using the formula given below:

$$L_p = \alpha L + \beta D + \xi f_y d_b \tag{2}$$

Where L = member length between two joints, D = member depth, d_b = diameter of longitudinal reinforcement. Furthermore, Priestley, Seible et al. [47] have proposed some constants ($\alpha = 0.08$, $\beta = 0$ and $\xi = 0.022$) to calculate the plastic hinge length of the shear walls. Thus, the plastic hinge length of the shear wall is evaluated as below.

$$L_p = 0.08L_w + 0.022 f_y d_b \tag{3}$$

Paulay and Priestley [11] have also proposed another equation to calculate the plastic hinge length of the shear wall. Where the plastic hinge length is associated with L_w (length of shear wall) and (M/N).

$$L_p = 0.2L_w + 0.07(M/N) \tag{4}$$

A new approach for plastic hinge length was proposed by Bohl and Adebar [48]. The equation is defined as

$$L_p = (0.2L_w + 0.05L_v)(1 - 1.5\frac{P}{A_w f_c}) \leq 0.8L_w \tag{5}$$

where P= axial load and A_w= wall area.

2.1. RC Coupled Shear Walls

The reinforced concrete (RC) coupled shear walls (CSWs) consist of two wall pier, and these wall piers are interconnected by coupling beams (CB) [49–50]. The concrete-steel composite and fiber-reinforced concrete CBs are usually constructed in high-rise or multi story buildings for their superior lateral resistance, stiffness, deformation, and effective energy dissipation capability [51]. The researchers have been carried out a series of experimental and numerical studies about the design parameters of RC CSWs [52–54].

The CB is designed as a deep beam with heavy reinforcement. During an earthquake, large cyclic shear deformations occur at the CBs. Hence, the plastic hinges are formed at both ends of the CB. A ductile behavior usually is expected from the CB. Thus, improving the behavior of CB is a very important issue. However, most of the researchers have focused on improving the shear and flexural failure behavior of CB. A few parameters significantly affect the performance of CBs; such as concrete strength, shear-span depth ratio, loading type, layout of horizontal and vertical reinforcement. In addition, both shear walls and coupling beams must be designed as ductile.

By reducing the required moment of CSW system, when compared with one in two individual walls and effectively dissipating earthquake energy over height of the wall are main advantages of CSW, when compared to the conventional RS shear walls. However, the CSWs have an effective lateral stiffness, which is higher than the sum of its wall piers [55].

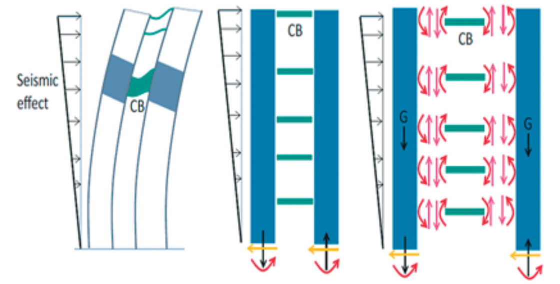


Figure 10.
Coupled shear wall systems [56]

Zhao et al. [51] studied the seismic performance of CSW systems manufactured with steel fiber-reinforced concrete, where the fibers were mixed as volume proportion of 1% and 2%. The use of steel fiber has a significant effect on the crack pattern and deformation capacity, as well as initial stiffness, ductility, and energy dissipation capacity (Fig. 11). Furthermore, increasing the steel fiber ratio increases the ductility and energy dissipation capacity.

Galano and Vignoli [57] tested the coupling beams with different reinforcement layouts as the classical and diagonal scheme, without confining ties. The CBs with the diagonal scheme, confining ties, and inclined bars are formed in a rhombic scheme for varying concrete strengths under cyclic loading. The results showed that, the coupling beams with the diagonal or rhombic reinforcement layout exhibited better performance than the ones with the classical scheme. The CBs with the rhombic reinforcement layout, were more ductile and also, presented greater energy dissipation capability, than the classical ones. Furthermore, the concrete strength considerably affects the performance of CSW.

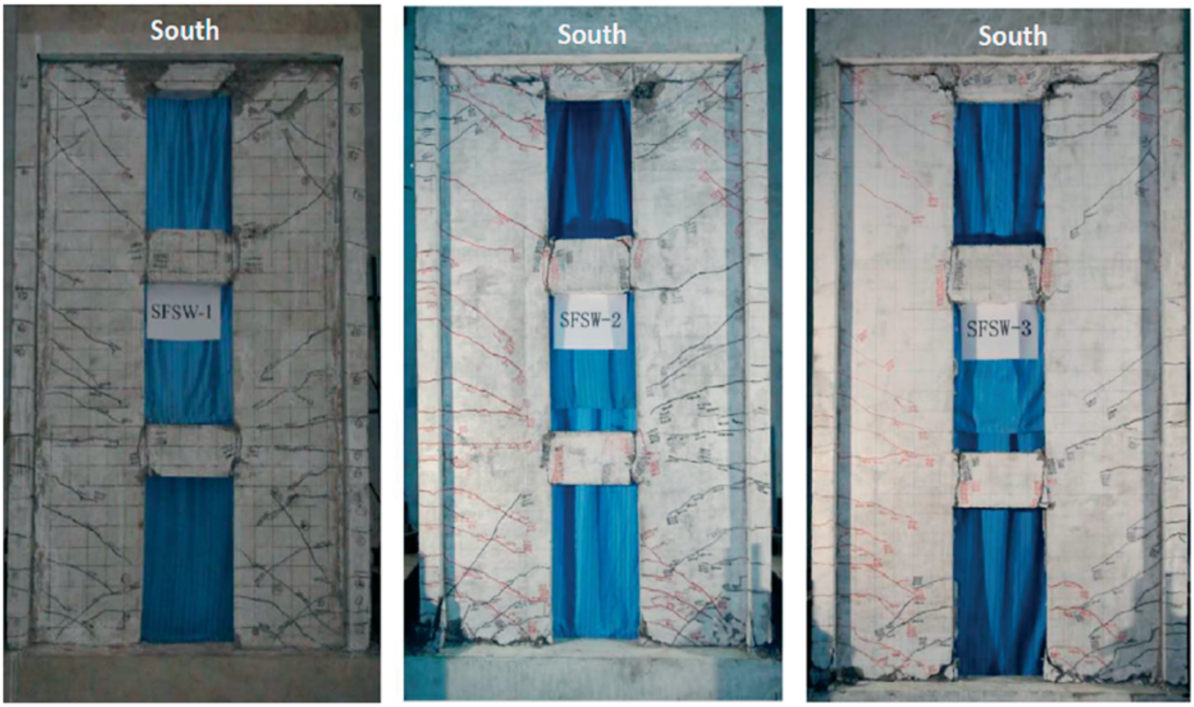


Figure 11.
Crack patterns of CSWs [56]

Zhang et al. [58] carried out an experimental study on the shaking table behavior of RC coupled shear walls. The main parameters were the opening ratio, the web reinforcement ratio of the wall limbs, the style of inclined reinforcement, and the inclined reinforcement of coupled beams; while the concrete strength and geometric dimensions were similar. The dynamic performance and failure mode of the CSWs were evaluated and analyzed throughout the mentioned work. The results showed that, the RC CSW with inclined steel bars has better performance than RC CSW without inclined steel bars.

Wang et al. [59] used the metallic damper that yields first during an earthquake, as absorbing a large amount of energy and guarding the coupling beam to improve the seismic performance of the CSW. The results of experimental and parametric study of two CSWs, one with the traditional coupling beam and the other with the hybrid coupling beam were tested under cyclic loading are described in their paper. As a result, the hybrid coupling beam could reduce the base shear force by more than 30% and improve the seismic performance of CSW.

Ji et al. [60] conducted an experimental investigation on CSW system to determine the seismic behavior and replicability of the replaceable coupling beams, which differs in type of beam-to-link connections. The CSW systems were adopted including end plate; which shear link were jointed to extended, end plate using complete-joint-penetration (Fig. 12a); splice plate, which the link web was spliced to the beam web in double shear (Fig. 12b), bolted web that the shear link consisted of back-to-back double channel sections (Fig. 12c), and adhesive web that a double channel link was connected with the web of the beam segment through the web connection (Fig. 12d).

The strength capacity of shear link is improved by the link-to-beam connections. As the shear link is damaged, it can be replaced easily. The coupling beams with end plate connections have better hysteric behavior than the others. The coupling beams adopted the splice plate connection and bolted web connection, have exhibited inelastic behavior. However, the coupling beam, with the adhesive web connection, is damaged at the beginning of test; owing to the brittle failure of adhesive.

