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The Pure Torsional Behavior of Hybrid Fiber RC Shear Walls

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Abstract:

The reinforced concrete (RC) shear walls are widely used to serve as the primary lateral load-resisting member in the high-rise buildings. An experimental investigation of the mechanical behaviour of hybrid fibre (carbon and steel) reinforced self-compacting concrete (HFRSCC) shear walls under pure torsion moment is presented in this paper. The nine HFRSCC shear walls with the same longitudinal reinforcement ratio were tested under pure torsion moment and no axial load. The effect of hybrid fibre ratio and horizontal reinforcement amount and aspect ratio on the failure characteristics, torsional behaviour, energy dissipation capacity, ductility of shear walls was studied. Results indicate that both hybrid and horizontal reinforcement ratio are increased the ultimate torsional moment capacity and angle of rotation and that the hybrid fibre ratio is the key parameter that determines the failure mode of the HFRSCC shear walls. Torsional moment capacity increased, when the hybrid fiber ratio rose up from 0% to 1.0% and then 1.5%. However, this increase was larger in case of increasing the hybrid fiber ratio from 0% to 1.0%. Increasing the hybrid fiber ratio from 1.0% to 1.5% did not result in a performance increase as in the first case.

Key words: Shear wall, hybrid fiber, torsional moment

1. Introduction

The reinforced structural buildings in areas that may be subjected to high seismic loads usually use either moment resisting space frames, shear walls or a combination of both. The shear wall systems exhibit better performance than space frame systems do. Shear walls that are resisted to lateral force can exhibit either ductile or non-ductile behaviour. Although the bending moment has an effect on the failure mode of the ductile shear walls, the shear force is effective on the failure mode of the non-ductile shear walls. Because of their effective and economic advantages, non-ductile shear walls are usually preferred to be used in low-rise buildings. Since the height to length ratio of shear walls used in low-rise buildings is less than 2, they are called squat shear walls [1].

The RC shear walls can be classified according to several characteristic parameters. One of these parameters is height-to-length ratio (H/L) known as the aspect ratio. RC shear walls with H/L ratio greater than 2 are usually referred to as slender structural walls. which dominated by the flexural moment [2]. Even though review of literature indicates that the numerous studies were carried out in the past to investigation the strength and behaviour of normal concrete structural walls, the study

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on the behaviour of fibre or hybrid fibre concrete shear walls in the literature is limited.

Concrete has been the most used structural material worldwide since the production of cement. But plain concrete has a few disadvantages like brittleness, low tensile strength and low strain capacity. After the steel reinforcement was used in concrete, the tensile weakness of the concrete was eliminated. However, the researchers focused on the disadvantages of unreinforced concrete. As a result of these researches, using concrete admixture such as fibres became o common trend in modern construction [3]. The using of steel fibre reinforced concrete in the concrete technology have begun around the early 1960s, and the researchers have interested in the carbon fibres in 1990s. The main applications of fibre reinforced concrete are the structures subjected to damage concentrated and dynamic load such as infrastructure and industrial applications. The researchers have reported that the fibre reinforced concrete have exhibited the more durable than plain concrete. The effect of carbon fibre on the properties of the concrete increase with volume fraction unless the carbon volume fraction is so high that the air void content increases with fibre content and air voids tend to have a negative effect on properties of concrete like compressive strength. Although ıncreasing the carbon fibre volume fraction decreases the workability of concrete, the carbon fibre has a few advantages such as attractive tensile and flexural strength, low drying shrinkage, high specific heat, low thermal conductivity, high corrosion resistance and weak thermoelectric behaviour as well as the catholic protection of steel reinforcement in concrete.

Compared with conventional concrete, hybrid fibre concrete has better tensile strength, flexural strength, energy dissipation capacity, post cracking capacity, impact resistance and crack propagation, fatigue properties. In recent years, the rang of research projects of hybrid fibre reinforced concrete have focused more on mechanical properties of concrete such as compressive strength, tensile strength and flexural strength. The researchers and engineers have made concrete with better compressive strength, toughness and fracture energy than single fibre reinforced concrete by mixing different fibres [4].

The original value of this study is to experimentally examine the effects of fiber ratio, horizontal reinforcement ratio and size effect (H/L) on torsional behavior in shear walls produced with hybrid fiber SCC.

