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ORIGINAL ARTICLE

Experimental study of seismic torsional behavior of reinforced concrete walls

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Abstract

In this paper, the seismic torsional behavior of reinforced concrete walls has been studied experimentally. Reinforced concrete walls having 7, 6, and 5 aspect ratios have been produced on a 1/2 scale. Three specimens have been produced from each aspect ratio. In addition to these specimens, a reference specimen having a 6 aspect ratio has been produced. The reference specimen test has been used for determining the loading protocol. It has been tried to determine optimum load increase by changing load increments in the reference specimen test. Thus, ten seismic torsion tests have been carried out by using these specimens. The main purpose of the tests is to experimentally investigate the pure seismic torsional behavior of reinforced concrete walls which are under axial load. Moreover, it has been aimed to investigate the effects of the aspect ratio on torsional behavior using the tests. As a result of the study; cracking and maximum torsional moments, torque-twist angle curves, torsional stiffnesses, energy consumptions, damage patterns of the reinforced concrete walls have been obtained. It is observed from the results that the reinforced concrete walls having large cross-sections have greater torsional strengths and torsional stiffnesses. The average cracking and maximum torsional moments have increased 65.7% and 45.5% as the aspect ratio increased from 5 to 7. Furthermore, a significant decrease of torsional stiffness of the reinforced concrete walls has occurred with the occurrence of torsional cracking. The average ratios of post-cracking torsional stiffness to pre-cracking torsional stiffness have been calculated as 0.0781, 0.0922, and 0.0843 for the walls with 5, 6, and 7 aspect ratios, respectively. It has been concluded to study that choosing the aspect ratio of 5 or 6 would be appropriate in terms of torsional behavior.

Keywords Reinforced concrete wall · length/width aspect ratio · Seismic torsional behavior · Torsional strength · Torsional stiffness

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1 Introduction

Countries that are especially located in earthquake zones aim to minimize earthquake effects by publishing various earthquake standards. When these earthquake standards are examined, it is seen that structural irregularities are considered a very important factor in earthquake-resistant building design. For this reason, many measures are taken to prevent these structural irregularities. As can be understood from this situation, if structural irregularities cannot be prevented in buildings, the buildings are inevitably damaged under earthquake effects. One of the most important structural irregularities is torsional irregularity. When mass center and rigidity center do not coincide in buildings, torsional irregularity can occur. Irregular geometry and stiffness distribution in the plan are the most important causes of torsional irregularity in buildings. If the structural elements are placed irregularly or asymmetrically in the plan, undesirable torsional effects have occurred in the buildings. Reinforced concrete walls which are not placed regularly or symmetrically are caused torsional irregularities in buildings. These torsional irregularities can cause torsional damages to the structural elements of the buildings. For this reason, many experimental studies have been carried out to investigate the torsional behavior of reinforced concrete structural elements.

It has been determined in the literature research that experimental investigation of torsional behavior of concrete and reinforced concrete elements has been carried out since the early 1900s. It is stated in some sources that the first studies have been carried out by Paul Andersen in the 1930s and by Henry J. Cowan in the early 1950s. It is found out that the torsional strength of circular and rectangular cross-section concrete and reinforced concrete beams have been investigated in these studies (Andersen 1935; Andersen 1937; Cowan 1951; Zia 1960). It is seen that more comprehensive experimental studies have been carried out in the 1960s. When these comprehensive studies are examined, it is seen that although there are studies related to columns and slabs, the studies are generally carried out on beams (Ersoy and Ferguson 1968; Hsu 1968a; Hsu 1968b; Doudak and Ersoy 1969; Hsu and Kemp 1969; Onsongo and Collins 1972; Ersoy 1973; Karlson et al. 1974; Onsongo 1978; Narayanan and Kareem-Palanjian 1986). Torsional effects that may occur in reinforced concrete structural system elements have been investigated by many experimental studies in recent years (Wafa et al. 1992; Rahal 1993; Wafa et al. 1995; Csikos and Hegedus 1998; Chiu et al. 2007; Tirasit and Kawashima 2007; Prakash 2009; Prakash et al. 2010; Li and Belarbi 2011; Peng and Wong 2011; Okay and Engin 2012; Peng 2012; Chalioris and Karayannis 2013; Defialla et al. 2013; Wang et al. 2014; Kim et al. 2015; Mohammed et al. 2016; Alabdulhady et al. 2017; Wang et al. 2018; Luo et al. 2019; Yalciner et al. 2019; Ibrahim et al. 2020; Hoult 2021; Hoult and Beyer 2021). Torsional strength and stiffness, twist angle, crack pattern, torsional behavior of structural system elements have been investigated by these experimental studies. To summarize the previous studies; in some experimental studies, the pure torsional behaviors of reinforced concrete beams and columns have been investigated. In these studies, the effects of reinforcement arrangements, cross-section dimensions, and concrete grades of reinforced concrete elements have been investigated on torsional behavior. In addition, it is seen in the literature research that the behavior and strength of structural system elements have been examined for effects of the torsional moments in combination with other internal forces, such as bending moments or shear forces, etc. It has been mentioned that there are many studies on torsion for reinforced concrete elements. However, comparing the experimental studies on other internal forces and torsional moments, it is seen that there are very few studies on torsional moments. The reason for this situation is that torsional effects are considered less important than other internal forces in the designs of reinforced concrete elements. Since the occurrence of torsion can affect the capacities of reinforced concrete elements, the effects of torsion on the behavior of reinforced concrete elements should also be investigated.

Considering all these mentioned, the torsional behavior of reinforced concrete walls has been investigated in this study. By the literature search, it is concluded that studies related to torsion are generally carried out on reinforced concrete beams and columns. However, there are not many studies related to torsion in reinforced concrete walls. Moreover, it has been determined that studies related to reinforced concrete walls are generally carried out to investigate the bending effects of earthquakes (Beyer et al. 2015; Rosso et al. 2016; Villalobos et al. 2017; Ni et al. 2019; Dashti et al. 2020; Kucukgoncu and Altun 2020; Bisch et al. 2021; Özdemir et al. 2021; Wei et al. 2022). Due to this, reinforced concrete walls have been preferred to investigate the pure torsional behavior of reinforced concrete walls in this study, experimentally. Experiments in the study have been performed under axial compression loads and reversed cyclic lateral loads. Since the reinforced concrete walls are vertical structural system elements, they have been exposed to axial loads as well as horizontal loads in the tests. In this direction, the pure torsion mentioned in the scope of this study has been considered as a torsional effect with axial load effect without bending and shear effects. In addition, the effects of length/width ratio (aspect ratio) on the torsional behavior of reinforced concrete walls have been revealed with the study. Torsional strength and stiffness, torque-twist angle relation, energy consumption, and damage-crack pattern of reinforced concrete walls have been obtained from the results of experimental studies. Then, these results have been evaluated and compared in detail. This study has major originality and novelty in terms of two points. Firstly, comprehensive studies investigating the torsional behavior of reinforced concrete walls which are under axial loads have not been found in the literature. Secondly, studies examining the aspect ratio of the reinforced concrete walls in terms of torsion have not been found in the literature. Moreover, in the literature research, it has been seen that the limit values of the aspect ratios of the reinforced concrete walls are different in the design or earthquake standards of the countries. This situation reveals that there is uncertainty in this regard. With this study, it has been tried to investigate the optimum aspect ratio in terms of torsion. The relationship between the aspect ratio and the torsion properties of the walls has been tried to be revealed (Turkay 2019).