Cheng et al. [55] conducted an experimental study consisting of two CSWs which one was the control specimens using diagonal RC CBs and the other was the hybrid CSW with low yield point steel (LYP) (f_y = 100 MPa) web that was consisted of three parts: the mid-span region and two end regions under cyclic lateral load as well as constant axial load. The experimental results indicate that the CB with the connec-

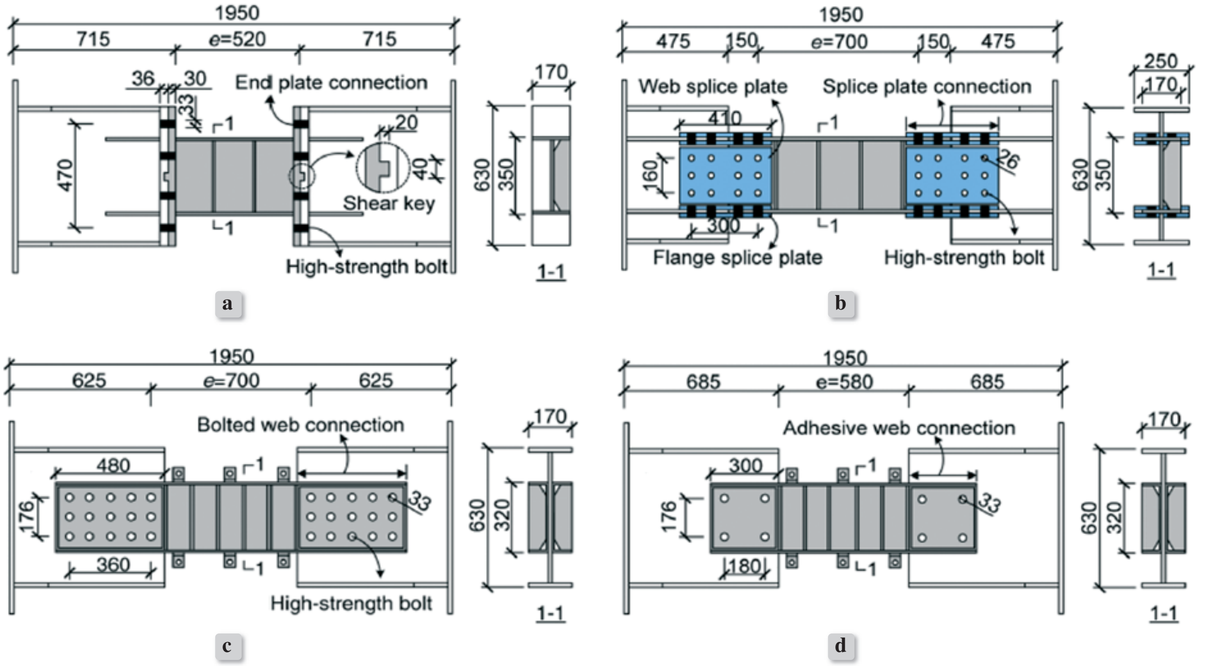


Figure 12.
Geometry and dimensions of tested specimens [60]

tion type of LYP steel exhibit ductile behavior that separates the shear and moment transfer mechanism between the RC shear wall and steel coupling beam.

2.2. Composite Shear Walls

In recent years, several super tall buildings have been constructed all over the world; especially in the highly seismic regions, such as China, Japan, and Hong Kong. For the super high-rise buildings; high levels of seismic response and large lateral stiffness are very important issues, as well as cost and speed of the construction. Hence, the engineers have been tended to composite shear walls consisting of the concrete and core tube that is one of the most important elements of the structural system to provide adequate deformability and energy dissipation. The investigation of composite shear walls [61–63] started especially in Japan at 1980s [64] Nowadays, the steel plate-concrete composite walls are divided to the steel-plate reinforced concrete [65–66] and concrete filled double-steel plates (CFDSP) are used in the practice. The different types of CFDSP and proposed by the researchers' composite shear walls are shown in Fig. 13 [67] And also three types of composite structural systems are explained in Fig. 14 according to the EuroCode-8 part 7.10 [68].

Nie et al. [67] proposed a new type of composite shear wall that was made of detailed concrete filled double-steel-plate wall, by using high-strength concrete under high axial load ratio, as well as cyclic loading. The proposed new composite shear wall is made of concrete steel tubular columns at the end of two sides of the wall. The concrete filled double-steel-plate wall that is divided by vertical stiffeners is transversely connected by distributed batten plates. The composite shear walls have different dimensions, shear span ratio, concrete comprehensive strength, steel plate thickness of boundary columns and wall body and steel content ratio as well as the axial load ratio. It was found that the proposed composite shear wall exhibited very good ductile behavior and large deformation capacity. The shear walls' parameters and the results of hysteric curves of tested specimens are shown in Table 3 and Fig. 15. On the other hand, the applied axial load ratio is different from conventional RC shear walls and is calculated from the Equation 6.

$$n_d = \frac{1.25N}{f_c^1 A_c/1.4\ + f_y A_s/1.11} \tag{6}$$

where n_d is the axial load ratio and N is the axial comprehensive force, $f_c{}^1$ is compressive strength of concrete, A_c is the cross section of shear wall, f_y yield strength of longitudinal reinforcement, A_s is the cross section area of longitudinal reinforcement.

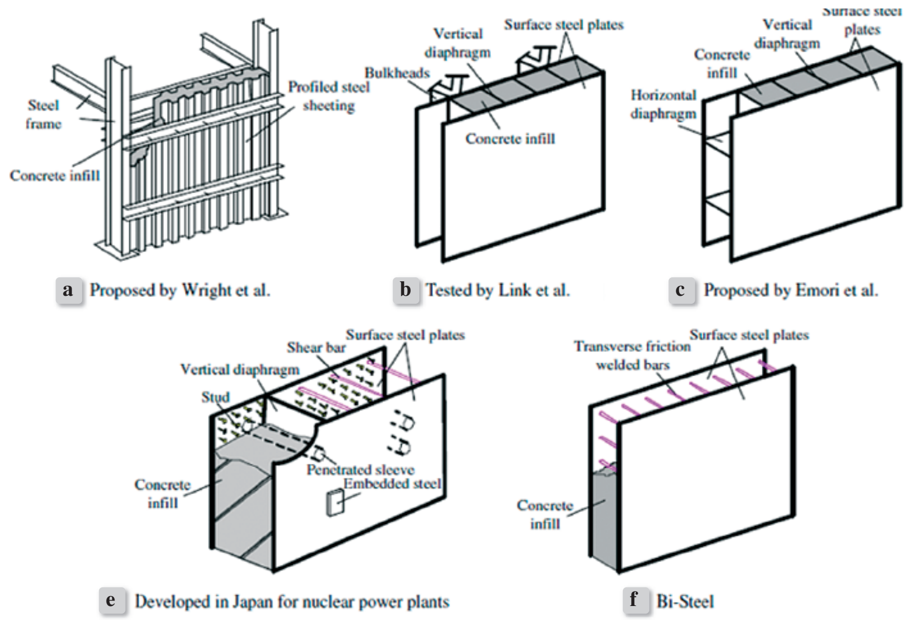
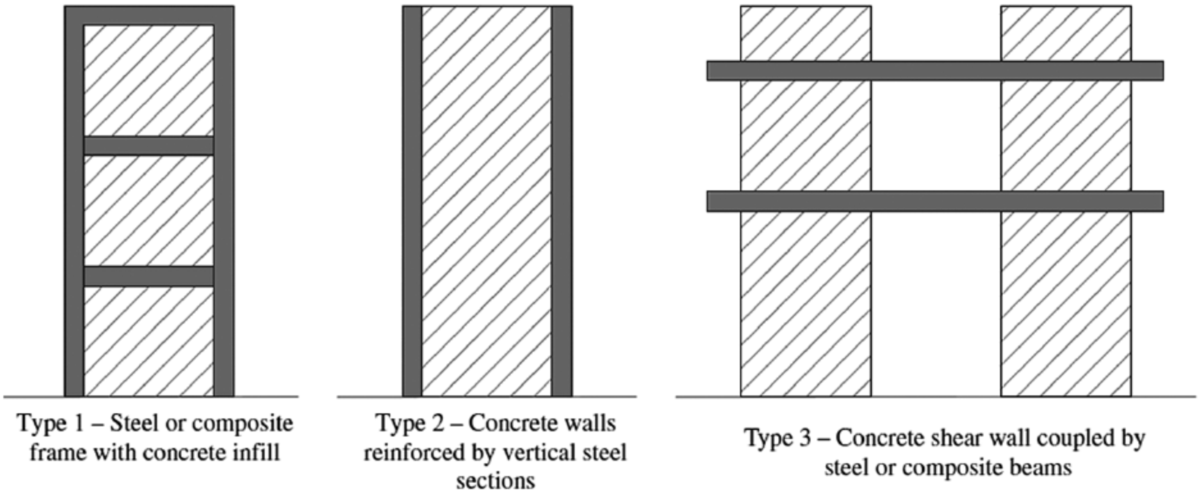