2. Materials and Method

It is aimed to control the cracks in the plastic hinge region that will be caused by the torsional moment by utilizing the high modulus of elasticity and rigidity of steel and carbon fibers. The fact that the elastic deformation capabilities of carbon fibers are much higher than that of steel has been the reason for preference. However, in order to minimize the peeling problem that may be encountered in the possible fiber-concrete adhesion, not only carbon fiber but also carbon-steel combination is preferred. It is aimed to make use of the high elastic properties of carbon fibers as well as the bridging effect of steel and carbon fibers against cracks with the random distribution of fibers in the concrete and thus presenting an innovative approach to the literature for shear walls to be produced with hybrid fiber SCC. The technical properties of steel and chopped carbon fiber fibers are given in Table 1. Within the scope of the study, nine 1/2 scale reinforced concrete shear walls were produced in Atatürk University Engineering Faculty Civil Engineering Department Building and Construction Material Application Laboratory. Foundation dimensions, concrete class and reinforcement used in the foundation shoe, longitudinal reinforcement ratio and wall thickness were kept constant in all samples. The basic part of the samples does not affect the parameters reached as a result of the test, exhibits a rigid behavior and any cracks etc. under the load effect.

Table 1. Technical Properties of Steel and Chopped Carbon Fibers

	Steel	Carbon
Length (mm)	50	50
Diameter (mm)	1	1
Tensile strength (MPa)	1200	1400
Aspect ratio	50	50
Elastic modulus (GPa)	200	119
Density (gr/cm^2)	7,17	1,6

The common and variable parameters of the test samples are presented in Table 2. While selecting the size and reinforcement parameters of the samples, the relevant codes in the Turkish Building Earthquake Code (TBDY-2018) [4] and the American Concrete Institute Regulation [5] (ACI318-2019) were taken into account in order to comply with both national and international regulations. In addition, within the scope of the experimental program, the samples were produced with three types of concrete: SCC, 1.0% hybrid fiber SCC and 1,5% hybrid fiber SCC. 0,5% hook steel fiber and 0,5% carbon fiber by volume were used in the 1,0% hybrid fiber SCC mixture. In the 1.5% hybrid fiber mixture, SCC was produced with 0.75% hook steel fiber and 0.75% carbon fiber by volume. The geometry of the shear walls was chosen so that they were gapless and short shear walls, and their reinforcement was made. The wall height and thickness of the wall are 1500 mm and 150 mm, respectively, and are constant in all samples.

Table 2. Parameters of Test Samples

	Width (mm)	H/L	Longitudinal reinforcement ratio	Transverse reinforcement ratio	Steel fiber ratio	Carbon fiber ratio
SW1	1200	1,25	0,0088	0,0056	-	-
SW2	1200	1,25	0,0088	0,0056	0,50	0,50
SW3	1200	1,25	0,0088	0,0056	0,75	0,75
SW4	1000	1,5	0,0090	0,0056	-	-
SW5	1000	1,5	0,0090	0,0056	0,50	0,50
SW6	1000	1,5	0,0090	0,0056	0,75	0,75
SW7	1000	1,5	0,0090	0,0028	-	-
SW8	1000	1,5	0,0090	0,0028	0,50	0,50
SW9	1000	1,5	0,0090	0,0028	0,75	0,75

Concrete mixture was calculated according to the principles determined in TS 802 [6]. 1m^3 concrete mixing ratios are given in Table 3.

Table 3. Concrete Mixing Ratios

	SCC	1% SCC	1,5% SCC
Cement (kg/m^3)	475	475	475
Water (kg/m^3)	216	288	288
Silica fume (kg/m^3)	25	25	25
Carbon fiber (kg/m^3)	-	8	12
Steel fiber (kg/m^3)	-	35	53
Plasticizer (lt/m^3)	10	10	10
Marble dust (kg/m^3)	152	134	132
Fine aggregate (kg/m^3)	794	700	692
Coarse aggregate (kg/m^3)	528	466	460
Water/binder ratio	0,43	0,57	0,57

The mechanical and physical properties of the mixtures are presented in Table 4. As can be seen from Table 4, the diameter was measured as 600 mm for all three concrete types. As it is known, the addition of fiber in the SCC type reduces the spreading diameter. Addition of 1.0% and 1.5% hybrid fiber to the SCC strain increased the t_{500} time by 26.67% and 40%, respectively. Addition of 1.0% and 1.5% hybrid fiber to the SCC strain increased the V-funnel transit time by 18.57% and 31.43%, respectively. Addition of 1.0% and 1.5% hybrid fiber to the SCC strain decreased the L-box ratio by 6.52% and 13%, respectively.

