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Research Article

Nonlinear finite element study on the improvement of torsional strengthening of RC beams with diagonal shear reinforcement

Rojda Orman Subasi[1,6], Naci Caglar*[2,3], Gamze Demirtas[4] and Hakan Ozturk[5]

[1] Department of Civil Engineering, Faculty of Engineering, Istanbul Arel University, Istanbul (Türkiye); rojdaorman@arel.edu.tr
[2] Department of Civil Engineering, Faculty of Engineering, Sakarya University, Sakarya (Türkiye); caglar@sakarya.edu.tr
[3] Department of Civil Engineering, Faculty of Engineering and Natural Sciences, Bursa Technical University, Bursa (Türkiye); caglar@btu.edu.tr
[4] Department of Civil Engineering, Faculty of Engineering, Sakarya University, Sakarya (Türkiye); demirtas@sakarya.edu.tr
[5] Department of Civil Engineering, Faculty of Engineering, Sakarya University, Sakarya (Türkiye); hakanozturk@sakarya.edu.tr
[6] Department of Civil Engineering, Institute of Natural Sciences, Sakarya University, Sakarya (Türkiye); rojda.subasi@ogr.sakarya.edu.tr
*Correspondence: caglar@sakarya.edu.tr (C. Naci)

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Abstract: Experimental and numerical studies are carried out by many researchers in order to examine the nonlinear behavior of reinforced concrete (RC) beams under the torsion moment and to improve the torsional moment capacity. In this study, a numerical study is performed to investigate efficiency of diagonal shear reinforcement (DSR) on the response of RC beams subjected to pure torsion. A nonlinear numerical model was constituted to simulate the response of the RC beams by using ABAQUS software program and verified with the selected experimental results from literature. The numerical analysis results proved that the nonlinear numerical model is quite successful in simulating the nonlinear behavior of RC beams and DSR makes a very significant contribution to the torsional moment capacity of the RC beam subjected to pure torsion.

Keywords: Nonlinear numerical model, RC beam, pure torsion, diagonal shear reinforcement.

1. Introduction

In addition to shear and bending, torsional moment also affects the structural members of reinforced concrete (RC) structures under the influence of dynamic and static loads. Torsional moment of elements is usually caused by the irregular geometry of the structural system or unsymmetrical loading (Ozturk, 2007). Some examples of torsion that may occur in reinforced concrete beams in the building system are given in Figure 1. Due to the torsional effect, shear stresses on the element increase. These increased stresses create tensile cracks in the same direction as the principal stresses in RC elements with low tensile strength. Torsional stiffness decreases due to these cracks formed as a result of torsion. In order to prevent possible brittle fracture in a RC beam under the effect of torsional moment, longitudinal reinforcement, and most importantly transverse reinforcement, which also acts as torsion reinforcement, is placed on the element (Aydin and Bayrak, 2017).

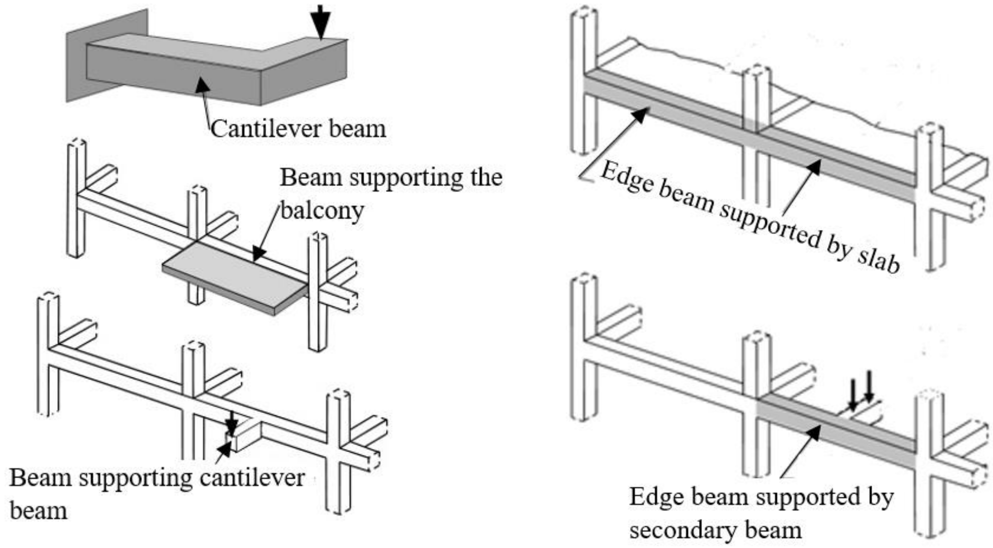

Figure 1. Some examples of torsion that may occur in reinforced concrete beams in the building system (Dogangun, 2013).