Figure 13.
Different types of CFDSP shear walls [69]


Type 1 – Steel or composite frame with concrete infill

Type 2 – Concrete walls reinforced by vertical steel sections

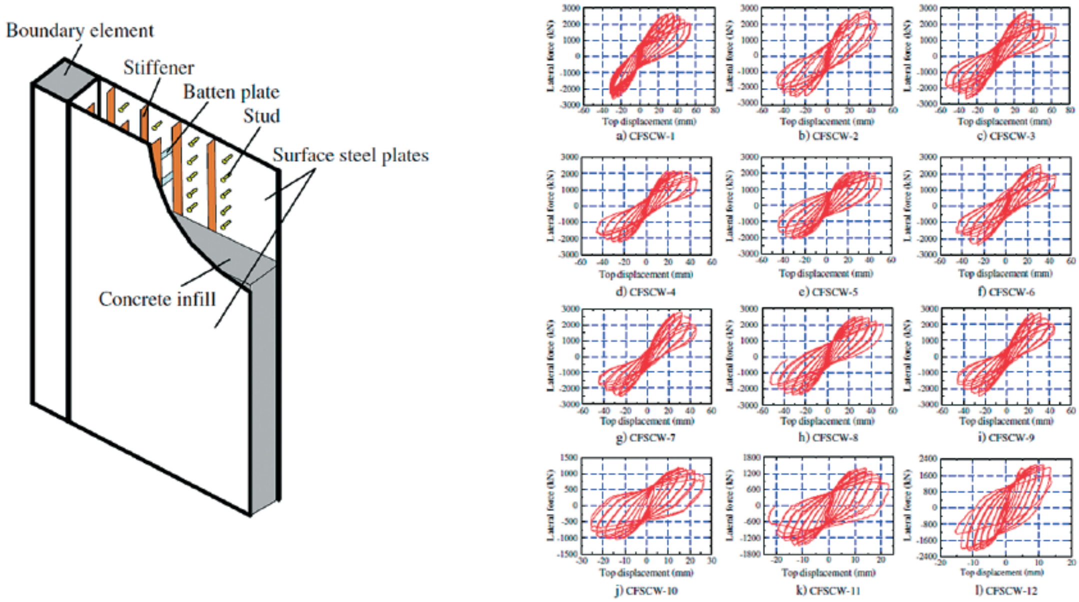
Type 3 – Concrete shear wall coupled by steel or composite beams

Figure 14.
Composite structural systems [68]

Another type of composite shear wall is the composite steel plate shear wall (CSPSW) consisting of a steel frame with an infill steel plate where the CSPSW has a significant earthquake or wind loading resistance, light weight, small thickness, and is easy for construction. And also, the shear studs or bolts are used to connect together the RC shear wall and steel plate. However, the buckling under the high axial loading is a very important problem for these shear wall systems. The buckling of the steel plate negatively effects the stiffness, the shear strength, and the energy dissipation capacity of the shear wall system. To prevent this problem, when the concrete layer is connected to one side of the steel plate, this system behaves like a stiffened steel plate shear wall system, in which the reinforced concrete panel has an important role of stiffener and prevents buckling of the steel plate. When the buckling of the steel plate is prevented by the concrete layer, the more ductile behavior and the greater lateral stiffness are exhibited by CSPSW system in comparison with the steel plate shear wall system. Meghdadaian and Ghalehnovi [69] carried out an experimental and analytical study. Their main concern was to observe the effect of openings on the per-

Table 3.
Shear wall parameters of tested specimens [69]

Specimen	Cross section (mm x mm)	Shear span ratio	Cubic compressive strength of concrete	Mesh reinforce-ment	Steel plate thickness of boundary column (mm)	Steel plate thickness of wall body (mm)	Steel content ratio (%)	Axial compressive force (kN)
CFSCW-1	1284x214	2.0	87.5	0	5	5	7.1	7375
CFSCW-2	1284x214	2.0	86.1	0	5	5	7.1	7319
CFSCW-3	1284x214	2.0	86.1	0	5	5	7.1	7319
CFSCW-4	1284x214	2.0	89.8	0	4	4	5.8	7535
CFSCW-5	1284x214	2.0	88..1	0	3	3	4.6	7404
CFSCW-6	1284x214	2.0	65.0	0	5	5	7.1	5863
CFSCW-7	1284x214	2.0	102.6	0	5	5	7.1	7900
CFSCW-8	1284x214	2.0	88.4	0	6	4	7.1	7807
CFSCW-9	1284x214	2.0	83.3	Ø8@130	5	5	7.1	7375
CFSCW-10	750x125	2.0	83.7	0	3	3	7.1	2756
CFSCW-11	750x125	1.5	80.7	0	3	3	7.1	2718
CFSCW-12	750x125	1.0	88.0	0	3	3	7.1	2816



a) CFSCW-1 b) CFSCW-2 c) CFSCW-3 d) CFSCW-4 e) CFSCW-5 f) CFSCW-6 g) CFSCW-7 h) CFSCW-8 i) CFSCW-9 j) CFSCW-10 k) CFSCW-11 l) CFSCW-12

Figure 15.
Shear wall parameters and the results of hysteric curves of tested specimens [69]

formance of CSPSW system, which is also called as "Concrete Stiffened Steel Shear Walls" by AISC (American Institute of Steel Construction) seismic provisions. The results of this research had shown that increasing of opening, negatively affected the stiffness, energy dissipation capacity and the displacement. The authors suggested that, the 45-degree direction of rebar at the corner of the opening prevented the cracking in the local areas. Furthermore, the thickness of the steel plate doesn't play an important role on the drift ratio of the system.

Park et al. [70] worked on the steel coupling beams of the walls for the connection strength, the failure mechanism, the hysteric response, the strength, the stiffness, the effective embedment length, and the energy dissipation capacity, experimentally. As a result, they have emphasized that, increasing the length of connection, increased the energy dissipation capacity of the shear wall.

Lan et al. [71] conducted experimental and analytical investigation for the steel-concrete composite shear walls, consisting of internal bracing to simulate

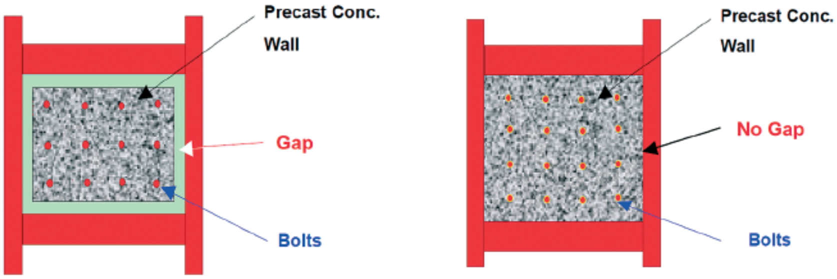


Figure 16.
Traditional and innovative shear walls [74]

an earthquake scenario under cyclic and a constant axial loading. The authors constructed four shear walls, labeled as SW1, SW2, SW3 and SW4, in which SW1 was constructed by using flat shaped steel at a spacing of 200 mm in the embedded column, without bracing; the SW2, and the SW3 models had three and four layers of "X" shaped steel bracing within the wall, respectively. The SW4 model was designed as the same layer of bracing with SW2, but different in the spacing of flat shaped steel in the boundary column. Based on the test result, the "X" shaped steel bracing has a significant effect on the shear capacity stiffness and energy dissipation capacity. The numbers of "X" shaped steel bracing (SSB) and flat shaped steel had affected the behavior of shear walls, in which increasing the number of "X" SSB had increased the shear capacity.

Mao et al [72] carried out an analytical study to observe the effect of the shape memory alloy (SMA) dampers as coupling beams to the behavior of the structural system. The authors wanted to take attention to the high repair cost and the difficulty level of the retrofitting after the earthquakes. To solve this problem, the authors suggested a new technique called SMA. This proposed damper system reduced the displacement response of the frame-shear wall structure.

The composite wall with encased steel bracing is the new type of steel-concrete wall that consists of a steel braced frame embedded in reinforced concrete. Ji et al. [73] carried out an experimental study about the composite shear wall system with encased bracing. They have constructed two composite shear walls, which one had an I shaped brace and the other one with "X" shaped bracing. The composite shear walls were subjected to a constant axial force and cyclic loading. The experimental results have shown very little difference, in terms of failure mode in which the crushing of concrete occurred in the web panel. However, the walls were similar in hysteric response and two types of bracing were buckled after yielding.

Dan et al. [68] presented a theoretical and experimental work on the composite steel-concrete shear walls with steel encased profiles (CSRCW). The CSRCWs have been used to provide lateral stiffness for structures that need significant high horizontal load capacity. The composite shear walls were constructed by using different types and number of profiles. The shear walls had similar amounts of vertical reinforcement and dimension. However, they had different types of reinforcement bars or structural steel used in the cross section, as the structural steel shape, i.e. tubular steel profile, or I profile. The test results showed that, the composite steel-concrete shear walls with encased profiles exhibited more ductile behavior than the conventional RC shear walls.