2 Experimental Study

In the experimental program, ten specimens have been produced and ten seismic torsion tests have been carried out successfully. First, the reference specimen test has been carried out. Since such torsion tests are limited in the literature, it has been desired to check the suitability of the test setup with the reference specimen test. In addition, it has been tried to determine suitable load steps in terms of torsion thanks to the reference specimen test. Thus, the loading protocol that can be applied in the tests has been determined. Production of the specimens and torsion tests has been carried out in Erciyes University Melikgazi Municipality Earthquake Research Laboratory, Kayseri, Turkey.

2.1 Specimen Details

Reinforced concrete walls have been designed as a high ductility level according to Turkey Building Earthquake Code 2018 (TBEC 2018) and Turkish Standard 500 (TS500 2000) rules (Fig. 1a). The walls have been designed to form the wall end zones and by considering through the critical wall height. Because it has been thought that the end zones of the walls are important in terms of the behavior of reinforced concrete walls. In addition, since it has not been desired to change the reinforcement layouts in the vertical, it has been requested that all of the walls remain through the critical wall height. According to TBEC 2018, the ratio of the wall height to the wall length is required to be greater than two for the formation of the wall end zones, and the upper limit for the critical wall height is given as twice the wall length. Considering these conditions and the lengths determined for the walls, the height of the walls has been determined as 2100 mm. The walls have been constructed on a 1/2 scale with aspect ratios of 7, 6, and 5. A practical real model approach has been used for scaling. The stress scale factor is taken as one for concrete and steel in this approach. In this case, the same materials are used in the real building model and the scale building model (Harris and Sabnis 1999; Özbayrak and Altun 2020). Laboratory material tests have been carried out on the samples taken according to the relevant standards. Mechanical properties of concrete and steel have been determined. As a result of the laboratory tests, the average cylinder compressive strength value for concrete has been determined as 27.413 MPa and

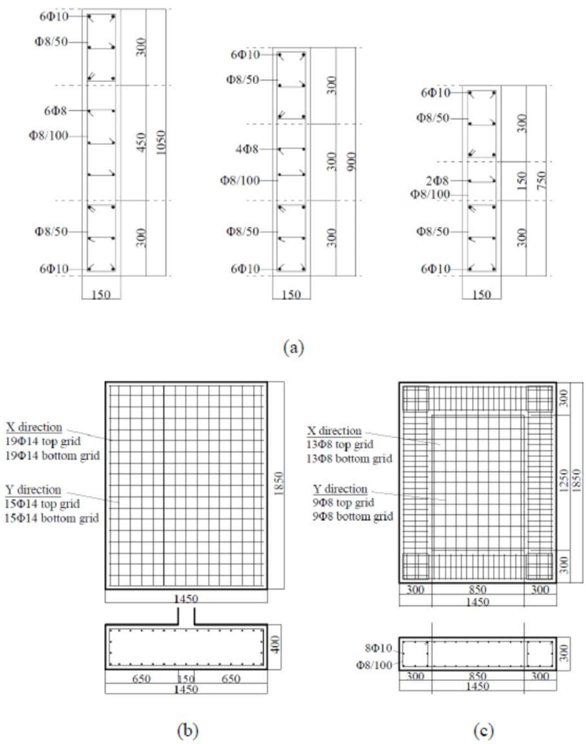

Fig. 1 Details of the specimens (unit: mm). (a) P7, P6, and P5 walls, respectively, (b) Foundations, (c) Slabs

the average yield strength value for reinforcement steel has been determined as 482.25 MPa. The aspect ratios of the reinforced concrete walls investigated in this study have been determined by considering limit values used in earthquake or building design standards of different countries (TBEC 2018; TERDC 2007; ACI 318 – 14 2014; Eurocode 2 2004; Eurocode 8 2004). In addition, foundations and loading slabs have been designed for the walls to perform experimental studies (Fig. 1b, c). Rigid loading slabs have been considered to apply axial and horizontal loads to the reinforced concrete walls. The test setup has been created considering the loading slabs. Torsional effects have been created in reinforced concrete walls thanks to the horizontal loads applied to the loading slabs. The foundations have top and bottom grids which are composed of U-shaped rebars. There are four beams that have the same arrangements of rebars in the slabs and there are also top and bottom grids which are composed of U-shaped rebars in slabs. Three-dimensional drawings of the specimens are illustrated in Fig. 2 and the dimensions of the specimens are given in Table 1. The walls have been labeled by considering as ten specimens. P7 walls have a 7 aspect ratio, P6 walls have a 6 aspect ratio, and P5 walls have a 5 aspect ratio. Since there are three walls from each aspect ratio, the coding has been arranged as P7-1, P7-2, P7-3, P6-1, P6-2, P6-3, P5-1, P5-2, P5-3. Furthermore, a reference specimen (P6-REF) which has the same properties as P6 walls has been produced. In this way, ten specimens have been constructed in the laboratory. The production stages of specimens are given in Fig. 3.

