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Research Article

The Behaviour of Hybrid Fiber RC Shear Walls Subjected to Monolithic Pure Torsion: An Analytical Study

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Keywords

RC Shear wall,
Analytical,
Hybrid fiber,
Carbon fiber,
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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 and analysis of the mechanical behaviour of hybrid fiber reinforced self-compacting concrete (HFRSCC) shear walls under pure torsion moment is presented in this paper. The nine HFSCC shear walls with the same height and longitudinal reinforcement ratio analytically were tested under pure torsion moment and no axial load. The effect of hybrid fiber ratio and horizontal reinforcement amount and aspect ratio on the failure characteristics, torsional behaviour, energy dissipation capacity of squat shear walls was studied. Result indicate that both hybrid and horizontal reinforcement ratio are increased the maximum torsional moment capacity and twist angle and that the hybrid fiber ratio is the key parameter that determines the failure mode of the HFSCC shear walls.

1. Introduction

RC structural walls contribute a significant way to resist lateral loads like earthquake, wind etc. and thereby, RC shear walls usually are preferred by engineers as the primary lateral load resisting system in buildings. RC shear walls have a high in-plane stiffness, which helps decreasing the structural damage by limiting the drift during seismic events [1].

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 [2].

Many experimental and analytical investigations of the behaviour of RC shear walls have been carried out in the past. A large pool of test data exists in the literature. These studies have shown that it is very important to design shear walls as ductile. There are two critical issues to design the RC shear walls to behave as ductile. First, all of the structural members in the building must be detailed. Second, the strength of the shear wall should be control by flexural rather than by shear to RC shear walls to behave in a ductile manner owing to that a shear failure is less ductile to RC shear walls to behave in a ductile manner. For this purpose, shear capacity of RC shear walls must be larger than flexural strength [3] The seismic behaviour of the squat shear wall, which is defined as a shear wall with a height-to-length ratio of less than 2 (h_w/l_w<2), is controlled by shear forces [4]. The seismic force resisting systems comprises especially RC shear walls. The investigations of post-earthquake showed that RC shear walls significantly confine the earthquake induced damage. The low reinforcement ratios, the slenderness ratio less than 2,0 and poor seismic detailing is very important issue for RC shear walls. The failure modes of squat walls (slenderness ratio less 2,0) are diagonal cracks development with in wall panel, sliding apart of the wall from it supporting foundation and concrete crushing at the wall toe. The RC shear walls should have enough deformation and load carrying capacity to resistance the seismic forces [5].

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 [6]. 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 on the behaviour of fiber or hybrid fiber 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 fibers became o common trend in modern construction [7]. The using of steel fiber reinforced concrete in the concrete technology have begun around the early 1960s, and the researchers have interested in the carbon fibers in 1990s. The main applications of fiber reinforced concrete are the structures subjected to damage concentrated and dynamic load such as infrastructure and industrial applications. The researchers have reported that the fiber reinforced concrete have exhibited the more durable than plain concrete. The effect of carbon fiber on the properties of the concrete increase with volume fraction unless the carbon volume fraction is so high that the air void content increases

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with fiber content and air voids tend to have a negative effect on properties of concrete like compressive strength. Although ıncreasing the carbon fiber volume fraction decreases the workability of concrete, the carbon fiber 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 fiber concrete has better tensile strength, flexural strength, energy dissipation capacity, post cracking capacity, impact resistance and crack propagation, fatigue properties. In recent years, the range of research projects of hybrid fiber 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 fiber reinforced concrete by mixing different fibers [8].

The aim of this study is to analyze the torsional behavior of self-compacting concrete with carbon and steel fiber RC shear walls analytically. In addition, the effects of horizontal reinforcement ratio and cross-sectional area on the torsional behavior were also analyzed analytically.

2. Testing process

In this study, nine RC shear walls were modeled. Shear wall height (1500 mm) and longitudinal reinforcement ratio (0,0090) are constant for all samples. Horizontal reinforcement ratio, hybrid fiber ratio and cross-sectional area are different from each other. The details of the test samples are shown in Table 1.