In order to improve the torsional behavior of RC beams, different stirrup ratios and configurations are applied, as well as various fibers and reinforcements are added to the concrete as additives. However, due to the nonlinear behavior of the RC beam, the calculation of the torsional moment that may occur in the element is a very difficult and complex problem, and its exact solution is not yet known (Ozturk, 2007). For this reason, experimental and numerical studies continue to be carried out by several researchers in order to investigate the nonlinear behavior of RC beams under the effect of torsional moment and to prevent possible brittle fracture. Although there are existing experimental studies, numerical studies have been increasing recently due to reasons such as the high cost of experimental studies, long processes, and possible labor errors.

Chiu et al. (2007) examined the torsional behavior of beams with different concrete strength, cross section dimensions, longitudinal and transverse reinforcement ratios experimentally and numerically. The authors compared the crack shapes, maximum crack width, maximum torsional moment and torsional ductility values formed as a result of the experiment. While it was stated that high tensile strength increased the maximum torsional moment in beams, it was also stated that the section should have sufficient torsional reinforcement to reach the capacity and not fail in the first crack. In the theoretical study, it was emphasized that beams with normal concrete strength were compatible with the test results, but more theoretical studies should be conducted since they could not fully reflect the behavior of beams with high concrete strength (100 MPa and above).

Kim et al. (2015) experimentally and theoretically examined the torsional behavior of beams prepared using high performance fiber reinforced cementitious mortar (HPFRC). In addition, an equation was proposed by developing the formulas in the literature in order to estimate the torsional strength of beams. The shell part of some of the beams produced consisted of fiber concrete with high compressive and tensile strength. The values of the first cracking moment and the ultimate torsion moment and torsion angle values of the test specimens were compared. It was observed that the torsional strength of the specimens coated with composite mortar was almost 50% higher, and the crack widths formed were smaller. Thus, in order to improve the torsional behavior of the beams, it was stated that reinforcement can be made using the aforementioned method. Additionally, Bayrak (2015) studied the torsional behavior of RC beams by taking as variables parameters such as stirrup ratio, concrete class and type. Torsional moments found in the experimental study were compared with the torsion moments calculated with the European Standard (Eurocode-2, 2004), American Standard (ACI318, 1984) and Turkish Standards (TS500, 2000). As a result of the study, it was observed that high concrete strength increased the torsional moment capacity, and that the applied too much stirrup spacing had a negative effect on the torsion moment capacity. Karimipour et al. (2022) investigated the torsional behavior of rectangular beams constructed using polypropylene fiber and steel fiber reinforced high performance concrete (HPC). The variations in ultimate torsional moment, torsional angle, torsional stiffness, failure modes and maximum crack width were investigated using different amounts of fiber. The experimental study results and the ACI code were compared and a new model was proposed for the torsional behavior of high performance concretes.

Torsion behavior was investigated by strengthening reinforced concrete beams under torsion with CFRP (Santhakumar, 2007; Chalioris, 2008). As a result of the studies, it is seen that the fiber polymer improves the torsional behavior and contributes positively to the torsional capacity value after the first crack. Additionaly, Obaidat and Ashteyat (2019) examined numerically and experimentally the behavior of concrete beams exposed to torsional load and reinforced by bonding carbon fiber reinforcement polymers (CFRP) in different angles. In order to reflect the nonlinear behavior of the beams in question, a finite element model was developed with the ABAQUS program. It has been observed that the contribution of CFRP strips bonded to torsion at 45° angle is better than the strips bonded at 90° angle.

Mohammed et al. (2023) investigated the torsional behavior of reinforced concrete beams constructed using different transverse reinforcement configurations using the finite element method. Spiral reinforcement has been described to improve torsional behavior. In addition, it has been stated that spiral shear reinforcement increases the performance of the structure by contributing to the ductility and torsion capacity (Obaidat and Ashteyat, 2019; Karimipour et al., 2022; Mohammed et al., 2023).