Table 4. Fresh and hardened test results of SCC

	SCC	1% SCC	1,5% SCC
Compressive strength (MPa)	30	30	30
Tensile strength (MPa)	1,97	2,13	2,16
Flexural strength (MPa)	7,03	9,10	10,74
Flow diameter (mm)	600	600	600
t_{500} (sec)	3,0	3,8	4,2
V-funnel (sec)	7,0	8,3	9,2
L-box	0,92	0,86	0,80

Addition of 1.0% and 1.5% hybrid fiber to fiberless SCC increased the flexural strength by 29.4% and 52.8%, respectively, and the tensile strength by 8.1% and 9.6%, respectively. Especially due to the high tensile strength and modulus of elasticity of the fibers, the fibrous samples absorbed more energy and thus an increase in bending and tensile strength occurred.

Torsional moment is created by two hydraulic pumps as seen in Figure 1. While one of the pumps acted in the pressure direction, the other applied load in the tension direction. Thus, a torsional moment was created in the test specimen. Load cells were connected to the end of the hydraulic pumps and the forces applied during the experiment were recorded. Loading apparatuses are connected to the end of the load cells. A rigid head beam is designed so that the loading apparatus does not directly apply a load to the concrete of the samples. The two pumps are calibrated with each other to create a synchronous push and pull. The loading speed was applied as 10 mm/sec. Displacements due to horizontal loads during the experiment were measured with the help of LVDTs. Within the framework of the experimental program, the loading process was carried out with displacement control. The loading process was continued until the failure mode was reached in the test samples. The experiment was terminated when the failure load was reached. Failure was determined as the point where the maximum load decreased by 15%.

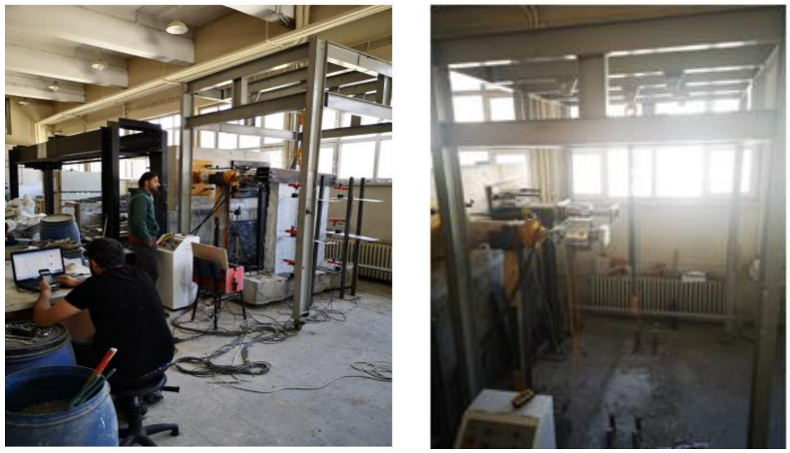

Figure 1. Test setup

3. Results

The experimental results of nine shear walls are shown in Table 5. As seen in Table 5, size effect, hybrid fiber ratio and horizontal reinforcement ratio parameters have effects on the shear wall torsional behavior. On the other hand, in the test samples, the torsional strength was obtained with a maximum of 57.12 kN.m in the SW3 sample. The highest rotation angle was also reached in the SW3 sample with a value of 15.56 deg/m. With a torsional moment of 30.32 kN.m and a rotation angle of 4.83 deg/m, the lowest strength and rotation angle were obtained in the SW7 sample. We can say that the use of hybrid fibers in the concrete mix and increasing this ratio increase the energy absorption capacity.