Table 1. Initial properties of test models

	L (mm)	H/L	ρ_h* (%)	Steel fiber ratio (%)	Carbon fiber ratio (%)
SW1	1200	1.25	0.0056	-	-
SW2	1200	1.25	0.0056	0.50	0.50
SW3	1200	1.25	0.0056	0.75	0.75
SW4	1000	1.50	0.0056	-	-
SW5	1000	1.50	0.0056	0.50	0.50
SW6	1000	1.50	0.0056	0.75	0.75
SW7	1000	1.50	0,0028	-	-
SW8	1000	1.50	0,0028	0.50	0.50
SW9	1000	1.50	0,0028	0.75	0.75

*horizontal reinforcement ratio

The ANSYS package program was used to solve the finite element method. The finite element method is a numerical analysis method with an acceptable approach by dividing the element that is being dealt with into finite parts for the solution of the problem in the construction element(s) in engineering applications. The behavior of each of the finite parts constitutes the behavior of the element. Finite element method is used in many branches of engineering. One of the important criteria in the finite element method is the meshing process, which means splitting the element into parts. The problem to be solved needs to be divided into a finite number of elements in order to give the closest results to the reality or experimental data.

The modeling phase of reinforced concrete shear walls first started with the selection of the analysis type. In the first window opened in the ANSYS program, the static analysis type is selected by dragging the "Static Structural" tab to the empty area.

The experimental stress-strain curve was used to define the material characteristics of the reinforcement. Linear and nonlinear regions are defined in the stress-strain curve. Yield and failure points and the corresponding deformations are entered into the program. Experimental stress-strain graphs of 10 mm and 12 mm rebars are shown in Figure 1. Elasticity modules and Poisson's ratios of 10 mm and 12 mm reinforcements were entered in the program as 220 GPa and 210 GPa, and 0.3 respectively.

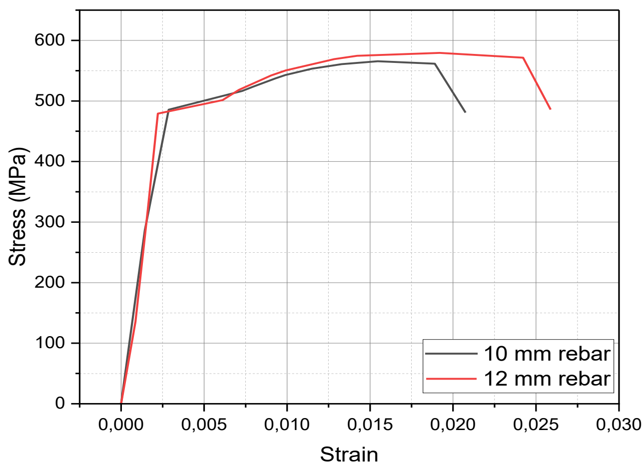


Figure 1. Experimental stress-strain results curve of 10 mm and 12 mm reinforcements

Concrete is a heterogeneous and anisotropic material, and it is a building material that behaves differently depending on time and force type. Therefore, in order to obtain a realistic solution, the stress-strain curve of the concrete obtained in the experimental study was defined in the ANSYS program. Since three different types of concrete were used, appropriate stress-strain curves were used for each sample with concrete properties of self-compacting concrete (SCC) without fiber, 1% Hybrid fiber self-compacting concrete (HFSCC) and 1.5% HFSCC. The experimental stress-strain curves used in defining the material properties of concrete in the ANSYS program are shown in Figure 2. The values obtained from the 28-day cylindrical samples were used as concrete compressive strength. The compressive strengths of SCC, 1.0% HFSCC and 1.5% HFSCC concretes were measured as 29.15 MPa, 31.15 MPa and 32.26 MPa, respectively. The tensile strengths of SCC, 1.0% HFSCC and 1.5% HFSCC concretes were entered into the program as 1.97 MPa, 2.13 MPa and 2.16 MPa, respectively. Experimental data were used as the tensile strength of concrete. The modulus of elasticity of the concrete types was also calculated from the slope of the linear portion of the experimental stress-strain curve. Elastic modulus of SCC, 1.0% HFSCC and 1.5% HFSCC concrete types were calculated as 33545.95 MPa, 34412 MPa and 36746 MPa, respectively. In addition, the Poisson ratio of all three types of concrete was taken as 0.2. The length of 6 cm steel fiber and the length of 5 cm carbon fiber were used in the concrete mix. The technical properties of steel and carbon fibers are shown in Table 2.