Fig. 2 Drawings of the specimens

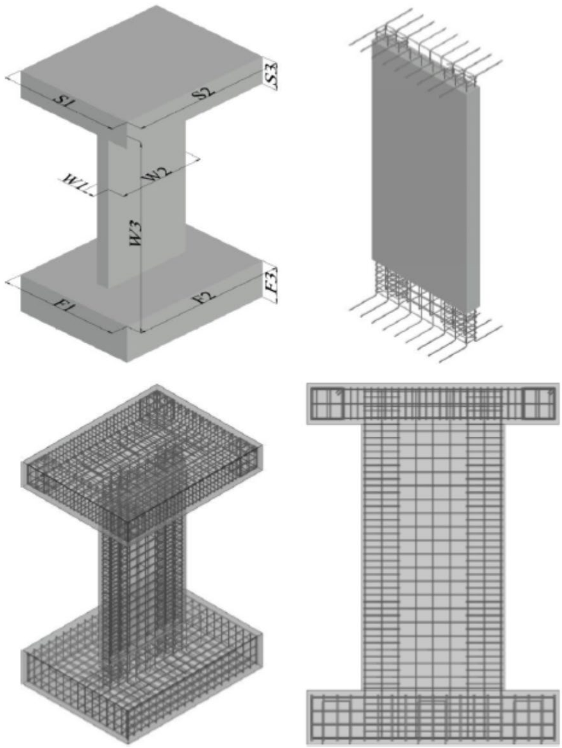

Table 1 Dimensions of the specimens (unit: mm)

Specimens	S1	S2	S3	W1	W2	W3	F1	F2	F3
P7	1450	1850	300	150	**1050**	2100	1450	1850	400
P6	1450	1850	300	150	**900**	2100	1450	1850	400
P5	1450	1850	300	150	**750**	2100	1450	1850	400

Fig. 3 Production of the specimens

2.2 Test Setup and Instrumentation

The Test setup is so crucial in terms of performing experiments correctly and obtaining desired results. For this reason, the test setup is properly designed and installed according to desired conditions of the experiment. Based on this scope, an appropriate test setup has been created for pure torsion tests within the scope of the study (Fig. 4). The test setup created for this study is different from the conventional test setup of reinforced concrete walls under lateral loading. In a conventional test setup, a horizontal load hydraulic jack is used. Bending effects are created on reinforced concrete walls using this hydraulic jack. In this study, two horizontal load hydraulic jacks have been used to obtain the torsional effects. Moreover,

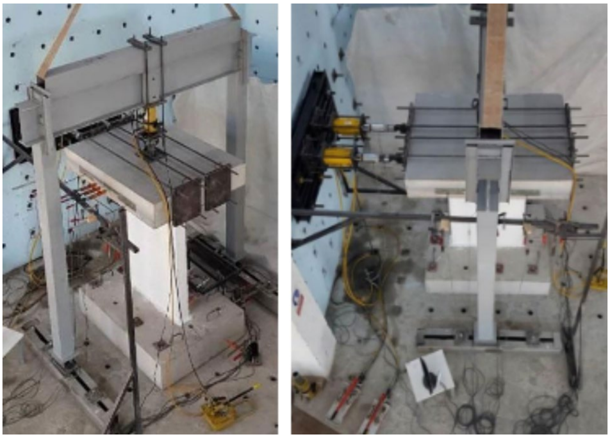

Fig. 4 Test setup

since displacements in the bending direction are important in the conventional test setup, the displacement transducers are placed in the bending direction. However, since the twist angles are also very important in this study, the displacement transducers have been placed along the wall length considering this issue.

During the tests, load and displacement values have been obtained by using suitable measuring instruments. Three load cells have been used to measure applied loads. Two load cells that have 300 kN push and pull capacities have been used to measure horizontal loads. One load cell which has 500 kN push capacity has been used to measure axial loads. Loads have been applied using hydraulic jacks and pumps during the tests. Displacement transducers have been placed on the specimens at certain intervals to obtain twist angles of the reinforced concrete walls. The displacement transducers which have been used in the tests are linear variable differential transformers (LVDTs) and resistive linear position transducers (potentiometric scales). The potentiometric scales have 300 mm (± 150 mm) and LVDTs have 100 mm (± 50 mm) measuring capacity. Potentiometric scales have been placed at end regions of the top of the walls because they have greater displacement measurement capacity than LVDTs. Data obtained from the measurement devices have been recorded by two data collection devices and compatible computer software. Fourteen channels have been used for data collection. Eleven of these channels have been used for displacement transducers. Three of these channels have been used for load cells.

The first step of the test setup is fixing the specimens to a strong floor. The holes in the foundations of the specimens and the holes in the strong floor have been matched to each other and the specimens have been fixed to the strong floor by means of shafts that have 36 mm diameter. Two hydraulic jacks have been used for horizontal loads. Distance between the horizontal load hydraulic jacks has been determined as 500 mm. In this way, distances between each horizontal load hydraulic jack and axis of the reinforced concrete walls have been determined as 250 mm. It is very important that the distances between each horizontal load and wall axis must be equal to obtain pure torsion. Hinges of the horizontal load hydraulic jacks have been placed in direction of rotation, not in direction of bending. In this way, while the specimens rotate under the effects of torsion, there is no strain on the horizontal load hydraulic jacks thanks to the hinges (Fig. 5a). Axial loads have been applied by using one hydraulic jack. A special hinge has been designed and produced for the axial load hydraulic jack. The special hinge has been rotated easily and axial loads have been applied correctly due to this special hinge during the rotation of the specimens (Fig. 5b). Eleven displacement transducers have been used in the test setup. Twist angles of the reinforced concrete walls have been calculated with the data obtained from these displacement transducers. Two potentiometric scales and three LVDTs have been placed at the top of the walls; five LVDTs have been placed at the bottom of the walls. In addition, one LVDT has been used to control foundation movements. The displacement transducers placed at the top of the walls have been named in the range of TOP1-TOP5 and the displacement transducers placed at the bottom of the walls have been named in the range of BOTTOM1-BOTTOM5. The displacement transducers distance between the top of the walls and the bottom of the walls has been determined and applied as 2000 mm. Glass plates have been glued on the specimens so that the displacement transducers have measured correctly (Fig. 6).

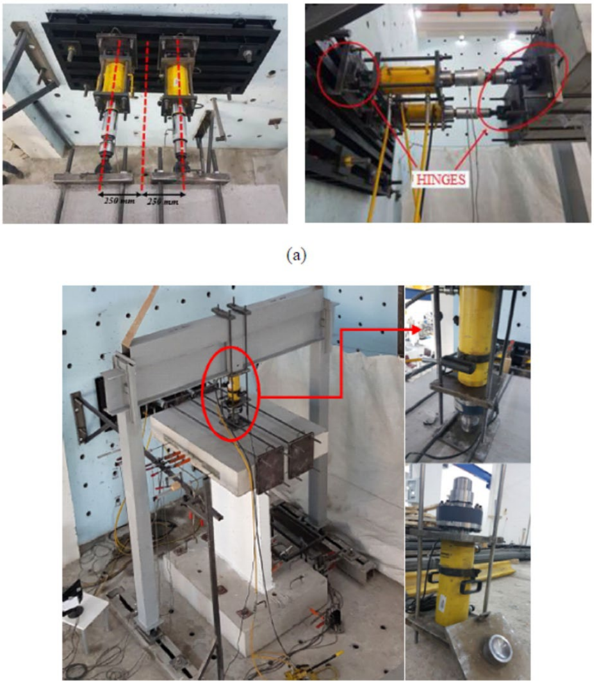

Fig. 5 Hydraulic jacks. (a) Horizontal load hydraulic jacks, (b) Axial load hydraulic jack