The main objective of this study is to numerically investigate the use of Diagonal Shear Reinforcement (DSR) (Ozturk, 2016; Ozturk et al., 2019), to improve the torsional strengthening of reinforced concrete beams, which has been previously proposed in the literature as an alternative reinforcement configuration to increase shear capacity (Eom et al., 2014). Finite element model of conventional beam specimens from the experimental study by Chalioris and Karayannis (2013) was created. These beams were numerically analyzed and the results of the finite element model were compared with the experimental results. Diagonal shear reinforcement was added to the validated numerical models and its effect on the torsional behavior of the beam was investigated. In addition, the effect of the use of spiral reinforcement on the torsional behavior was investigated in the study by Chalioris and Karayannis (2013). The results of the beam with spiral reinforcement in that study are compared with the results of the finite element model with diagonal shear reinforcement. The nonlinear finite element model was created with the help of ABAQUS program.

2. Proposed new shear reinforcement configuration

In reinforcement concrete sections, axial force and bending moment create normal stress, while shear force and torsional moment create shear stress. The main purpose of the “Diagonal Shear Reinforcement (DSR)” (Ozturk et al., 2019), which is proposed by Chalioris ve Karayannis as a nonconventional type of shear reinforcement configuration and connected diagonally between stirrups, is to offset the shear stresses caused by the shear force in RC beams (Chalioris and Karayannis, 2013; Ozturk, 2016). Considering that the shear stresses due to the torsional moment reach their maximum values on the surfaces of the structural elements, the DSR can also be used to increase the torsional moment capacity. In this study, this nonconventional DSR will be placed in the center of the beam designed with conventional reinforcement in the study area, connected to each side surface and between the transverse reinforcements (Figure 2).

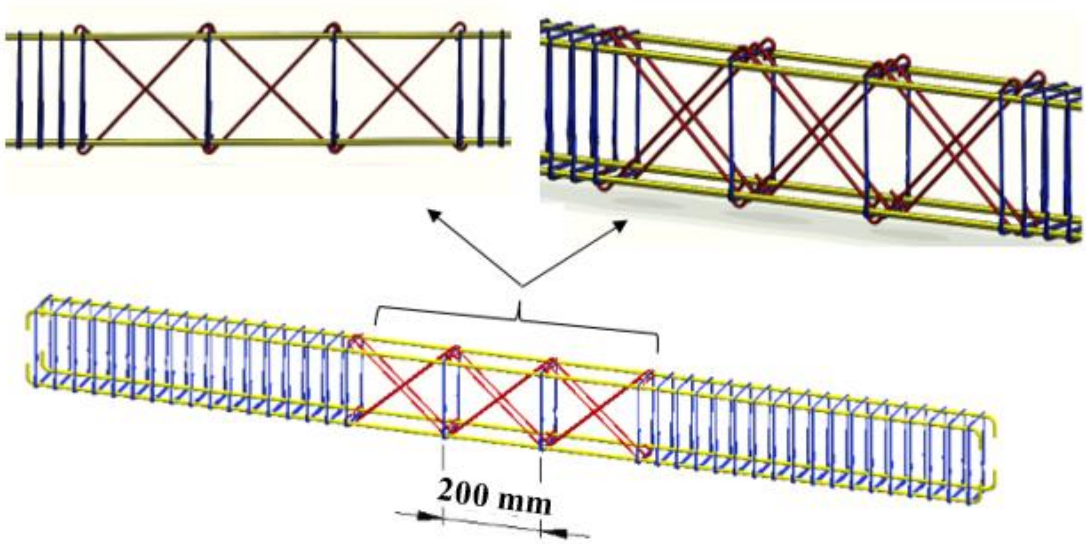

Figure 2. Application of diagonal shear reinforcement (DSR).

DSR has many important advantages compared to the techniques recommended in existing studies. The advantages of DSR are that it is simple to create and apply, can be used in the desired number and diameter, and facilitates the pouring of concrete by increasing the adherence between the concrete and the reinforcement. In addition, it works efficiently under the effect of cyclic load, significantly increasing the shear capacity of RC beams (Chalioris and Karayannis, 2013; Ozturk, 2016). In addition to all these advantages, DSR is very cost effective as it does not require any extra labor resources and equipment.

3. Experimental study

Chalioris and Karayannis (2013) experimentally examined the contribution of the use of continuous steel spirals reinforcement to torsional stiffness in reinforced concrete beams under torsion effect (Figure 3).

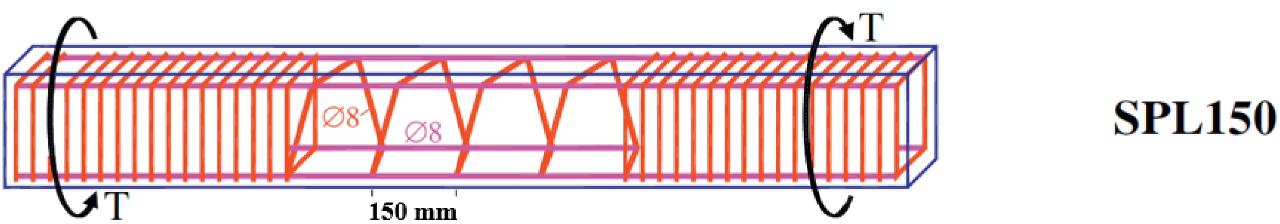

Figure 3. Details of continuous spiral reinforcement (Chalioris and Karayannis, 2013).