Table 2. The properties of steel fiber and carbon fiber

	Steel	Carbon
Fiber shape	Hooked end	chopped strand
Length (mm)	50	50
Diameter (mm)	1	1
Tensile strength (MPa)	1200	1400
Aspect ratio	50	50
Elastic modules (GPa)	200	119
Density (gr/cm3)	7,17	1,6

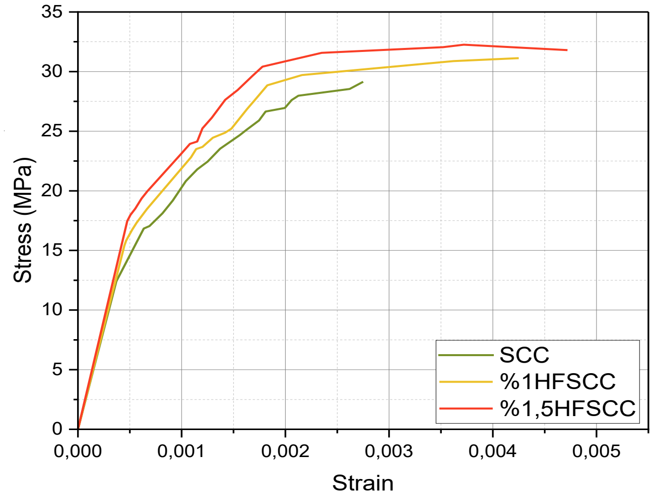


Figure 2. Experimental stress-strain curves of concrete types

The material properties of concrete are defined using the APDL command. Stress-strain values, elasticity modulus and Poisson ratio values of concrete are defined in the APDL command. In addition, the element type cpt215, which supports the "reinforcement" model type, is assigned for concrete [6]. CPT215 is a three-dimensional solid element with eight nodes. Eight nodes have degrees of freedom (Figure 3).

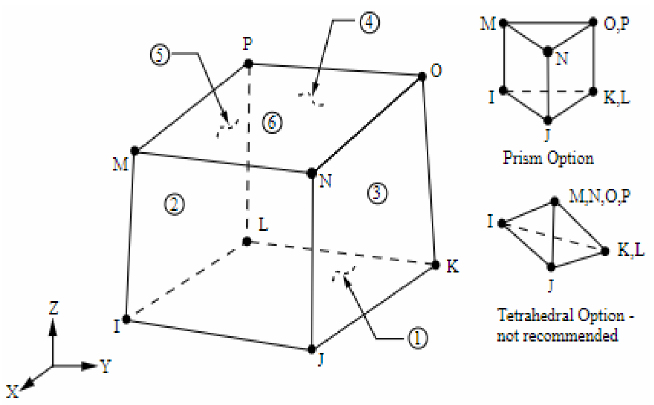


Figure 3. CPT215 element type (ANSYS manual)

In this study, the most suitable mesh for the test samples was chosen to be a cube of 25 mm dimensions. Reinforced concrete shear walls were modeled with 40 mm mesh spacing and mesh size was reduced at 5 mm intervals. The numerical results obtained at each interval were compared with the experimental data. The numerical results did not change with the reduction of 25 mm mesh size. Therefore, the mesh size was chosen as 25 mm in the models. Although concrete and reinforcement are divided separately, it is ensured that the mesh edges overlap each other.

Forces to be applied to the model and their directions are selected from the "Static Structural" section. Force and Force 2 loads are defined first. Force load is applied in the direction of compression and Force 2 load in the direction of tension. The area where the loads are applied is spread over an area 150 mm downwards from the upper part of the curtain, in order to be the same as the head on which the load is applied in the study. The calculated maximum force for each shear wall is defined in Force 1 and Force 2 in the model. Also, the "Large Deflection" option has been turned on. According to the ACI318-19 to appraise the shear strength capacity of walls ignore the impact to the axial compressive forces on increasing the shear strength capacity, which is the reason why the laboratory samples were designed with no axial load. The RC shear walls are controlled by shear forces because of low ductility. Therefore, the axial load can affect the behavior of squat shear wall performance. The force F1 was applied to the modeled sample in the direction of pressure, and the force F2 was applied in the direction of tensile. Two forces acting in the same direction but in opposite directions created a torsional moment on the sample. loading speed was chosen as 10 mm/sec.