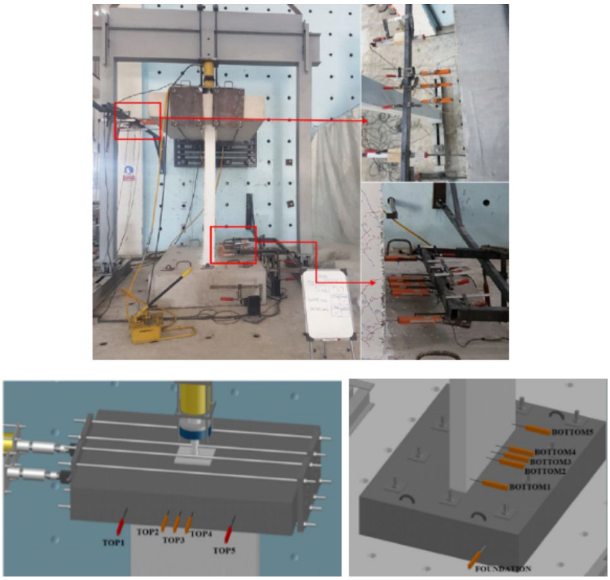

Fig. 6 Displacement transducers

2.3 Test Procedure

In this study, pure torsion tests of reinforced concrete walls have been carried out under the effects of axial loads and reversed cyclic lateral loads. Axial loads which have been determined as 10% of the wall's carrying capacity have been imposed on specimens. In this way, axial loads have been determined 308.4 kN for P5 walls, 370.1 kN for P6 walls, and 431.75 kN for P7 walls, respectively. Axial loads have been applied on the specimens and they have been constant during the tests.

Horizontal loads hydraulic jacks are equidistant from the wall axis to obtain pure torsional behavior in the tests. In addition, when one of the horizontal load hydraulic jacks applies pressure, the other horizontal load hydraulic jack must apply tension with the same load values for pure torsion. In this way, pure torsional loadings have been performed in tests. The tests have been carried out with 10 kN horizontal load increments for each horizontal load hydraulic jack and each cycle. In this way, 5 kNm torque increments have been applied to the reinforced concrete walls as reversed in each cycle. In every cycle, loads and displacements measured by the load cells and displacement transducers have been recorded by the data logger system. In the tests, each cycle consists of two steps. In the first step, when the right horizontal hydraulic jack has applied pressure, the left horizontal hydraulic jack has applied tension with the same load values. In the second step, when the right horizontal hydraulic jack has applied tension, the left horizontal hydraulic jack has applied pressure with the same load values (Fig. 7). The loads have been tried to keep constant while the cracks have been marked. The crack distributions have been traced and marked on the faces of the walls for each cycle. It has been tried to determine optimum load increase by changing load increments in the reference specimen test. 5 kNm torque increment value has been decided according to the reference specimen test.

The tests have been started with load-controlled loading. After the attainment of the peak torque, the tests have been conducted in a deformation-controlled loading. The 5 kNm torque increments have been achieved in load-controlled loadings. Displacement increments have been determined by considering displacement values for each cycle in deformation-controlled loading. After the tests have been conducted in a deformation-controlled loading, the tests have been terminated when torques have reached 75–80% of the maximum torques which have been defined as the failure of the walls.

3 Test Results and Discussion

Test results have been evaluated in detail. The difference between the tests is the different aspect ratios of the reinforced concrete walls. Thus, the effects of aspect ratio on the pure

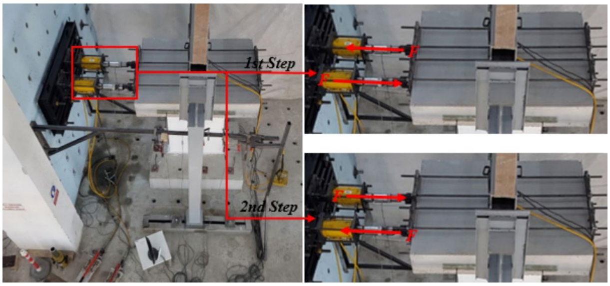

Fig. 7 Loading protocol of the horizontal loads

torsional strength and behavior of reinforced concrete walls have been investigated. Since the purpose of the reference specimen test is to determine the load increments optimally and to check the sustainability of the test setup, the findings of the reference specimen test have not been mentioned in detail.

3.1 Loading History and Torque-Twist Angle Relation

Torsional moments and twist angles of the specimens have been calculated by using data obtained from the tests. The data are load values obtained from load cells and displacement values obtained from displacement transducers. Torques have been obtained by using applied loads and distances between the wall axis and loads. Moments have been shown with positive values in the first step and they have been shown with negative values in the second step for each cycle. Twist angle has been defined as the average angular deformation per unit length. Twist angles of the walls have been calculated by using three parameters. The first parameter is values obtained from displacement transducers. The second parameter is horizontal distances between the displacement transducers. The last parameter is the vertical distance between top displacement transducers and bottom displacement transducers. Twist angles are easily calculated geometrically by using these parameters. The deformed shape of the specimens which has been used in the geometrical calculation of the torque and twist angle values is given in Fig. 8.

Torsional effects have been created by applying reverse cyclic lateral loads to the specimens. The torque values of the specimens have been calculated by using the horizontal load values and the distance between the horizontal loads. Since the tests are related to torsion, loading programs given for horizontal loads have been shown with torque-cycle graphs. Loading histories are given in Fig. 9, including one sample from each aspect ratio. The number of cycles in which the tests have been completed are given in Table 2.

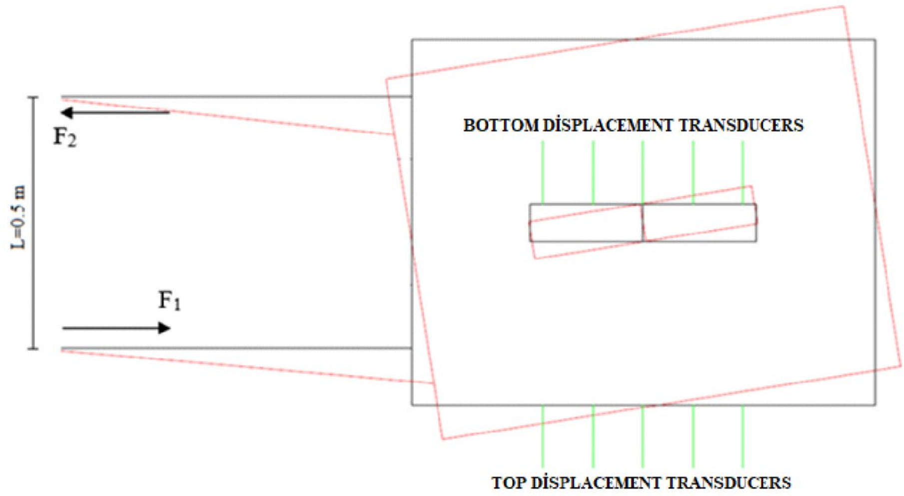

Fig. 8 The calculation of torsional moments and twist angles

Table 2 The number of cycles of the tests

Specimen	Cycle	Specimen	Cycle	Specimen	Cycle
P5-1	13	P6-1	15	P7-1	20
P5-2	14	P6-2	16	P7-2	21
P5-3	12	P6-3	15	P7-3	18