Another point for the composite shear walls is their challenging usage in the nuclear power plants, where the safety is the most important problem that must be considered under an earthquake for radiation protection. Li and Li [64] studied the out-of-plane seismic behavior of steel plate and concrete infill composite shear walls under cyclic loading. The test parameters were chosen as the thickness of steel plate, vertical load and grading of the concrete. According to their work, the thickness of steel plate and vertical loading were the most impressive parameters of the ultimate bearing capacity and lateral stiffness, where the grade of concrete had a little effect on the behavior of composite shear walls. However, the composite shear walls exhibited more ductile behavior than the conventional ones.

Astaneh-Asl [74] studied the cyclic testing of a traditional and an innovative composite shear wall. The main difference between the traditional and innovative composite shear wall was that the innovative shear wall had a gap between the concrete wall, the boundary columns, and the beams. The traditional shear and innovative proposed shear walls are illustrated in Fig. 16. The results of this research have shown that, the proposed shear wall exhibits more ductile behavior than the traditional one, which has

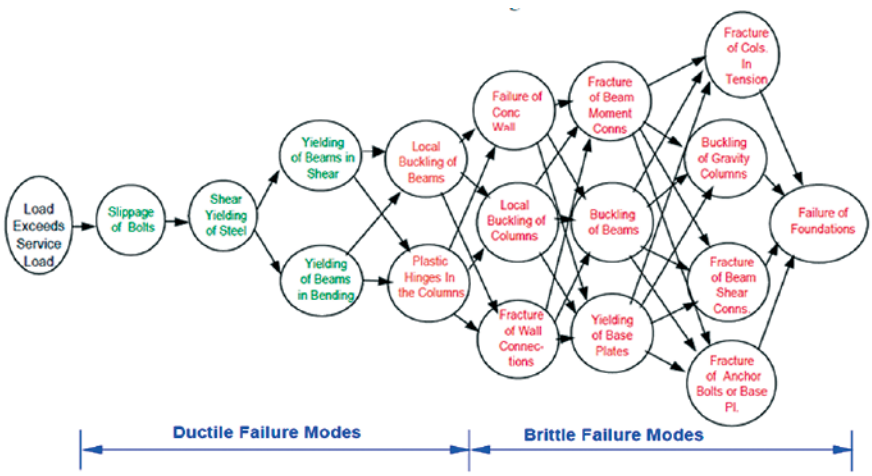


Figure 17.
Hierarchical order of failure modes of composite shear walls [74]

no gap around the concrete wall and therefore, concrete is directly bearing against boundary column and beams. On the other hand, very little difference in the term of strength between traditional and innovative shear walls are observed, while the strength of traditional one's was a bit higher than the proposed one. However, the buckling of both shear walls was similar before yielding. Furthermore, the hierarchical order of failure modes for composite shear walls is shown in Fig. 17.

2.3. RC Walls with Opening

Structural walls sometimes have openings at the different locations of the wall, due to architectural necessaries or functional reason, such as doors, windows, or duct spaces. The location, shape, dimension, ratios of the openings also affect the performance of the shear walls. To obtain the proper performance of the shear walls, some design details and restrictions were provided according to the seismic design codes. When the opening is small at the shear wall base, the effect of opening can be neglected. However, when the opening gets larger or located at the plastic hinge region, the expected performance has to be evaluated before manufacturing the shear wall. The opening located around the center of the shear wall, partially decreases the moment capacity and the shear strength. In contrast, the opening located near the boundaries will affect not only the shear strength, but also the flexural strength of the shear wall.

These openings usually divide shear walls into narrow and vertical segments, that must provide the shear strength, during earthquakes. According to the ACI 318-14, the wall piers at the edges have to be designed with special horizontal reinforcement. Thus, the shear strength can be transferred into the wall segments. Yeh et al. [75] conducted a study to evaluate the effect of horizontal reinforcement on the wall pier segment. They have experimentally investigated four shear walls with varying openings. The first of the shear wall models were designed as the control specimen without opening. The second one was designed with an opening with extension of 600 mm from the corner. The third model had both opening and special horizontal reinforcement, while the fourth one is manufactured with opening and wrapped by CFRP, to determine the effect of openings on the wall behavior. The results showed that the special horizontal reinforcement layout or wrapped vertical wall segment by CFRP, increased the shear strength of the model. Besides, the proposed strut-and-tie model can be used to predict the shear strength of the shear wall.

Wang et al. [76] constructed three storied single-span shear walls, with eccentric openings. The three storied single-span shear wall models were manufactured in 40% scale, and the openings were localized near the inner column of the models with the ratios of 0.3, 0.34, and 0.46. The shear walls were tested under cyclic loading as well as a constant axial load to evaluate the shear capacity. Based on the results, the shear wall with small opening has higher shear capacity and the shear stiffness than the other models. However, the shear wall with large opening behaves more ductile than the ones with small and medium opening.

Massone et al. [77] carried out an experimental and numerical study to evaluate the effect of central opening at the base of the shear wall subjected to constant axial and cyclic loading. For this purpose, they have constructed four shear wall models with same dimensions, but different in opening shapes. The two of the shear walls had 15% and 30% opening of the wall length. The rest of the models manufactured with 11% and 22% opening of the wall height. The experimental results revealed that all models with openings exhibit less ductile behavior. However, the effect of opening width is more effective than the opening height for the displacement capacity.

Another approach for shear walls with opening is the strut-and-tie model. As a result of complex stress distribution within the shear walls, this concept is one of the most important one. Qian et al. [78] conducted an experimental and analytical study on the stress distribution of shear walls with irregular openings. Furthermore, the shear walls were analyzed according to the strut-and-tie model. For these purposes, the authors constructed the shear walls with irregular and varying openings in dimensions. They compared the experimental results with analytical ones from the strut-and-tie model. However, the analytical model may undervalue the ultimate strength by 51%. Thus, the authors developed an improved new strut-and-tie model that was based on the experimental observations and finite-elements. The proposed strut-and-tie model can provide a more exact prediction for the ultimate strength of shear walls with irregular openings. The results of the proposed strut-and-tie model were differing from the experimental ones about 30%. Taylor et al. [9] conducted an experimental and analytical study for the slender shear walls with openings at the wall base. Their main purpose was to evaluate the displacement-based concept for the selection of transverse boundary reinforcement. They constructed two slender shear walls with similar geometries and reinforcement details. The openings were located at the wall base with varying dimensions (small and large opening). Furthermore, the authors suggested another strut-and-tie-model. The results showed that, the shear force was the main characteristic parameter of the shear walls with openings, compared with the solid ones, as expected. Moreover, the proposed strut-and-tie model was effective for the shear design of the shear walls with openings.

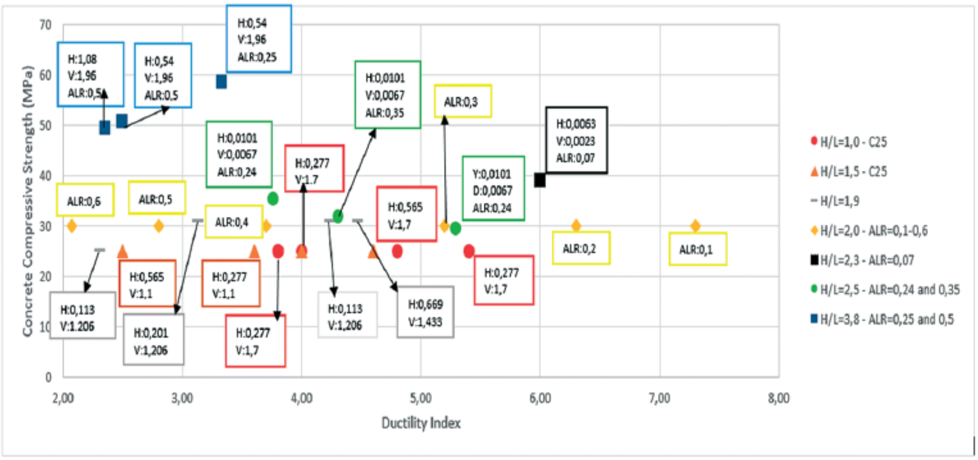
A few techniques use different materials such as steel, concrete, FRP etc. which can be applied for strengthening or retrofitting shear walls with openings. Vojdan and Aghayari [79] focused on shear walls with openings and strengthened by different schemes of Fiber Reinforced Polymer (FRP). Furthermore, they worked on the effect of different size and location of openings to the characteristic parameters such as ductility, stiffness, energy dissipation capacity under the cyclic loading. The results presented that, the location of opening has an important effect on the shear wall behavior. As an example, when the opening is located at the base of the shear wall, the ductility and energy absorption capacity of the wall is decreased. When this shear wall was strengthened by FRP, the energy dissipation capacity increased about 148%. Furthermore, the FRP thickness plays a significant role in shear strength, and the increase in FRP thickness increased the shear strength. Deng et al. [80] focused on the behavior of slotted shear walls with carbon (CFRP) and glass (GFRP) type FRPs. They also compared the models with and without FRPs. While the shear walls with GFRP exhibited good deformation capacity, the shear walls with CFRP exhibited well in stiffness.