3. Results and Discussion

The experimental stress-strain curve was used to define the material characteristics of the reinforcement. Linear and non-linear regions are defined in the stress-strain curve. Concrete is a heterogeneous and anisotropic material, and it is a building material that behaves differently depending on time and loading. Therefore, in order to obtain a realistic solution, the stress-strain curve of the concrete obtained in the experimental study was defined in the ANSYS program. Since three different types of concrete are used, appropriate stress-strain plots of each sample's concrete characteristic (SCC, 1.0% HFSCC and 1.5% HFSCC) were used. The material properties of concrete were defined using the APDL command. Stress-strain values, elasticity modulus and Poisson ratio values of concrete were defined in the APDL command. In addition, SOLID 185 element type, which supports the "reinforcement" model type, is assigned for concrete.

In the present study, the most suitable mesh for the test sample was chosen to be a cube of 25 mm dimensions, according to given literature and pre-numerical modelling attempts. RC shear walls were modeled with 40 mm mesh spacing and mesh size was reduced at 5 mm intervals. The numerical results obtained at each interval were compared with the experimental data. The numerical results did not change with the reduction of the 25 mm mesh size. It is modeled as a built-in support on which the twist and movement of the basic part of the shear walls are fixed in all three axes. The analysis method was determined at the last stage of the modeling section. Due to the linear-elastic behavior of both concrete and reinforcement, nonlinear behavior method is preferred. Thus, since the linear-elastic limit will be exceeded and permanent shape/displacement will occur in the experimental model, non-linear analysis method was applied to get closer and realistic values to the experimental results. Newton-Raphson convergence method was used to make numerical results closer to experimental results and reality.

The numerical results obtained from the test specimens under the torsional moment are presented in Table 3. The analytical torsional moment-twist angle graphs are shown in Figure 4.

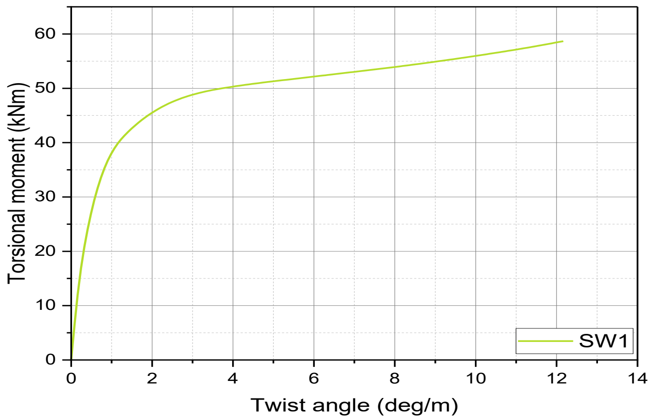
The numerical torsional moment of the fibrous concrete samples was closer to each other after the crack. The reason for this is that the fibrous concrete samples exhibited the performance parameters expected from the fibrous concrete homogeneously in numerical models. The maximum and minimum critical torque values were obtained in SW3 and SW7 samples, respectively. Increasing the hybrid fiber ratio and horizontal reinforcement ratio increased the critical torsional moment. Increasing the cross-sectional area decreased the critical torsional moment. Increasing the fiber ratio increased the torsional moment at yielding point. Similarly, increasing the fiber content increased the θa value. Samples modeled with fibrous concrete exhibited a more ductile behavior compared to the others. The maximum and minimum torsional moments were obtained in the SW3 sample with a value of 78.1 kNm and SW7 sample with a value of 41,54 kNm. The SW7 sample reached 46.8% higher maximum value than the SW3 sample.

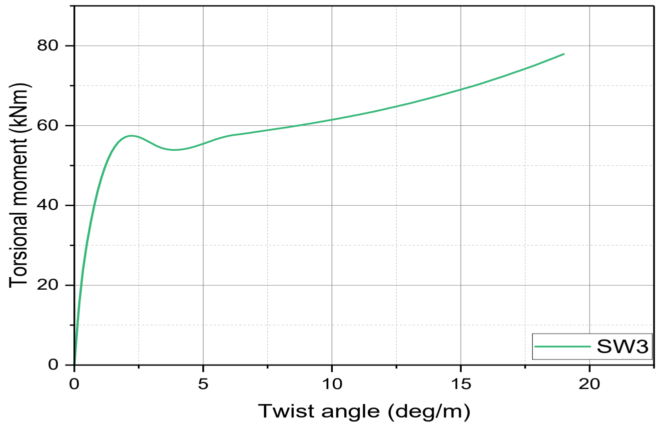
Two points are noteworthy here. Firstly, these principals must be met by horizontal reinforcements that run at an angle of approximately 45 degrees on the shear wall. Secondly, these principal stresses must be moderated by the concrete as well as the contribution of the horizontal reinforcements. Thus, there was a difference between the minimum use of horizontal reinforcement ratio and its double use. In the samples where the reinforcement ratio was doubled, more horizontal reinforcement removed these principal tensile stresses. Therefore, doubling the horizontal reinforcement ratio relative to the minimum case has resulted in higher torsional moment capacities and values of the samples. However, the contribution of fiber in concrete remained at a limited level. In the samples where the horizontal reinforcement ratio is minimum, but 1.0% and 1.5% hybrid fiber is used, it has an effect on meeting the principal tensile stresses of the fiber concrete, as in the second case mentioned above. As seen in Figure 4, the torsional moment-rotation angle graphs of the modeled samples are in accordance with the classical torsional moment-rotation angle graph. A linear behavior is observed in the first part of the samples. The linear behavior continues up to the yield point. After the yield point, linear behavior disappears and non-linear behavior is observed.