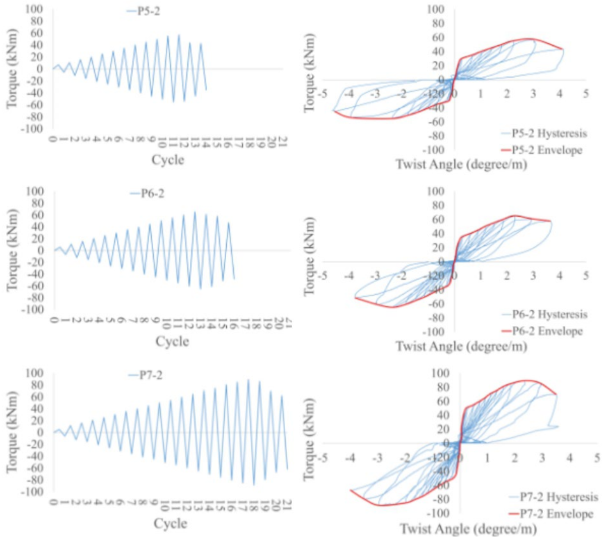

Fig. 9 Loading history and hysteresis-envelope curves of the walls

Torque-twist angle hysteresis and envelope curves have been composed by using calculated torsional moments and twist angles. Hysteresis and envelope curves are given in Fig. 9, including one sample from each aspect ratio. These curves have great importance in displaying behaviors of the building elements under applied loads. In addition, the cycles of the specimens in which they exhibit linear and non-linear behavior, energy consumptions of the specimens under the effects of applied loads, and stiffnesses of the specimens are determined by these curves. Cracking and maximum torsional moments are also determined from these curves.

Envelope curves of the specimens have been drawn by using torque-twist angle hysteresis curves. Envelope curves are very important to show torque-twist angle relations and characteristics of hysteresis curves. When the envelope curves are obtained, it can be clearly seen that hysteretic behaviors of the specimens are appropriate for reversed loads. Sudden torsional stiffness decrease with the occurrence of torsional cracking can be seen in the envelope curves obtained for the specimens. This situation is expected for the pure torsional behavior of reinforced concrete elements. It is demonstrated by means of envelope curves that specimens have exhibited a linear behavior up to torsional cracking. In addition, it is also understood from the envelope curves that large twist angles have occurred in the non-linear region, as there is a sudden stiffness decrease with the occurrence of torsional cracking.

Comparisons of the specimens have been made by using envelope curves. First, the specimens which have the same aspect ratio have been compared with each other. Then average envelope curves have been formed by using specimens that have the same aspect ratio.

The effects of aspect ratio on cracking torsional moment, maximum torsional moment and torsional stiffness have been compared by using the average envelope curves. It is seen in the comparisons that the cracking and maximum torsional moments of the specimens which have a large aspect ratio are higher (Fig. 10).

3.2 Torsional Strength and Stiffness

Pre-cracking torsional stiffness $K_{pre-cracking}$ and post-cracking torsional stiffness $K_{post-cracking}$ of reinforced concrete walls have been calculated by using the torque-twist angle hysteresis and envelope curves. Pre-cracking and post-cracking torsional stiffnesses of the specimens have been obtained by using the slope of the torque-twist angle curves (Eqs. 1 and 2). Then, the ratio of the $K_{post-cracking}$ to the $K_{pre-cracking}$ has been obtained for each specimen. Cracking torsional moments T_{cr} and corresponding twist angles θ_{Tcr}, maximum torsional moments T_{max} and corresponding twist angles θ_{Tmax} have been calculated for the calculations of torsional stiffnesses by using hysteresis and envelope curves. Moreover, cracking

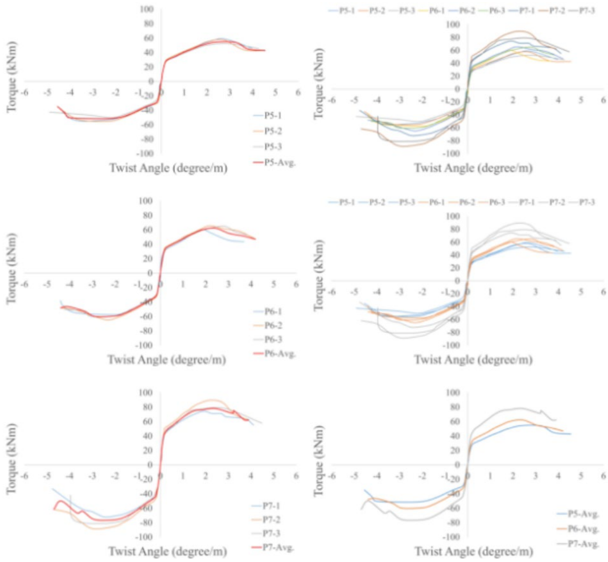

Fig. 10 Envelope curves of the reinforced concrete walls

Table 3 Torsional strength of the walls

Specimen	Cycle of T_{cr}	T_{cr} (kNm)	θ_{Tcr} (degree/m)	Cycle of T_{max}	T_{max} (kNm)	θ_{Tmax} (degree/m)
P5-1	6	26.7860	0.2014	12	58.6811	2.9258
P5-2	6	27.5707	0.2101	12	57.4174	3.0328
P5-3	5	-23.8602	-0.1649	11	52.2724	3.1532
P6-1	6	30.8127	0.1652	12	60.0550	1.9177
P6-2	6	29.6554	0.1822	13	65.3939	2.2830
P6-3	6	29.9032	0.2014	13	65.0035	3.0549
P7-1	9	43.6820	0.2113	15	74.3095	2.1039
P7-2	9	45.2804	0.1662	18	89.5059	2.3445
P7-3	8	40.6462	0.2113	16	-81.1004	-2.3129

and maximum torsional moments which are important parameters in terms of torsion have also been evaluated and compared (Tables 3 and 4).

$$K_{pre-cracking} = \frac{T_{cr}}{\theta_{T_{cr}}} \tag{1}$$

$$K_{post-cracking} = \frac{T_{\max} - T_{cr}}{\theta_{T\max} - \theta_{T_{cr}}} \tag{2}$$

The cracking and maximum torsional moment values of the specimens which have the same cross-sections are similar to each other as expected. When the specimens which have different cross-sections have been compared, it has been found that the cracking and maximum torsional moments of the walls which have a higher aspect ratio are greater. Moreover, it is seen that the ratios of the maximum torsional moments to cracking torsional moments are approximately two times in the tests. After the twist angles corresponding to the cracking torsional moments have been obtained, it is observed that the twist angles have appeared similar values in almost all of the specimens. When the twist angles corresponding to the maximum torsional moments of the specimens have been investigated, it is seen that the twist angles have occurred similar values as in cracking torsional moments. In this case, it shows that reinforced concrete walls with a higher aspect ratio have higher strengths at the same twist angles.