Carrillo and Alcocer [81]carried out a study, where the variables were the wall geometry (solid wall and wall with opening), type of concrete (normal and lightweight), web reinforcement ratio (0.125% and 0.25%), and type of web reinforcement (deformed bars and welded-wire mesh). The shear walls were tested by a shaking table to evaluate the shear wall behavior, such as shear strength, displacement capacity as well as cracking pattern. The test results illustrated that the type of web reinforcement plays an important role in the displacement capacity, in contrast to the brittle behavior of the shear wall.

3. DISCUSSION

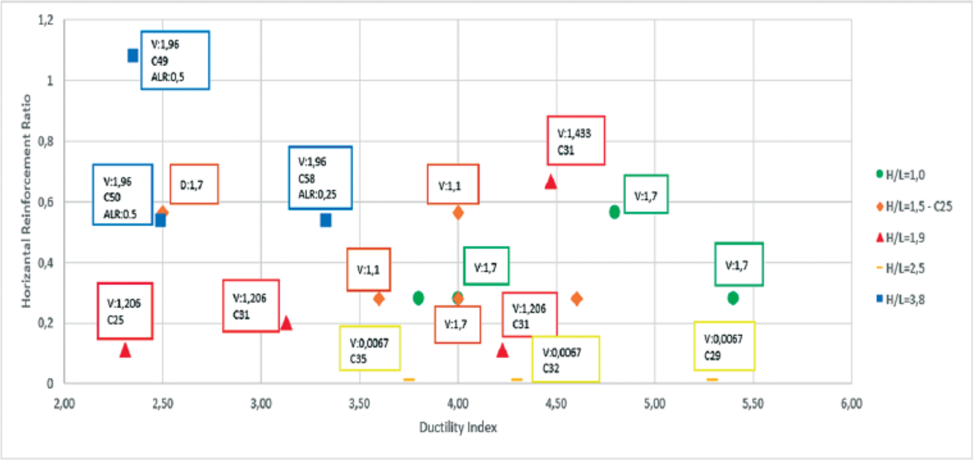
Figs. 18, 19, 20, 21 and 22 are drawn based on the studies by Farvashany et al [18], Christidis and Trezos [31], Dong et al. [40], Zhang and Wang [41], Salonikios [43]. As can be seen from Fig. 18, the decrease of the axial load ratio (ALR) increased the ductility. Furthermore, the increment of the H/L ratio of the shear walls, increased the ductility index, while the concrete compressive strength and the reinforcement ratios were the same. While this increment increases the H/L ratio from 1 to 1.5, the ductility index is increased about 2 times.

The increment in the horizontal reinforcement ratio decreased the ductility index. However, the ductility increased with the increasing vertical reinforcement ratio. While the vertical load is decreased about 25%, the ductility index is increased about 29%. Furthermore, 35% increase of the vertical reinforcement increases the ductility index about 13%. In this



H: Horizontal reinforcement ratio, V: Vertical reinforcement ratio, ALR: Axial load ratio ($ALR=N/f_cb_wt$)

Figure 18.
Concrete compressive strength – ductility index

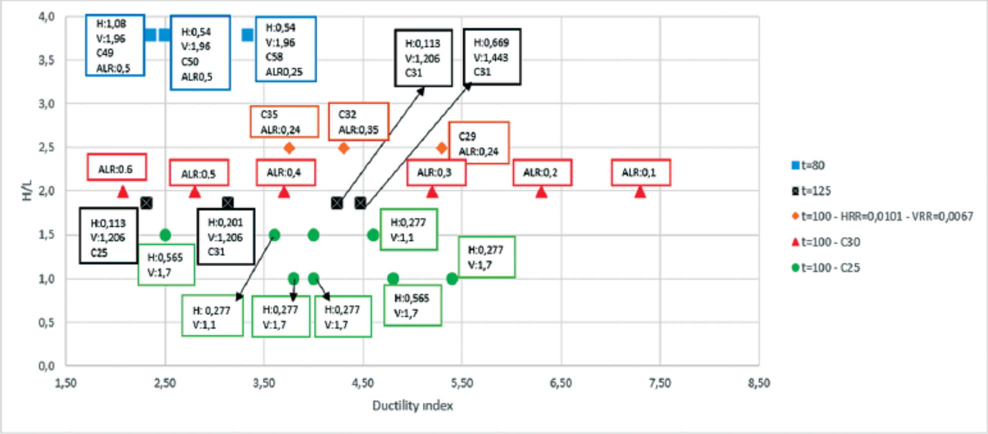


V: Vertical reinforcement ratio, ALR: Axial load ratio ($ALR=N/f_cb_wt$), C: Concrete compressive strength

Figure 19.
Horizontal reinforcement ratio – ductility index

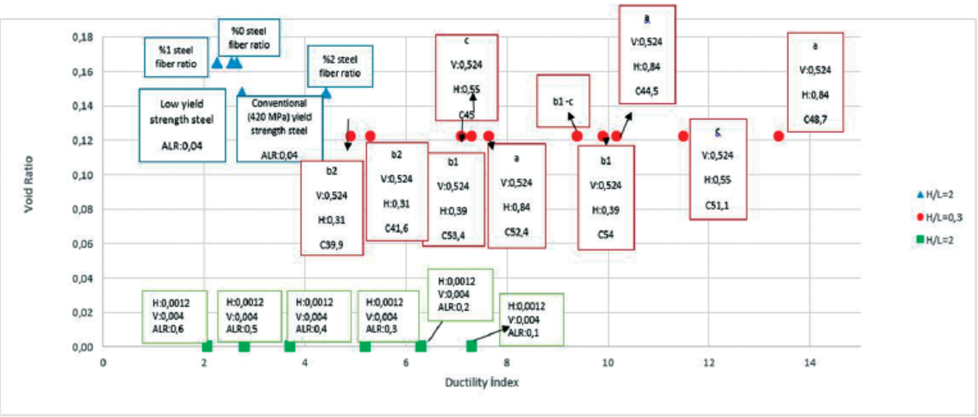
H: Horizontal reinforcement ratio, C: Concrete compressive strength, ALR: Axial load ratio ($ALR=N/f_cb_wt$)

Figure 20.
Vertical reinforcement ratio – ductility index



H: Horizontal reinforcement ratio, V: vertical reinforcement ratio, ALR: Axial load ratio (ALR=N/$f_c b_w t$), C: Concrete compressive strength, t: shear wall thickness

Figure 21.
H/L – ductility index



H: Horizontal reinforcement ratio, V: vertical reinforcement ratio, ALR: Axial load ratio (ALR=N/$f_c b_w t$), C: Concrete compressive strength

Figure 22.
Void Ratio – Ductility index for varying reinforcement details

context, it is seen that the ALR is at least 2 times more effective on the ductility rather than the vertical reinforcement ratio. Moreover, 1% increase in the maximum shear capacity is enhancing the ductility index at the same rate. On the other hand, the ductility index is increased about 30% by tolerating the increase in the horizontal reinforcement ratio, while the increment of horizontal reinforcement, vertical reinforcement, and the H/L ratios are about 70%, 16%, and 21%, respectively. This is the result of decrease in the width and height of the shear wall about 38% and 22%, respectively. In other words, the shear wall height and width are required to be discussed not only as a ratio but also, separately.

Figs. 19 and 20 show the relationship between horizontal and vertical reinforcement ratio and ductility index. Although the ductility index is constant the maximum shear force is decreased about 34%. And also, the shear walls heights and the displacement for the maximum shear force are increased about 34% and 24%, respectively, although the shear wall width is constant. In this case, it is understood that, the shear wall height does not cause a significant increase in the ductility index.

Fig. 21 shows the relationship between H/L and ductility index. As seen in Fig. 21, although the axial load ratio increased about 40%, the ductility index was solely increased about 2% for the shear walls with C30 type concrete. However, the H/L ratio increased about 20% although the axial load ratio increased about 40%. However, the displacement is increased about 2 times for the maximum shear load. This result is coherent with the increase in shear wall height.