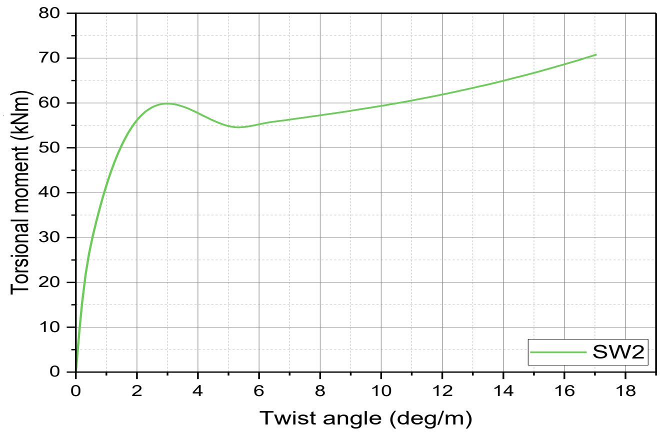
Table 3. Analytical results

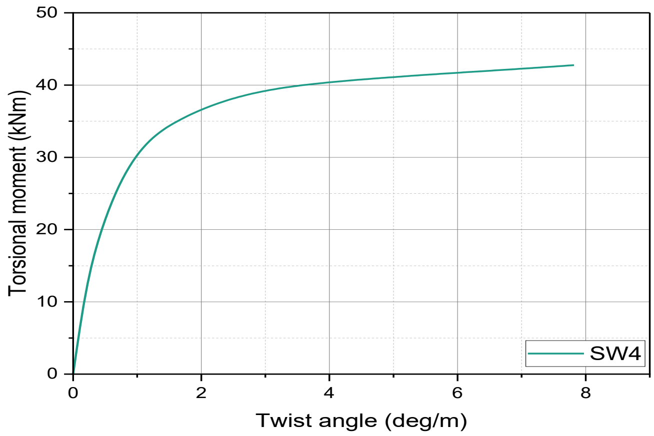
	SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8	SW9
T_{cr} (kNm)	35,21	42,48	46,8	25,66	29,38	33,16	24,92	28,72	30,60
Θ_{cr} (deg/m)	0,80	2,40	2,10	0,71	0,92	1,81	0,65	0,78	0,79
T_a (kNm)	44,01	53,1	56,4	32,07	36,73	41,45	31,16	35,87	38,25
Θ_a (deg/m)	1,62	4,64	2,80	1,21	1,43	3,71	1,18	1,32	1,41
T_{max} (kNm)	58,68	70,8	78,1	42,76	48,97	55,26	41,54	47,83	51,10
Θ_{max} (deg/m)	12,16	17,05	19,02	7,82	12,48	16,57	5,79	11,20	11,76