By evaluating the pre-cracking and post-cracking torsional stiffnesses, the torsional stiffnesses of the specimens which have the same aspect ratio are similar both pre-cracking and post-cracking. In addition, it is observed that the torsional stiffness has increased with the increase in the aspect ratio. The ratio of post cracking torsional stiffness to pre cracking torsional stiffness is one of the most important parameters in terms of the torsional behavior of reinforced concrete elements (Table 4). This ratio has been calculated for all specimens. When these ratios are examined, a sudden stiffness decrease can be seen as expected in the pure torsional effects. The accepted value range for this ratio in the literature is seen as 0.03–0.10. The values obtained for this ratio from the tests have provided this range.

Table 4 Torsional stiffness of the walls

Specimen	$K_{pre-cracking}$ (kNm^2/degree)	$K_{post-cracking}$ (kNm^2/degree)	$\frac{K_{post-cracking}}{K_{pre-cracking}}$
P5-1	133.0051	11.7073	0.0880
P5-2	131.2092	10.5741	0.0806
P5-3	144.7245	9.5076	0.0657
P6-1	186.5717	16.6860	0.0894
P6-2	162.7648	17.0118	0.1045
P6-3	148.4832	12.3005	0.0828
P7-1	206.7551	16.1828	0.07827
P7-2	272.5190	20.3026	0.0745
P7-3	192.3901	19.2486	0.1001

3.3 Energy Consumption

Huge energy is released with the occurrence of earthquakes. The main purpose of earthquake-resistant building design is to consume this energy. The energy consumed by a building or a building element is proportional to the area under load-displacement or moment-curvature curves. In this study, energy consumptions of the specimens have been calculated by using torque-twist angle curves. Twist angles that have been calculated at the top of the reinforced concrete walls have been used in energy consumption calculations. Torque-top twist angle curves have been formed by using twist angles of the top of the walls. Energy consumptions of the specimens have been evaluated by using the areas under these curves. These curves have been used in calculations to obtain more appropriate energy consumption units with area calculations. Energy consumptions of the walls have been analyzed under three parameters: energy consumption in a cycle, cumulative energy consumption, and total energy consumption.

Energy consumption in a cycle has been determined by using torque-top twist angle hysteresis curves obtained from the tests. The energy consumed in any cycle has been determined as a closed area under the torque-top twist angle hysteresis curve for that cycle. Energy consumption per cycle of the specimens is graphically given in Fig. 11. Energy consumption per cycle has been calculated for all cycles. It is clearly understood from the graphs that the specimens have consumed more energy with the occurrence of torsional cracking. Sudden stiffness degradation has occurred with torsional cracking in the specimens. Specimens have had larger twist angles with a decrease in stiffness. Specimens have been able to consume more energy in nonlinear regions with large twist angles.

In Fig. 11, the energy consumption of the specimens in each cycle is seen independently from other cycles. However, the energy consumption of the entire loading is more important than energy consumption per cycle. Therefore, it is very important to calculate the

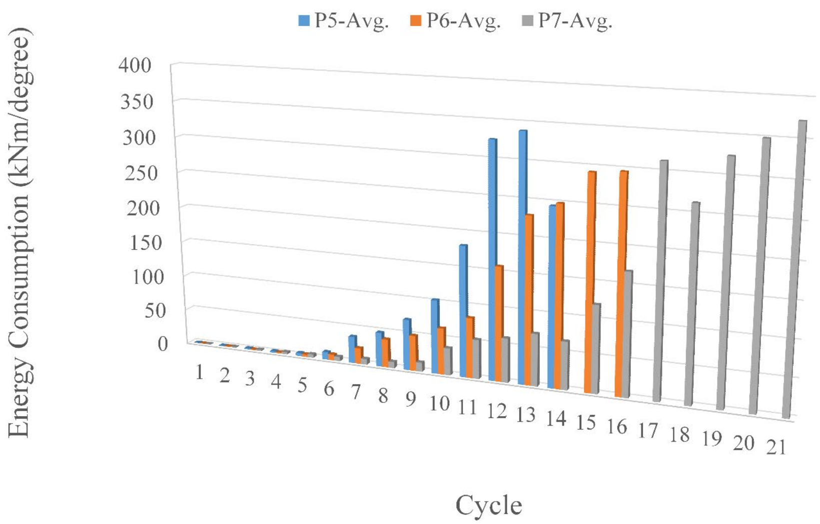

Fig. 11 Average energy consumption per cycle of the walls

cumulative energy consumption. Cumulative energy consumptions of the walls have been calculated by summing up energy consumptions per cycle (Fig. 12). Energy consumption changes can be seen more clearly by calculating the cumulative energy consumption. As shown from the graphs, energy consumption in the linear or elastic region is very small and close to each other for all specimens. In the non-linear region, the differences between specimens have appeared more clearly. It is clearly seen in the graphs that specimens that have large cross-sections have consumed more energy.

Total energy consumptions of the walls have been calculated using the areas under the torque-top twist angle envelope curves. The calculations have been made for the level at which 80% strength reduction from the maximum moment in each test (failure limit). It is understood from the calculations that the increase in total energy consumption has occurred with the increase in cross-section dimensions of the specimens (Table 5). The energy consumptions of the specimens in the linear and the non-linear region are given in Table 5. It is understood from the table that a significant part of the total energy has been absorbed after the torsional cracking in other words in the non-linear region.