Table 5. Experimental Results

	T_{cr} (kN.m)	θ_{cr} (deg/m)	T_a (kN.m)	θ_a (deg/m)	T_{maks} (kN.m)	θ_{max} (deg/m)	T_u (kN.m)	$\boldsymbol{\theta}$u (deg/m)	E (kN.deg)
SW1	27,59	1,18	34,49	1,40	45,98	9,86	39,09	12.04	479,42
SW2	31,77	1,36	35,33	1,69	52,93	13,69	44,99	17.56	812,54
SW3	34,27	1,58	42,84	2,07	57,12	15,56	48,55	20.12	1010,90
SW4	23,57	0,94	26,36	1,44	35,15	6,46	29,87	7.88	239,00
SW5	26,56	1,05	30,58	1,66	44,26	10,43	37,63	12.64	481,51
SW6	28,24	1,36	32,28	1,81	47,06	12,67	40,00	16.50	674,52
SW7	21,33	0,87	22,75	1,04	30,32	4,83	25,77	5.40	140,49
SW8	24,27	1,13	27,44	1,63	40,45	8,87	34,38	10.92	372,02
SW9	27,91	1,24	30,45	1,71	43,44	10,86	36,92	12.09	447,91

Torsional moment-rotation angle graphs of test specimens are shown in Figure 2. As can be seen in Figure 2, the use of hybrid fiber increased the torsion moment provided the other parameters were the same. However, increasing the fiber ratio from 1.0% to 1.5% increased the torsional moment of the shear wall. In addition, the use of hybrid fibers in shear walls caused a more ductile behavior. The use of hybrid fiber did not cause a significant effect on the linear regions of the test samples. However, when the non-linear region is passed, the efficiency of the fiber becomes more evident. In other words, the activity of the fibers was not revealed until the first crack occurred in the test samples. After the first crack occurs, fiber activity is observed. A similar situation is observed when looking at the slopes of the torsional moment-rotation angle graphs. The slopes of the graphs of the test specimens are very close to each other before the crack occurs. After the crack has formed, the slopes of the graphs differ. However, the remarkable test sample here is SW7. The SW7 sample differs in the linear regions of the SW8 and SW9 samples. By reducing the horizontal reinforcement ratio to the minimum value, the slope of the liner region of the SW7 sample produced from SCC concrete was different compared to the samples with fiber concrete. By adding hybrid fiber, the slope in the linear regions of the test samples was increased. Thus, the fibers tolerated the decrease in the horizontal reinforcement ratio.