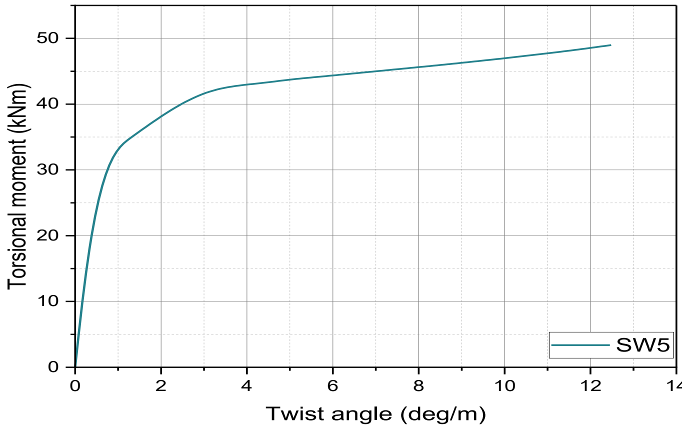
(T_{cr}: critical torsional moment, θ_{cr}: twist angle corresponding to the T_{cr}, Ta: torsional moment at yield point, θ_a: twist angle corresponding to the Ta, T_{max}: maksimum torsional moment, θ_{max}: twist angle corresponding to T_{max}, T_u: ultimate torsional moment, θ_u: twist angle corresponding to the T_u)