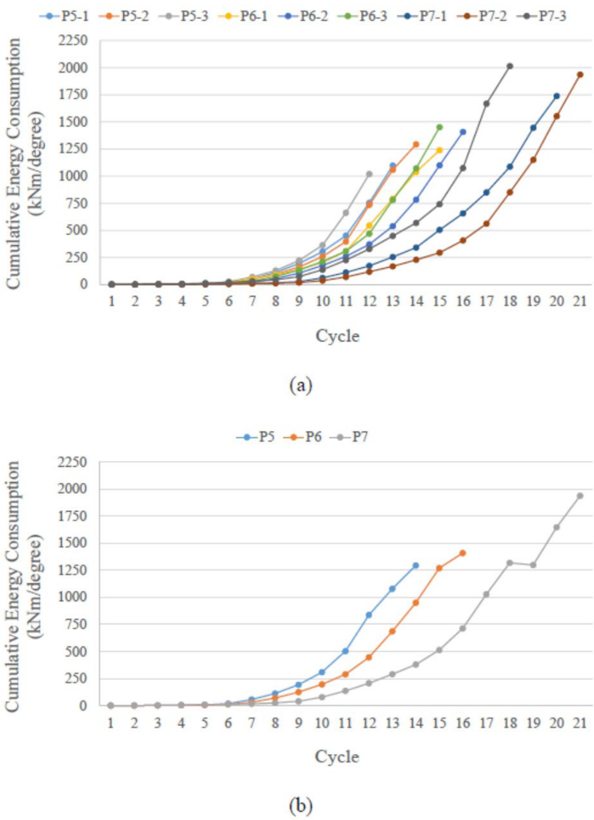

Fig. 12 Cumulative energy consumption of the walls. (a) Each wall, (b) Average of the walls

Table 5 Total energy consumptions of the walls for linear and non-linear regions

Specimen	0 - T_{cr} (kNm/degree)	T_{cr} - T_{max} (kNm/degree)	T_{max} - %80 T_{max} (kNm/degree)	0 - %80 T_{max} (kNm/degree)
P5-1	8.107	523.4163	293.5095	825.0327
P5-2	8.7078	531.1303	249.0261	788.8642
P5-3	12.3211	454.3112	374.2979	840.9301
P6-1	13.5717	429.0854	297.8800	740.5371
P6-2	12.5677	469.4319	332.2102	814.2099
P6-3	13.8511	603.1424	328.8112	945.8047
P7-1	23.5154	525.6790	454.1012	1003.2956
P7-2	16.6565	781.2977	280.3134	1078.2676
P7-3	32.0867	1005.6001	390.8147	1428.5014

3.4 Damage Pattern

One of the most useful parameters in determining the pure torsional behavior of reinforced concrete elements is the determination of crack development and distribution. For this reason, cracks that have occurred in each cycle in the tests have been drawn. The number of cycles has been written on the cracks. As stated before, each cycle has consisted of two steps reversibly. The cracks that have occurred in the first step have been drawn with a blue colored pencil and the second step cracks have been drawn with a red colored pencil. Levels have been determined on the walls in proportion to the wall width (h) to monitor the level of the crack development. Heights and development zones of the cracks could be determined with the help of these levels. In addition, four faces of the reinforced concrete walls have been named to facilitate the evaluation of crack distributions (Fig. 13).

When damage patterns or crack distributions of the walls are observed, it can be said that the cracks formed on all faces of the walls are diagonal cracks and cracks have a slope of approximately 45 degrees as expected under pure torsional effects. In addition, considering that the diagonal cracks formed on two opposite faces are perpendicular to each other, it can be concluded that pure torsional effects have occurred in the specimens. Furthermore, as observed in all tests, few cracks have occurred in the torsional cracking cycle. However, numerous cracks have occurred in the next cycle of the torsional cracking cycle. This situation can be explained by a sudden degradation in the torsional stiffness of reinforced concrete walls with the formation of torsional cracking.

By comparing the crack distributions of the specimens, it can be said that the crack distributions are similar in all specimens. It can be said that the change of the cross-section dimensions has an effect on the expansion and progress of the cracks, but it has no effect on the distribution of the cracks or damage patterns. The cracks have formed later and at higher loads with the increase of the cross-section dimensions as expected. Moreover, crust concrete fracture and core zone damage have been detected at higher loads with the increase of the cross-section dimensions. Plastic hinges are expected to occur at the wall bases under the effects of bending. In the case of torsional effects, the plastic torsional hinges are expected to occur in areas close to the middle of the walls. In the tests, plastic torsional hinge regions of the reinforced concrete walls have occurred in areas close to the middle of the walls. All these findings related to crack distributions show that the pure torsional effect is achieved in the specimens. In other words, the occurrence of plastic torsional hinges in the middle of the walls in all specimens is demonstrated as a result of the pure

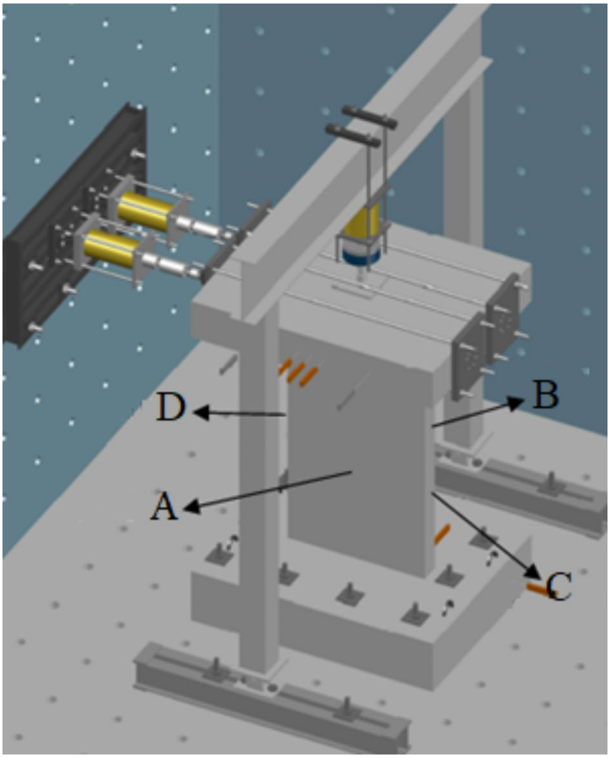

Fig. 13 Faces of the walls

torsional effect. The increase in the number and width of the cracks has continued until the end of the tests. Crust concrete fractures and core zone cracks have been observed in the last cycles. All of the specimens have been damaged as brittle at the end of the tests. Samples for deformed forms and damage patterns of reinforced concrete walls are given in Figs. 14, 15, 16, 17 and 18, respectively.