In case where the height increases about 20%, since the axial load ratio remains in the same order, the increase is kept at a level of 2% for the ductility

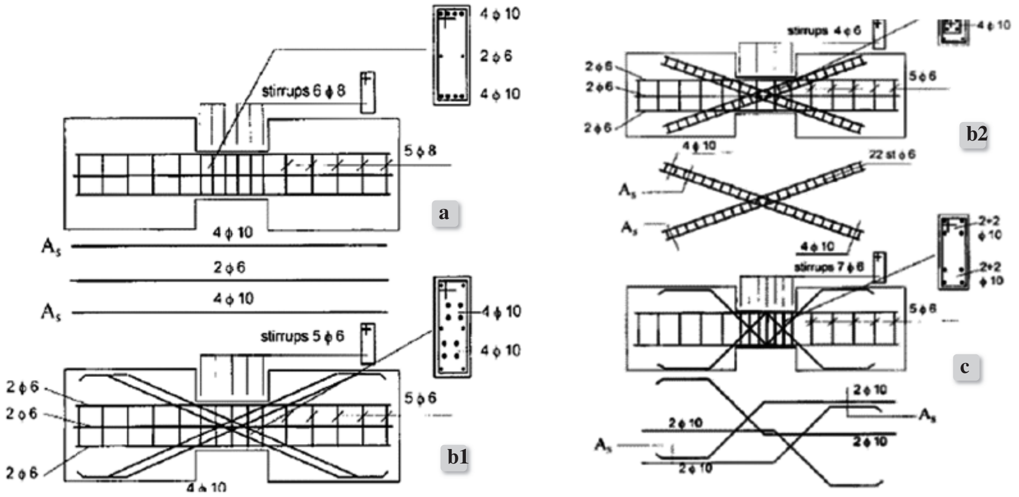


Figure 23.
Reinforcement details for shear walls with openings [57]

index. Hence, for the axial load ratio below 20%, the variations which can be in the ductility index are directly related to the shear wall height.

The opening of the shear wall is defined with the term void ratio; which is the division of opening area to surface of the shear wall in 2D (Fig. 22). Above mentioned reinforcement details, for the shear walls with openings, are presented in Fig. 23. The rhombic layout of the main reinforcement gave the highest rotational ductility values. However, the rhombic layout produced lower values of strength with the same geometrical percentage of steel area. Comparable energy dissipation quantities were achieved with the diagonal and the rhombic layout.

However, the increase in the axial load ratio decreases and increases the ductility index for the shear walls without and with openings, respectively. This concern is related to the reinforcement type and layout. Furthermore, for the fiber-reinforced concrete type, the expected ductility increase by the fiber inclusion in the concrete, remains at a negligible level as for the axial load ratio increase. This can be explained by considering bending behavior, in which the fibers are effectively assigned.

Although there is limited cyclic loading and/or shaking table tests for the shear walls with and without openings, the shaking table behavior should be investigated, and their loading parameters should be

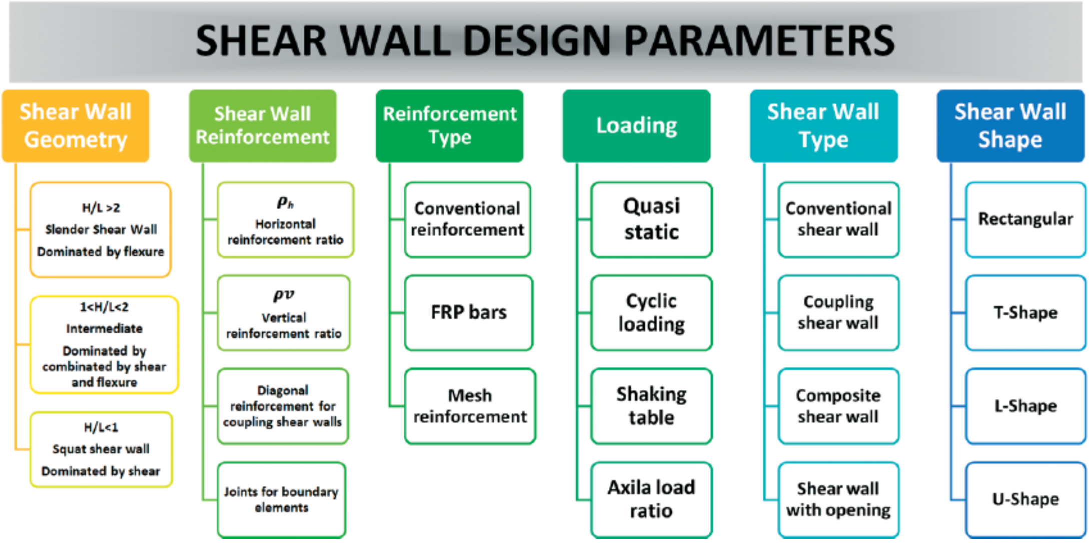
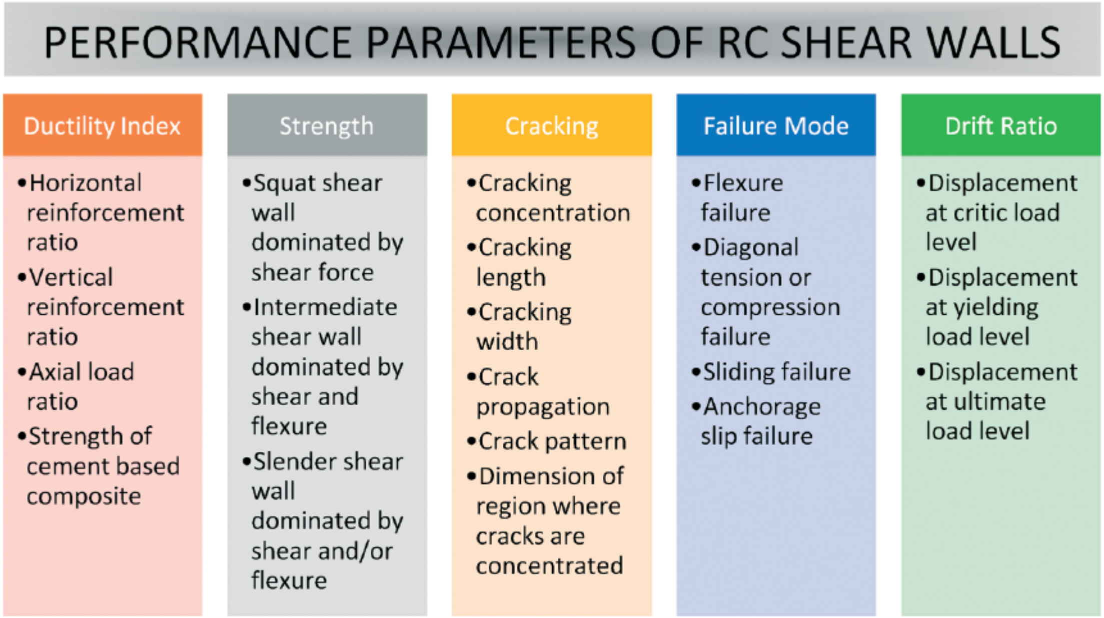


Figure 24.
Scheme for design parameters of shear walls



PERFORMANCE PARAMETERS OF RC SHEAR WALLS

Ductility Index	Strength	Cracking	Failure Mode	Drift Ratio
•Horizontal reinforcement ratio •Vertical reinforcement ratio •Axial load ratio •Strength of cement based composite	•Squat shear wall dominated by shear force •Intermediate shear wall dominated by shear and flexure •Slender shear wall dominated by shear and/or flexure	•Cracking concentration •Cracking length •Cracking width •Crack propagation •Crack pattern •Dimension of region where cracks are concentrated	•Flexure failure •Diagonal tension or compression failure •Sliding failure •Anchorage slip failure	•Displacement at critic load level •Displacement at yielding load level •Displacement at ultimate load level

Figure 25.
Scheme of performance parameters of shear walls

adapted according to earthquake characteristics/parameters by optimization with numerical methods such as artificial intelligence and fuzzy logic, etc.

4. CONCLUSIONS

To model the shear wall behavior analytically, the shear wall height, width and thickness have to be discussed for their separate effects on the ductility index. However, this comprehensive experimental plan will be possible by including the concrete type, horizontal, and vertical reinforcement, also other parameters. Especially, numerical modeling should be organized by probable partial equations and contribution of uncertain efficiency parameters, such as maximum shear force and ductility index should be examined. The models supported by a statistical study that will be made by artificial intelligence/artificial neural networks will be also the initial steps for obtaining the shear wall behavior analytically. The external effects such as shear force, axial load, etc. are required to be updated in parallel with the developments in the concrete/composite technology by means of the numerical models. On the other hand, the contribution of the reinforcement type to the ductile behavior was neglected in the effect of environmental factors in terms of both geometry and strength. The future studies should be conducted on time-varying adherence features of the reinforcements to the ductile behavior, with surface treatment (GFRP, CFRP, or steel reinforcement). Smart materials and shape memory alloys are very prominent at present. Thus, the smart materials and shape memory alloys can be a striking concept for cement-based composite philosophy. Withal, when above mentioned concepts merged with laminated composite design technique, it can be an illuminating way of high-energy absorption capable not only for the shear walls, especially, but also for the structural engineering in the future. Furthermore, extensive research is needed in the matter of evaluating the ductile behavior independently from loading features of the opening/void ratio for the concrete shear walls. Particularly, the effect of loading features (including the axial load ratio) and variation on the opening/void ratio should be taken into consideration. The ductile behavior has to be investigated for the special cement-based composites, including not only the above-mentioned parameters but also, the crack propagation, and intensity, aggregate texture, and granulometry, fiber type, and properties, etc.