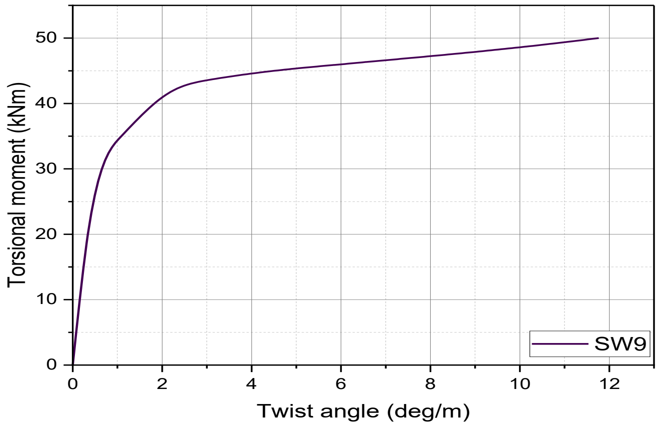


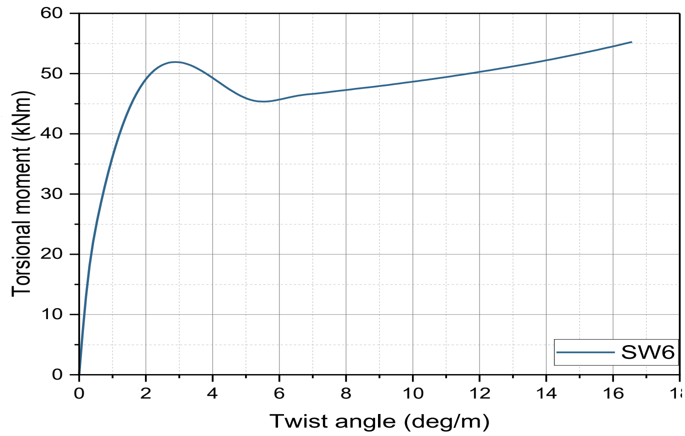


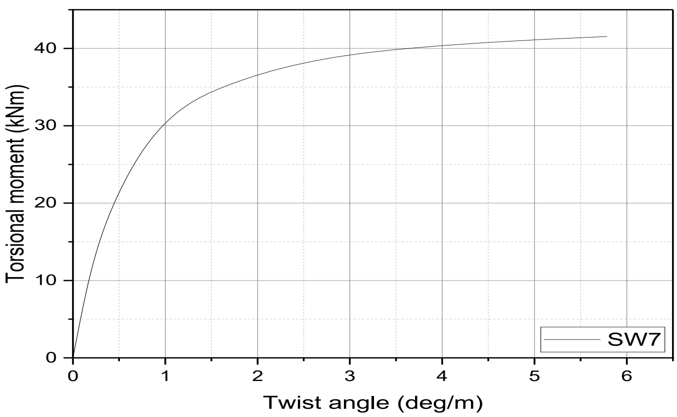












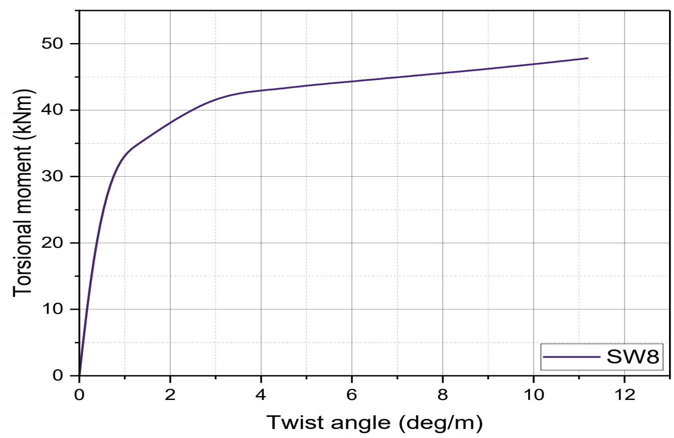


Figure 4. Torsional moment-twist angle of samples

The energy dissipation capacities of the modeled samples are shown in Figure 5. energy dissipation capacities were calculated from the area under the torsional moment-rotation angle graph. In addition, maximum, minimum and average values are shown on the graph. The minimum and maximum energy dissipation capacities were calculated for the SW7 and SW3 samples, respectively. There is a parallelism between the energy absorption capacity and the torsional moment-rotation angle graph. The average energy absorption capacity is 599.71 kNdeg. The increase in the ratio of hybrid fiber and horizontal reinforcement increased the energy absorption capacity. The reduction of the cross-sectional area, on the other hand, decreased the energy dissipation capacity. The use of 1% hybrid fiber gave the most ideal results. The use of 1% hybrid fiber gave the most ideal results. Increasing the fiber ratio from 1% to 1.5% increased the energy absorption capacity. However, this increase rate was not as effective as increasing the fiber content from 0% to 1%. Therefore, it was decided that the most ideal fiber ratio was 1%.

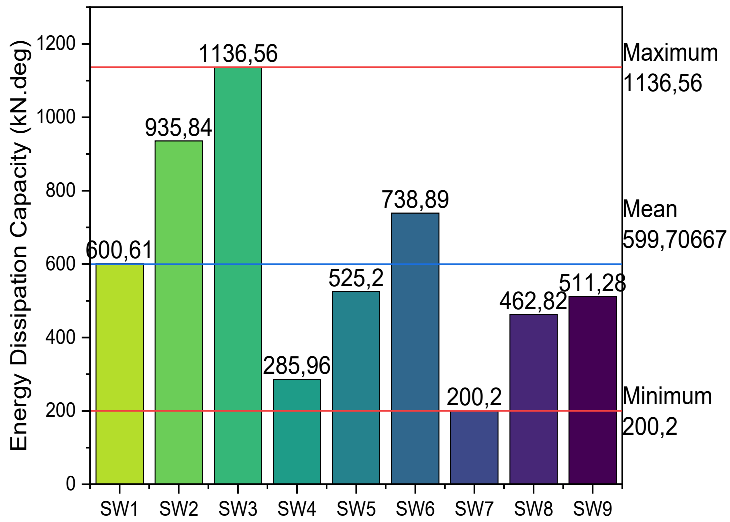


Figure 5. Energy dissipation capacity of samples

In Figure 6, the Von-Misses strains of the longitudinal, transverse and all reinforcements are presented. As expected, the strains in the longitudinal reinforcements of the test samples were generally greater on the tensile side than on the compression side. On the other hand, the strain values of horizontal reinforcements were greater especially in the middle regions.