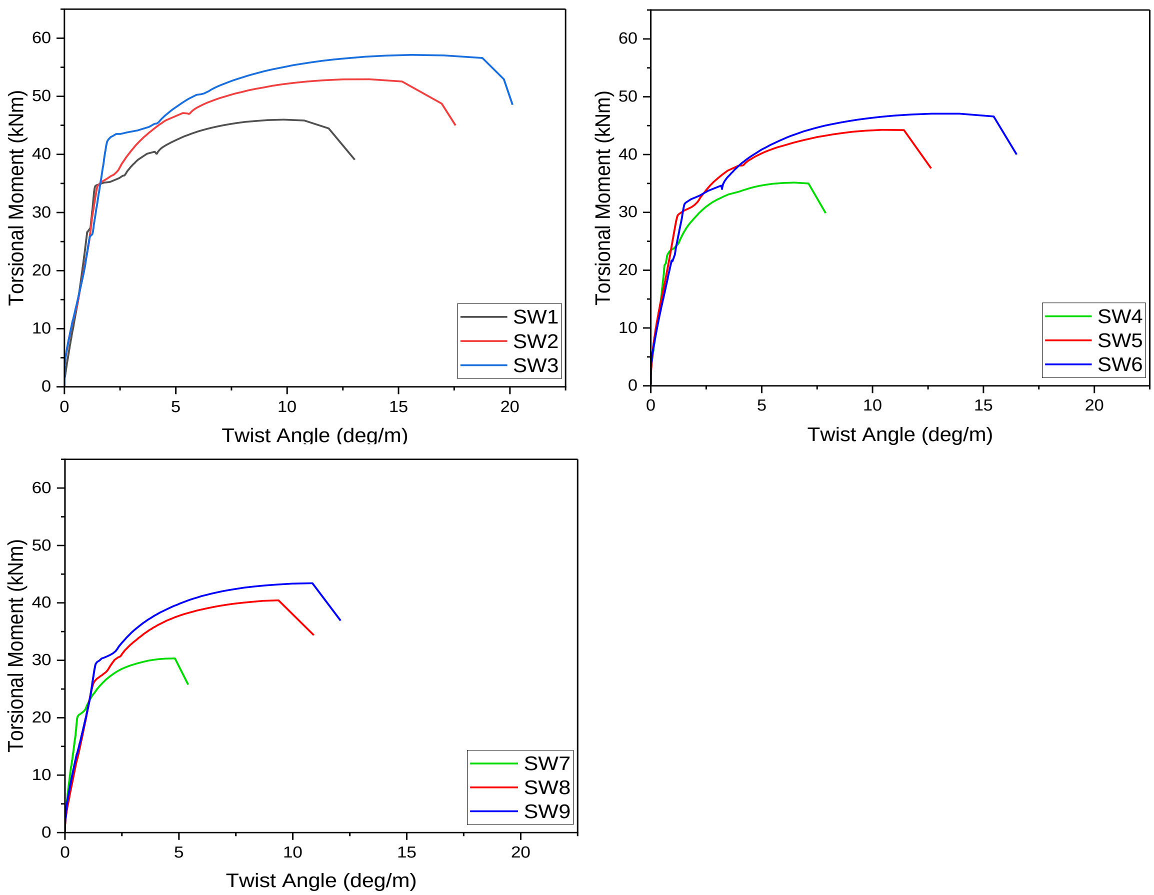

Figure 2. Experimental torsional moment-twist angle curves

Another remarkable point in Figure 2 is the region where flow occurs. In the samples produced with fibrous concrete, the areas where the following took place lasted longer than the samples with SCC. Considering that the yielding that starts in the longitudinal reinforcement is followed by the horizontal reinforcement, the fibers take the stresses on themselves at the points where the yielding occurs in the reinforcements and delays the yielding. Thus, the slope in these regions also differs. In the test specimens reaching the maximum torsion moment, failure occurred more rapidly in fiberless concrete shear walls. Especially when the percentage changes between θ_{max} and θ_u of the test samples are examined, the difference is more in the samples with fibrous concrete.

However, increasing the amount of fiber also increases the required bond between the concrete and the fibers. 8 kg carbon, 35 kg steel fiber per cubic meter in 1.0% hybrid fiber concrete, 12 kg carbon and 53 kg steel fiber per cubic meter in 1.5% hybrid fiber concrete was used. Therefore, it will be more difficult to fully ensure the adherence between the concrete and the fibers in the 1.5% fiber concrete. In addition to the difficulty of ensuring adherence, the stripping of the fibers was easier than the fibers in the 1.0% mixture. Therefore, increasing the fiber ratio from 1.0% to 1.5% was not as effective as increasing it from 0% to 1.0%. In the samples with 1.5% hybrid fiber, the stripping of the fibers from the matrix was easier than the samples with 1.0% hybrid fiber.

The effect of the aspect ratio on the torsional moment-rotation angle graphs is shown in Figure 2. As can be seen from the graphs, as the cross-sections of the shear walls increase, the torsional moment capacities and rotation angle values also increase. In addition, the increase in the cross-section caused the reinforced concrete shear walls to exhibit a more ductile behavior. In the graphs, the slopes of the test samples in the linear regions are almost the same with each other. In addition, the points where the graphs pass from the linear region to the non-linear region vary according to the cross-section. In samples with larger cross-sections, this transition region occurred at higher torsional moment values.

Samples SW4 and SW7, SW5 and SW8 and SW6 and SW9 were compared in order to examine the effect of the horizontal reinforcement ratio on torsional moment behavior and to examine the relationship of this effect with the hybrid fiber utilization ratio. For this purpose, SW7~9 groups are equipped with horizontal reinforcement ratio and SW4~6 groups are equipped with twice the horizontal reinforcement ratio. In addition, it has been predicted that reducing the horizontal reinforcement ratio will reduce the torsional strength, and the relationship of this reduction with the use of hybrid fiber and increasing the hybrid fiber ratio has been discussed. It is also aimed to avoid the problem of concrete settling in shear walls by tolerating the decrease in torsional moment strength caused by the use of hybrid fiber due to the horizontal reinforcement ratio.

Reducing the horizontal reinforcement ratio decreased the torsional strength of both non-fiber and fibrous concrete samples. Samples with higher horizontal reinforcement showed a more ductile behavior. The behavior of the test samples in the linear regions was almost the same. The difference in the graphs appeared especially after the first crack and/or leakage. Therefore, it is seen that the horizontal reinforcement ratio does not have a significant effect in the linear region. Increasing the horizontal reinforcement ratio also increased the torsional strength and rotation angle capacities.