4 Conclusions

This study aims to experimentally investigate the pure seismic torsional behavior of reinforced concrete walls which have different aspect ratios. Pure torsional effects have been created by applying reversed cyclic lateral loads to reinforced concrete walls which are under axial loads. Ten specimens have been produced and ten torsion tests have been performed in experimental studies. Torque-twist angle relation, torsional strength and stiffness, energy consumption, and damage pattern of the specimens have been obtained and evaluated in detail. After comparing the test results with both each other and the studies in the literature, it is clearly seen that compatible results have been obtained in terms of the pure torsional behavior of reinforced concrete elements. In other words, when the results of this study are investigated in general, all test results show that pure torsional behavior has occurred in reinforced concrete walls. Based on the test results, the following concluding remarks and suggestions can be drawn:

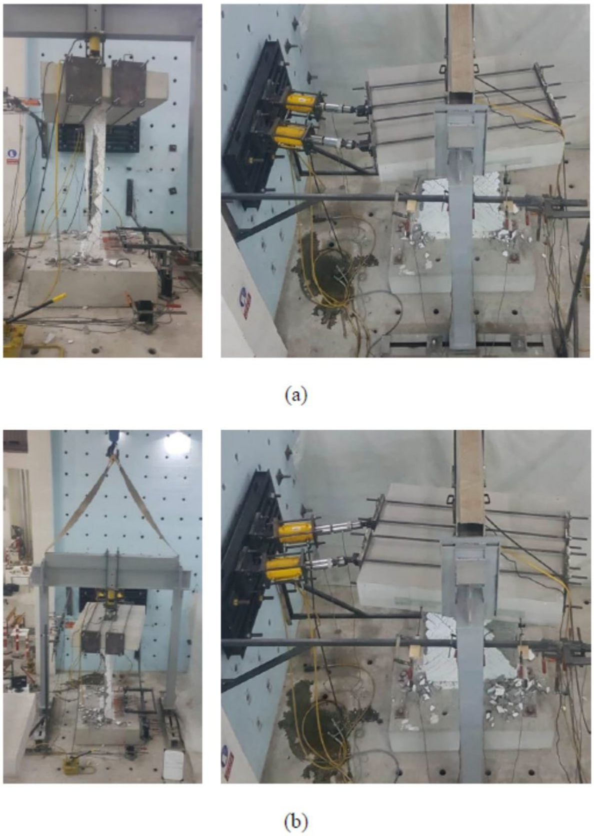

Fig. 14 Deformed shapes of P7-1 wall. (a) Last cycle's first step, (b) Last cycle's second step

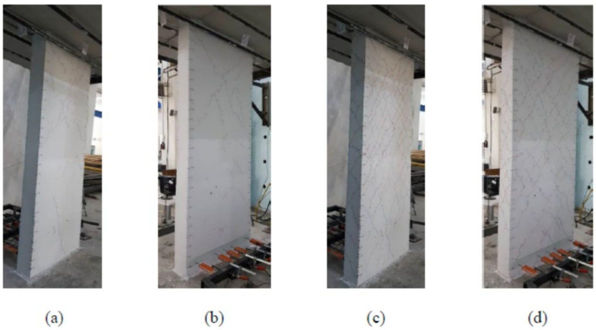

Fig. 15 Torsional cracking cycle and next cycle of P5-1 wall. (a) 6. cycle A-D faces, (b) 6. cycle B-C faces, (c) 7. cycle A-D faces, (d) 7. cycle B-C faces

- When the torque-twist angle hysteresis and envelope curves are examined, it is seen that the specimens have exhibited hysteretic behavior under the effects of reversed loads.
- When the slopes of the torque-twist angle envelope curves in elastic and inelastic regions are compared, sudden torsional stiffness decrease caused by torsional cracking can be clearly seen in the specimens. The sudden stiffness degradation of torsional cracking is

Fig. 16 Crack distributions of P5-2 wall for all faces (A, B, C, D faces)

Fig. 17 Crack distributions of P6-2 wall for all faces (A, B, C, D faces)

Fig. 18 Crack distributions of P7-2 wall for all faces (A, B, C, D faces)

very important to reveal the torsional behavior in studies. This can be clearly seen in the torque-twist angle curves.

- Cracking and maximum torsional moments have been obtained with the help of torque-twist angle curves. The cracking and maximum torsional moment values of the specimens which have the same aspect ratio are similar. The average cracking torsional moments of P5, P6, and P7 walls have been determined 26.0723 kNm, 30.1238 kNm, and 43.2029 kNm respectively. The average maximum torsional moments have been calculated as 56.1236 kNm, 63.4841 kNm, and 81.6386 kNm respectively. It has been observed that the cracking and maximum torque values of reinforced concrete walls which have larger cross-sectional dimensions are greater as expected. When the torsional moment values are compared, it is seen that although there is no big increase between P5 and P6 walls, an increase that can not be ignored has occurred between P6 and P7 walls. Considering that end zones of the walls are the same, it is revealed that the wall web zones have caused differences.

- Energy consumptions of the specimens have been calculated by using torque-twist angle curves. When the energy consumption values and graphs are examined, it is seen that more energy consumption has occurred with the occurrence of torsional cracking. In other words, most of the energy which has been consumed is in the inelastic or nonlinear region. The average energy consumptions up to torsional cracking of P5, P6, and P7 walls are 9.712 kNm degree, 13.3302 kNm degree, and 24.7529 kNm degree respectively. Average energy consumptions up to the failure or collapse limit (80% T_{max}) have been calculated as 818.276 kNm degree, 833.5172 kNm degree, and 1170.0215 kNm degree respectively. In this case, 1.2% of the energy consumed up to the failure limit for P5 walls has been consumed in the cycles before the torsional cracking. This ratio has been calculated as 1.6% for P6 walls and 2.1% for P7 walls. The large increase in energy consumption after torsional cracking has also revealed that the large decrease in stiffness has occurred with torsional cracking and very large twist angles have occurred. It is also observed that specimens that have large cross-sectional dimensions have consumed more energy.
- Diagonal cracks have occurred on all surfaces and levels of reinforced concrete walls as expected in pure torsional effects. Cracks have also occurred in the wall-foundation and wall-slab joints. Moreover, the oblique cracks which have formed on two opposite sides are perpendicular to each other and have a slope of approximately 45 degrees as expected in the pure torsional behavior of reinforced concrete elements. In addition, these crack patterns are important in terms of revealing torsional behavior.
- As a result, although the aspect ratio has changed in reinforced concrete walls, approximately the same twist angles have occurred for cracking and maximum torsional moments. Furthermore, increment in the aspect ratio of the walls has only increased stiffness and the twist angles have remained the same according to the results. Thus, it has been concluded that choosing the aspect ratio of 5 or 6 would be appropriate in terms of torsional behavior. The limit values of the aspect ratios of reinforced concrete walls are given as 7 in the TERDC 2007, 6 in the TBEC 2018 and ACI 318 – 14, and 4 in the Eurocode 2 2004. The limit values of the aspect ratio of the standards have been evaluated in terms of torsion with the study.

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