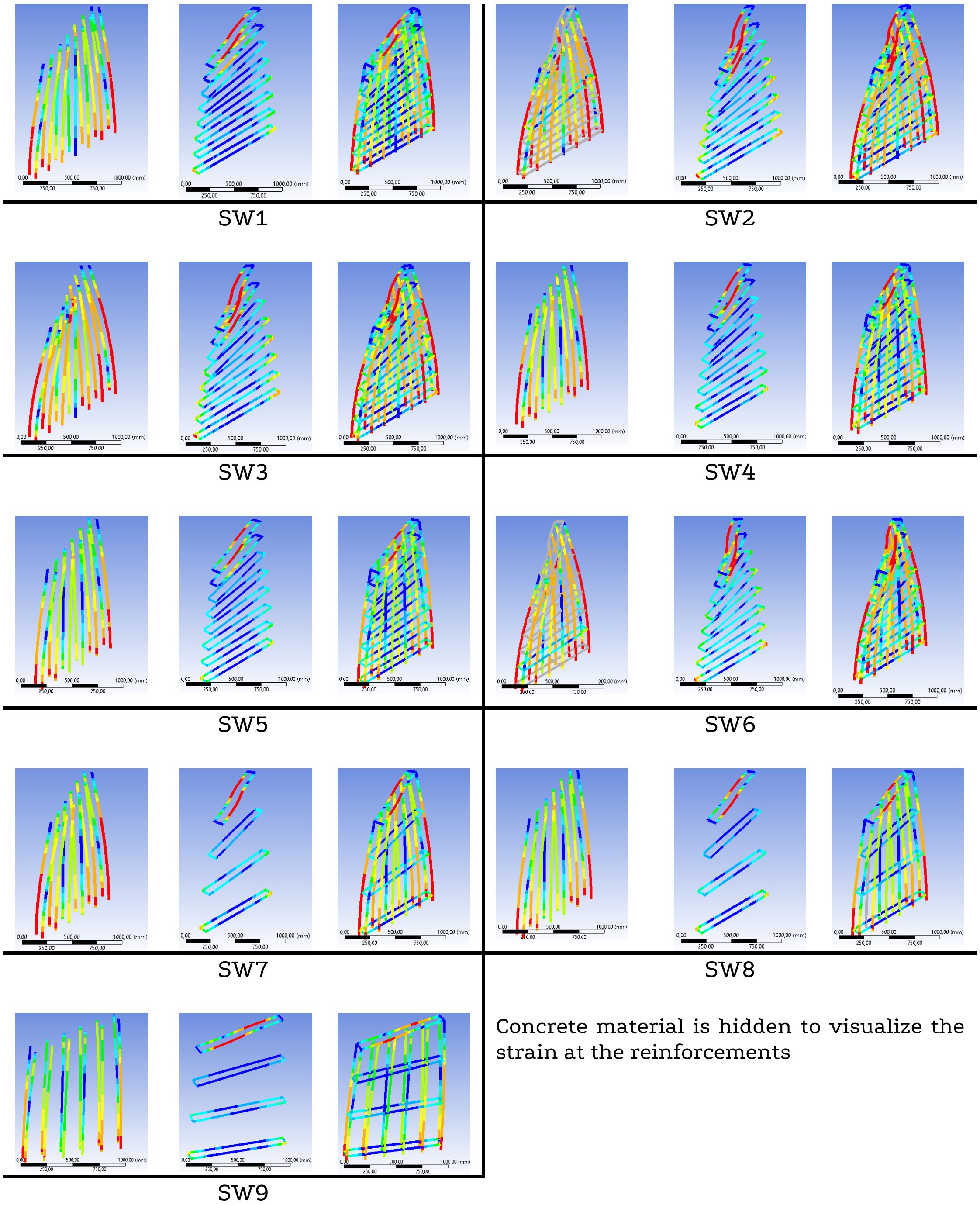


Figure 6. Strain in longitudinal and transverse reinforcements

Ganesan et al. [6], Hung and Hsieh [9], Lu et al. [10] and Zhao et al. [11] carried out an experimental study about effect of fiber on the shear behavior of RC shear wall. They reported that the use of the fiber increased the shear capacity of RC shear wall. However, Hidalgo et al. [12] reported that the increasing the cross-section of RC shear wall increased the shear capacity. The results in the literature are in line with the results in this study.

With the increase of hybrid fiber ratio, the maximum strain values were obtained in longitudinal and transverse reinforcements. Similar to the experimental study, hybrid fiber samples were exposed to more torsional moment due to the high tensile and strain capacity of hybrid fiber concrete. Therefore, the stresses and strains in the longitudinal and transverse reinforcements of these samples (i.e. samples produced with hybrid fiber) were also greater. On the other hand, the strains in the longitudinal reinforcements decrease from the edge reinforcements to the middle.

4. Conclusion

In this study, the effect of horizontal reinforcement ratio, hybrid fiber ratio and cross-section on RC shear walls subjected to pure torsion were investigated analytically. After the analytical study, the following conclusions were reached.

- Increasing the hybrid fiber ratio increased the torsional moment capacity. Increasing the hybrid fiber ratio from%0 to 1% and from 1% to 1,5% did not increase the torsional moment capacity to same extent. The 1% hybrid fiber ratio gave more ideal results.
- Reducing the horizontal reinforcement ratio decreased the torsional moment and twist angle capacities. However, use of hybrid fiber tolerated this reduction.
- Increasing the cross-sectional area increased the torsional moment capacity. By increasing the cross-sectional area and increasing the fiber ratio, the highest torsion moment and twist angle capacities were achieved.
- Increasing the hybrid fiber ratio and the horizontal reinforcement ratio increased the energy dissipation capacity of RC shear wall. Similarly, increasing the cross-sectional area also increased the energy dissipation capacity.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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