Figure 3 shows the effect of the test specimens on the torsional ductility. The samples with the highest and lowest torsional stiffness before cracking are SW8 and SW6, respectively. Considering the stiffnesses after the crack, the highest value was obtained in SW4 and the lowest value in SW3 and SW8 samples. Torsional stiffnesses before cracking in SW1~3, SW4~6 and SW7~9 groups were quite close to each other. It was concluded that the hybrid fiber ratio had the little effect on the torsional stiffness before cracking. However, there is a similar situation in SW4~6 and SW7~9 groups. It is understood that concrete class does not have a significant effect on the stiffness before cracking. However, when the stiffness values after the crack are examined, in other words, when the slope of the torsional moment-rotation angle graphs changes, the efficiency of the fibers becomes more evident. As the fiber ratio increases, the stiffness value after crack formation decreases.

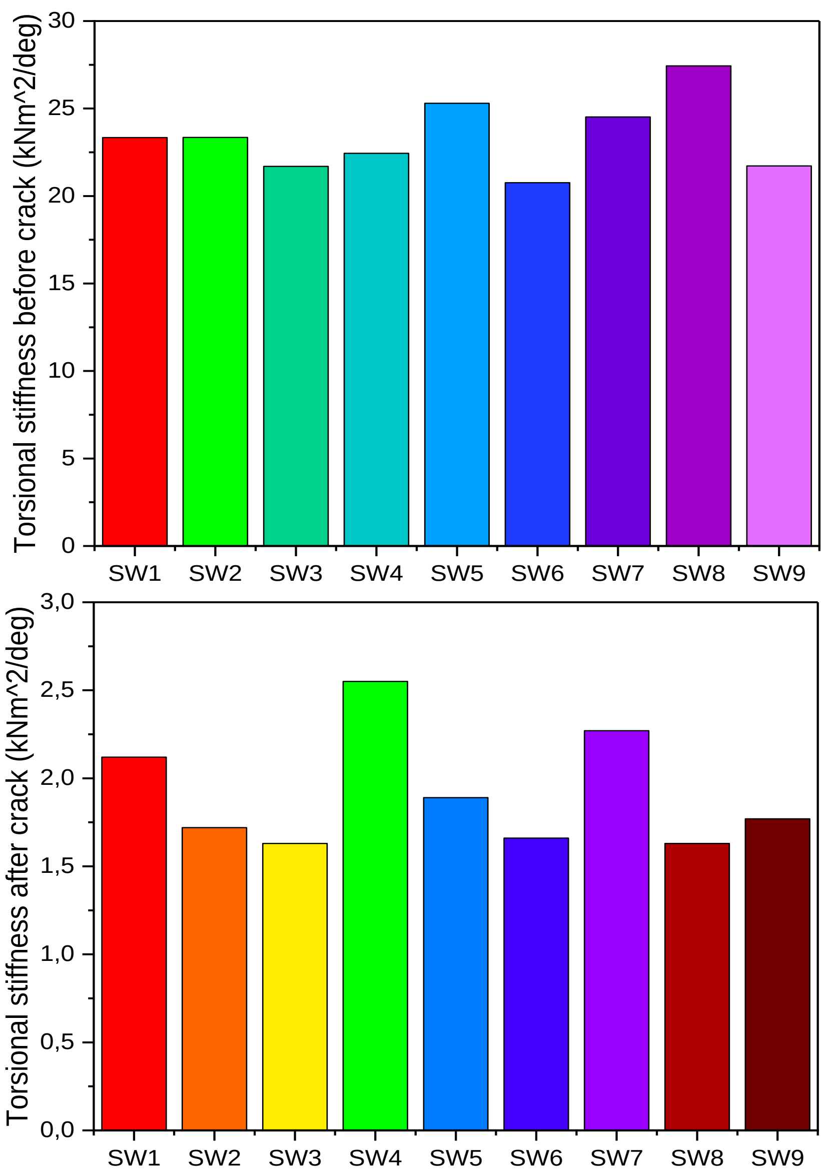

Figure 3. Torsional ductility index before and after of crack

The torsional stiffnesses of SW1 and SW4, SW2 and SW5, SW3 and SW6 samples before cracking are very close to each other. Thus, it was concluded that the size effect did not have a decisive effect on the torsional stiffness before the crack. Increasing the fiber ratio decreased the stiffness increase rate after cracking between the samples. Therefore, the presence of fibers reduced the negative effect of the size effect.