ACKNOWLEDGMENT

The research is part of the Ataturk University Projects No: FDK-2019-6923 and FBA-2020-7343. The authors would like to thank Ataturk University for funding the project.

REFERENCES

[1] Barda, F., Hanson, J.M., & Corley, W. (1977). Shear strength of low-rise walls with boundary elements. *Special Publication*, 53, 149–202.

[2] Cardenas, A., Russell, H., & Corley, W. (1980). Strength of low-rise structural walls. *Special Publication*, 63, 221–242.

[3] Cardenas, A.E., & Magura, D.D. (1972). Strength of high-rise shear walls-rectangular cross section. *Special Publication*, 36, 119–150.

[4] Oesterle, R., Aristizabal-Ochoa, J., Shiu, K. & Corley, W. (1984). Web crushing of reinforced concrete structural walls. *Journal Proceedings, 81*(3), 231–241.

[5] Oesterle, R., Fiorato, A., Aristizabal-Ochoa, J., & Corley, W (1980). Hysteretic response of reinforced concrete structural walls. 63, 243–274.

[6] Leafs, I.D., & Kotsovos, M.D. (1990). Behavior of reinforced concrete structural walls: strength, deformation characteristics, and failure mechanism. *Structural Journal, 87*(1), 23–31.

[7] Lefas, I.D., & Kotsovos, M.D. (1990). Strength and deformation characteristics of reinforced concrete walls under load reversals. *Structural Journal, 87*(6), 716–726.

[8] Salonikios, T. N., Kappos, A. J., Tegos, I. A., & Penelis, G. G. (1999). Cyclic load behavior of low-slenderness reinforced concrete walls: Design basis and test results. *Structural Journal, 96*(4), 649–660.

[9] Taylor, C. P., Cote, P. A., & Wallace, J. W. (1998). Design of slender reinforced concrete walls with openings. *Structural journal, 95*(4), 420–433.

[10] Mistri, A., Davis, R., & Sarkar, P. (2016). Condition assessment of fire affected reinforced concrete shear wall building – A case study. *Advances in concrete construction, 4*(2), 89.

[11] Paulay, T., & Priestley, M. N. (1992). Seismic design of reinforced concrete and masonry buildings.

[12] Ozturk, B. M. (2003). Seismic drift response of building structures in seismically active and near-fault regions. Doctoral dissertation, Purdue University.

[13] Dazio, A., Beyer, K., & Bachmann, H. (2009). Quasi-static cyclic tests and plastic hinge analysis of RC structural walls. *Engineering Structures, 31*(7), 1556–1571.

[14] Aydin, A. C., & Bayrak, B. (2019). The torsional behavior of reinforced self-compacting concrete beams. *Advances in Concrete Construction, 8*(3), 187–198.

[15] Maali, M., Kılıç, M., Yaman, Z., Ağcakoca, E., & Aydın, A. C. (2019). Buckling and post-buckling behavior of various dented cylindrical shells using CFRP strips subjected to uniform external pressure: Comparison of theoretical and experimental data. *Thin-Walled Structures*, 137, 29–39.

[16] Baltacıoğlu, A. K., Baki, Ö., Civalek, Ö., & Akgöz, B. (2010). Is artificial neural network suitable for damage level determination of RC-Structures. *International Journal of Engineering and Applied Sciences, 2*(3), 71–81.

[17] Baltacıoğlu, A. K., Yavaş, A., Civalek, Ö., Öztürk, B., & Akgöz, B. (2010). Using of Fuzzy Logic Based Expert Systems for Fast Damage Determination of Structures After Earthquake. *Journal of Balıkesir University Institute of Science, 12*(1), 65–74.

[18] Farvashany, F. E., Foster, S. J., & Rangan, B. V. (2008). Strength and deformation of high-strength concrete shearwalls. *ACI structural journal, 105*(1), 21.

[19] Derecho, A. T., Iqbal, M., Fintel, M., & Corley, W. G. (1980). Loading history for use in quasi-static simulated earthquake loading tests. *Special Publication*, 63, 329–356.

[20] Calvi, G. M., Kingsley, G. R., & Magenes, G. (1996). Testing of masonry structures for seismic assessment. *Earthquake spectra, 12*(1), 145–162.

[21] Ozturk, B. (2008). Investigation of seismic behavior of reinforced concrete shearwall building frames subjected to ground motions from the 1999 turkish earthquakes. In 14th World Conference on Earthquake Engineering.

[22] Carrillo, J., & Alcocer, S. M. (2013). Experimental investigation on dynamic and quasi static behavior of low rise reinforced concrete walls. *Earthquake Engineering & Structural Dynamics, 42*(5), 635–652.

[23] Bertero, V. V., Popov, E. P., Wang, T. Y., & Vallenas, J. (1977, January). Seismic design implications of hysteretic behavior of reinforced concrete structural walls. 6th World Conference on Earthquake Engineering, 1898–1904.

[24] Aktan, A. E., & Bertero, V. V. (1984). Seismic response of R/C frame-wall structures. *Journal of Structural Engineering, 110*(8), 1803–1821.

[25] Paulay, T., & Santhakumar, A. R. (1976). Ductile behavior of coupled shear walls. *Journal of the Structural Division, 102*(1), 93–108.

[26] Tiecheng, W., Tianyu, L., & Hailong, Z. (2017). Tensile-shear mechanical performance test of reinforced concrete shear wall. *Building Structure, 47*(2), 64–69.

[27] Ji, X., Cheng, X., & Xu, M. (2018). Coupled axial tension-shear behavior of reinforced concrete walls. *Engineering Structures*, 167, 132–142.

[28] Bakis, C. E., Bank, L. C., Brown, V., Cosenza, E., Davalos, J. F., Lesko, J. J., ... & Triantafillou, T. C. (2002). Fiber-reinforced polymer composites for construction – State-of-the-art review. *Journal of composites for construction, 6*(2), 73–87.

[29] Vecchio, F. J., de la Pena, O. A. H., Bucci, F., & Palermo, D. (2002). Behavior of repaired cyclically loaded shearwalls. *ACI Structural Journal, 99*(3), 327–334.

[30] Mosallam, A. S., Bayraktar, A., Elmikawi, M., Pul, S., & Adanur, S. (2015). Polymer composites in construction: an overview, SOJ Materials Science & Engineering.

[31] Christidis, K. I., & Trezos, K. G. (2017). Experimental investigation of existing non-conforming RC shear walls. *Engineering Structures*, 140, 26–38.

[32] Antoniades, K. K., Salonikios, T. N., & Kappos, A. J. (2005). Tests on seismically damaged reinforced concrete walls repaired and strengthened using fiber-reinforced polymers. *Journal of Composites for Construction, 9*(3), 236–246.

[33] Aydin, A. C., Yaman, Z., Ağcakoca, E., Kiliç, M., Maali, M., & Dizaji, A. A. (2020). CFRP effect on the buckling behavior of dented cylindrical shells. *International Journal of Steel Structures, 20*(2), 425–435.

[34] El-Sokkary, H., Galal, K., Ghorbanirenani, I., Léger, P., & Tremblay, R. (2013). Shake table tests on FRP-rehabilitated RC shear walls. *Journal of Composites for Construction, 17*(1), 79–90.

[35] Layssi, H., Cook, W. D., & Mitchell, D. (2012). Seismic response and CFRP retrofit of poorly detailed shear walls. *Journal of Composites for Construction, 16*(3), 332–339.

[36] Paterson, J., & Mitchell, D. (2003). Seismic retrofit of shear walls with headed bars and carbon fiber wrap. *Journal of Structural Engineering, 129*(5), 606–614.

[37] Qazi, S., Michel, L., & Ferrier, E. (2019). Seismic behaviour of RC short shear wall strengthened with externally bonded CFRP strips. *Composite Structures*, 211, 390–400.

[38] Carrillo, J., Lizarazo, J. M., & Bonett, R. (2015). Effect of lightweight and low-strength concrete on seismic performance of thin lightly-reinforced shear walls. *Engineering Structures*, 93, 61–69.

[39] Su, R.K.L., & Wong, S. M. (2007). Seismic behaviour of slender reinforced concrete shear walls under high axial load ratio. *Engineering Structures, 29*(8), 1957–1965.

[40] Dong, Y. R., Xu, Z. D., Zeng, K., Cheng, Y., & Xu, C. (2018). Seismic behavior and cross-scale refinement model of damage evolution for RC shear walls. *Engineering Structures*, 167, 13–25.

[41] Zhang, Y., & Wang, Z. (2000). Seismic behavior of reinforced concrete shear walls subjected to high axial loading. *Structural Journal, 97*(5), 739–750.

[42] Iliya, R., & Bertero, V. V. (1980). Effects of amount and arrangement of wall-panel reinforcement on hysteretic behavior of reinforced concrete walls. University of California, Earthquake Engineering Research Center.

[43] Salonikios, T. N. (2002). Shear strength and deformation patterns of R/C walls with aspect ratio 1.0 and 1.5 designed to Eurocode 8 (EC8). *Engineering Structures, 24*(1), 39–49.

[44] Tolou Kian, M. J., & Cruz-Noguez, C. (2018). Reinforced concrete shear walls detailed with innovative materials: seismic performance. *Journal of Composites for Construction, 22*(6), 04018052.

[45] Mohamed, N., Farghaly, A. S., Benmokrane, B., & Neale, K. W. (2014). Experimental investigation of concrete shear walls reinforced with glass fiber–reinforced bars under lateral cyclic loading. *Journal of Composites for Construction, 18*(3), A4014001.

[46] Mattock, A. H. (1967). Discussion of "Rotational capacity of reinforced concrete beams". *Journal of the Structural Division, 93*(2), 519–522.

[47] Priestley, M. N., Seible, F., & Calvi, G. M. (1996). Seismic design and retrofit of bridges. John Wiley & Sons.

[48] Bohl, A., & Adebar, P. (2011). Plastic hinge lengths in high-rise concrete shear walls. *ACI Structural Journal, 108*(2), 148.

[49] Park, W. S., & Yun, H. D. (2006). Seismic behaviour and design of steel coupling beams in a hybrid coupled shear wall systems. *Nuclear Engineering and Design, 236*(23), 2474–2484.

[50] Park, W. S., & Yun, H. D. (2005). Seismic behaviour of steel coupling beams linking reinforced concrete shear walls. *Engineering structures, 27*(7), 1024–1039.

[51] Zhao, J., Cai, G., Larbi, A. S., Zhang, Y., Dun, H., Degée, H., & Vandoren, B. (2018). Hysteretic behaviour of steel fibre RC coupled shear walls under cyclic loads: *Experimental study and modelling. Engineering Structures*, 156, 92–104.

[52] Aksogan, O., Arslan, H. M., & Choo, B. S. (2003). Forced vibration analysis of stiffened coupled shear walls using continuous connection method. *Engineering structures, 25*(4), 499–506.

[53] Chaallal, O., & Ghlamallah, N. (1996). Seismic response of flexibly supported coupled shear walls. *Journal of Structural Engineering, 122*(10), 1187–1197.

[54] Chaailal, O., Thibodeau, S., Lescelleur, J., & Maleenfant, P. (1996). Steel Fiber or conventional reinforcement for concrete shearwalls. *Concrete International, 18*(6), 39–42.

[55] Cheng, M. Y., Fikri, R., & Chen, C. C. (2015). Experimental study of reinforced concrete and hybrid coupled shear wall systems. *Engineering Structures, 82,* 214–225.

[56] Zhao, J., Cai, G., Larbi, A. S., Zhang, Y., Dun, H., Degée, H., & Vandoren, B. (2018). Hysteretic behaviour of steel fibre RC coupled shear walls under cyclic loads: Experimental study and modelling. *Engineering Structures*, 156, 92–104.

[57] Galano, L., & Vignoli, A. (2000). Seismic behavior of short coupling beams with different reinforcement layouts. *Structural Journal, 97*(6), 876–885.

[58] Zhang, J., Zheng, W., Yu, C., & Cao, W. (2018). Shaking table test of reinforced concrete coupled shear walls with single layer of web reinforcement and inclined steel bars. *Advances in Structural Engineering, 21*(15), 2282–2298.

[59] Wang, T., Shang, Q., Wang, X., Li, J., & Kong, Z. A. (2018). Experimental validation of RC shear wall structures with hybrid coupling beams. *Soil Dynamics and Earthquake Engineering*, 111, 14–30.

[60] Ji, X., Wang, Y., Ma, Q., & Okazaki, T. (2017). Cyclic behavior of replaceable steel coupling beams. *Journal of Structural Engineering, 143*(2), 04016169.

[61] Adams, P. F., Zimmerman, T. J. E., & MacGregor, J. G. (1987). Design and Behavior of Composite Ice-Resisting Walls. *Port and Ocean Engineering Under Arctic Conditions*., 1, 663–674.

[62] Matsuishi, M., & Iwata, S. (1987). Strength of Composite System Ice-Resisting Structures Steel/Concrete Composite Structural Systems, C-FER Publication No. 1. In Proceedings of a special symposium held in conjunction with POAC (Vol. 87).

[63] Oiino, F. (1987). Experimental Studies on Composite Members for Arctic Offshore Structures. POAC'87, 89–102.

[64] Li, X., & Li, X. (2017). Steel plates and concrete filled composite shear walls related nuclear structural engineering: Experimental study for out-of-plane cyclic loading. *Nuclear Engineering and Design*, 315, 144–154.

[65] Lu, X. L., Gan, C., & Wang, W. (2009). Study on seismic behavior of steel plate reinforced concrete shear walls. *Journal of Building Structures, 30*(5), 89–96.

[66] Chunyu, C.T.X.C.T., & Peifu, X. (2011). Experimental study of the compression-bending behavior of composite shear walls of high axial compression ratios [J]. *China Civil Engineering Journal*, 6.

[67] Nie, J. G., Hu, H. S., Fan, J. S., Tao, M. X., Li, S. Y., & Liu, F. J. (2013). Experimental study on seismic behavior of high-strength concrete filled double-steel-plate composite walls. *Journal of Constructional Steel Research*, 88, 206–219.

[68] Dan, D., Fabian, A., & Stoian, V. (2011). Theoretical and experimental study on composite steel–concrete shear walls with vertical steel encased profiles. *Journal of constructional steel research, 67*(5), 800–813.

[69] Meghdadaian, M., & Ghalehnovi, M. (2019). Improving seismic performance of composite steel plate shear walls containing openings. *Journal of Building Engineering*, 21, 336–342.

[70] Park, W. S., & Yun, H. D. (2006). Seismic behaviour and design of steel coupling beams in a hybrid coupled shear wall systems. *Nuclear Engineering and Design, 236*(23), 2474–2484.

[71] Lan, W., Ma, J., & Li, B. (2015). Seismic performance of steel–concrete composite structural walls with internal bracings. *Journal of Constructional Steel Research*, 110, 76–89.

[72] Mao, C., Dong, J., Li, H., & Ou, J. (2012, April). Seismic performance of RC shear wall structure with novel shape memory alloy dampers in coupling beams. In Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2012 (Vol. 8345, p. 83454G). International Society for Optics and Photonics.

[73] Ji, X., Leong, T., Qian, J., Qi, W., & Yang, W. (2016). Cyclic shear behavior of composite walls with encased steel braces. *Engineering Structures*, 127, 117–128.

[74] Astaneh-Asl, A. (2002). Seismic behavior and design of composite steel plate shear walls. Moraga, CA: Structural Steel Educational Council.

[75] Yeh, R. L., Tseng, C. C., & Hwang, S. J. (2018). Shear Strength of Reinforced Concrete Vertical Wall Segments under Seismic Loading. ACI Structural Journal.

[76] Wang, J., Sakashita, M., Kono, S., & Tanaka, H. (2012). Shear behaviour of reinforced concrete structural walls with eccentric openings under cyclic loading: experimental study. *The Structural Design of Tall and Special Buildings, 21*(9), 669–681.

[77] Massone, L. M., Muñoz, G., & Rojas, F. (2019). Experimental and numerical cyclic response of RC walls with openings. *Engineering Structures*, 178, 318–330.

[78] Qian, K., Li, B., & Liu, Y. (2017). Experimental and analytical study on load paths of RC squat walls with openings. *Magazine of Concrete Research, 69*(1), 1–23.

[79] Mohammadi Vojdan, B., & Aghayari, R. (2017). Investigating the seismic behavior of RC shear walls with openings strengthened with FRP sheets using different schemes. *Scientia Iranica, 24*(4), 1855–1865.

[80] Deng, K., Pan, P., Shen, S., Wang, H., & Feng, P. (2018). Experimental study of FRP-reinforced slotted RC shear walls under cyclic loading. *Journal of Composites for Construction, 22*(4), 04018017.

[81] Carrillo, J., & Alcocer, S. M. (2012). Seismic performance of concrete walls for housing subjected to shaking table excitations. *Engineering structures*, 41, 98–107.