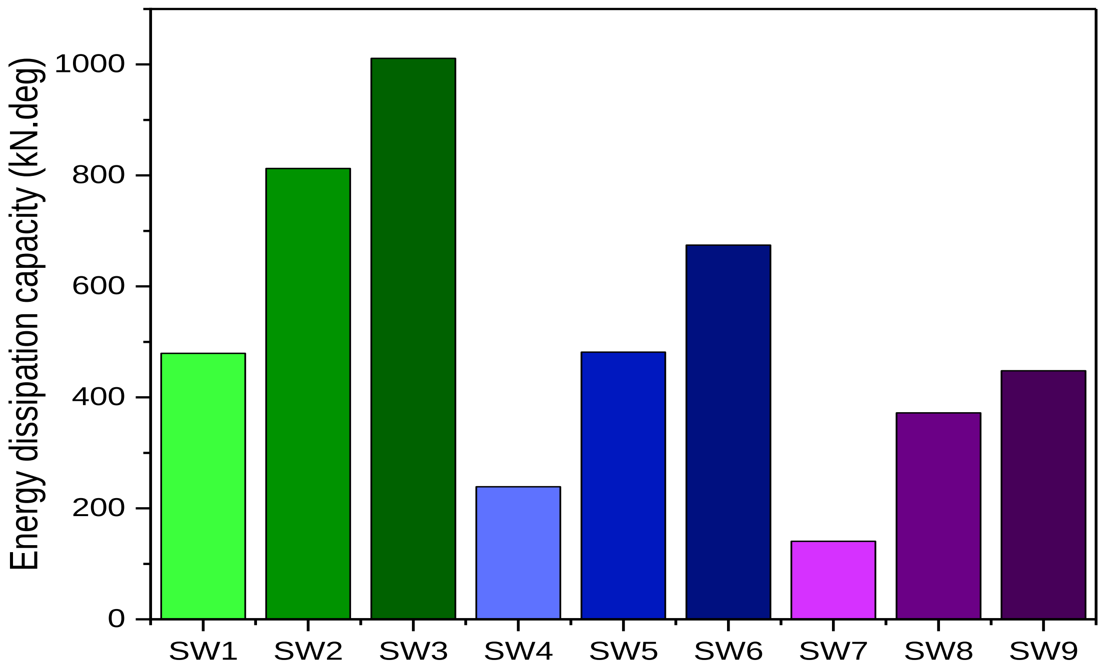

Figure 4. Energy dissipation capacity of samples

When the energy absorption capacities of the test samples are examined, the least energy is absorbed in the SW7 sample (Figure 4). Compared to the SW7 sample, the most energy-absorbing sample is the SW3 sample, with an increase of 619.55%. The total amount of energy absorbed by the SW4 sample is also compared to the SW7. It is 70.12% more. It is seen that hybrid if ratio, size effect and horizontal reinforcement ratio are highly effective on the total energy absorbed in reinforced concrete shear walls under torsional moment. The highest value in terms of energy absorption capacity was also reached in the SW3 sample. The highest values in terms of both size effect and hybrid fiber ratio were recorded in the SW3 sample.

Conclusions

The findings obtained as a result of this study, in which the effects of hybrid fiber ratio, size effect and horizontal reinforcement ratio on the torsion behavior of reinforced concrete shear walls are examined experimentally, are as follows.

By increasing the fiber ratio from 0% to 1.0%, significant increases occurred in the torsional moment parameters. In addition, there were significant increases in energy absorption capacity and torsional stiffness values. Increasing the fiber ratio from 1.0% to 1.5% could not provide the same amount of increase compared to the first case.

Reducing the H/L ratio from 1.5 to 1.25 also had an effect on the experimental torsional moment-rotation angle graphs.

When the energy absorption capacities of the test samples are examined, the least energy is absorbed in the SW7 sample. The SW7 sample absorbed an energy of 140.49 kN.deg. Compared to the SW7 sample, the most energy-absorbing sample is the SW3 sample, with an increase of 619.55%. The total amount of energy absorbed by the SW4 sample is 70.12% higher than that of the SW7. The torsional moment capacity (T_{max}) was highest recorded in the SW3 sample. The sample with the lowest torsional moment capacity is SW7.

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