In this study, the results of two experimental studies (ST150-ST200) performed by Chalioris and Karayannis (2013) were used to validate the nonlinear finite element model. The test specimens were 100x200 mm in size and 1600 mm in length. In the test specimens, 4 longitudinal reinforcements with a diameter of 8 mm and transverse reinforcements with a diameter of 8 mm with a spacing of 150 mm in the ST150 specimen and 200 mm in the ST200 specimen were used. The yield and tensile strengths of longitudinal reinforcements were 518 MPa and 656 MPa, respectively, and the yield and tensile strengths of transverse reinforcements were 365 MPa and 536 MPa, respectively. The compressive and tensile strengths of the concrete used in the test samples were 23MPa and 2.67MPa, respectively. As seen in Figure 4, a 600 mm long section was created in the middle of the beams as the pure torsion test zone.

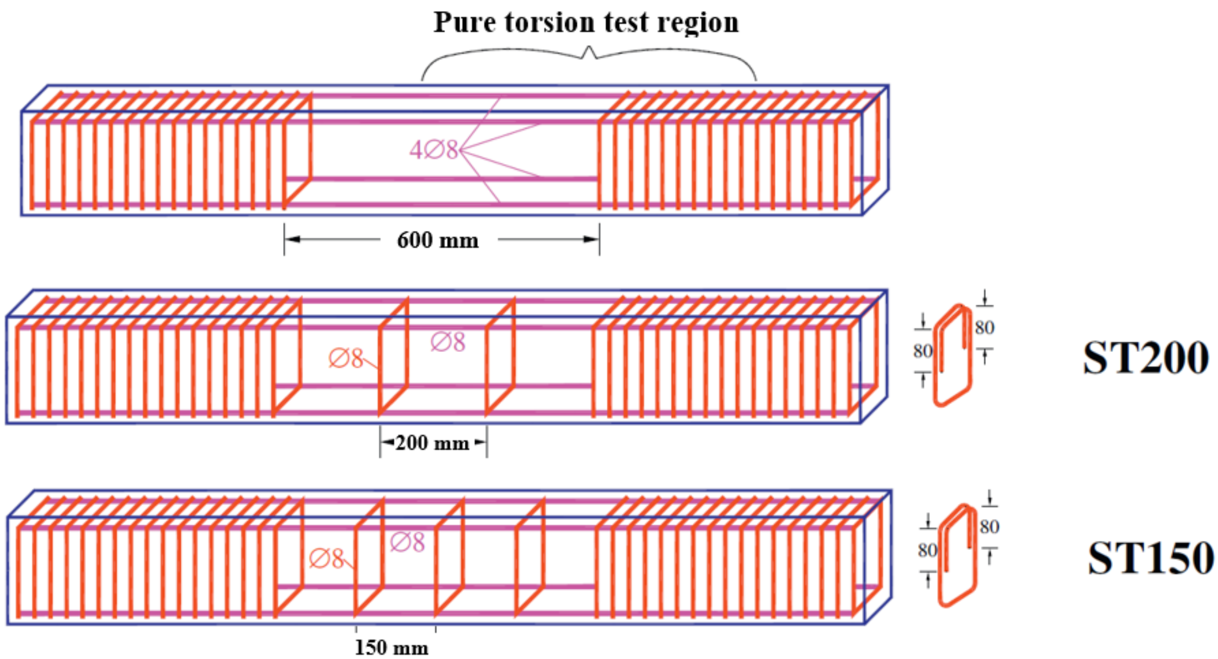

Figure 4. Dimensions and reinforcement details of beam samples (Chalioris and Karayannis, 2013).

The experimental setup developed by Chalioris and Karayannis (2013) is shown in Figure 5. The test specimens were attached at both ends with roller supports and the distance between the supports is 1300 mm. Steel arms were provided at the support areas of the specimens to prevent stress concentrations that may occur during loading. 500 mm long steel arms were fixed to the caps at the ends of the beams in opposite directions. These diagonally attached steel arms are combined with a steel spreader beam to create torsional moment at the beam ends and loaded at the midpoint.

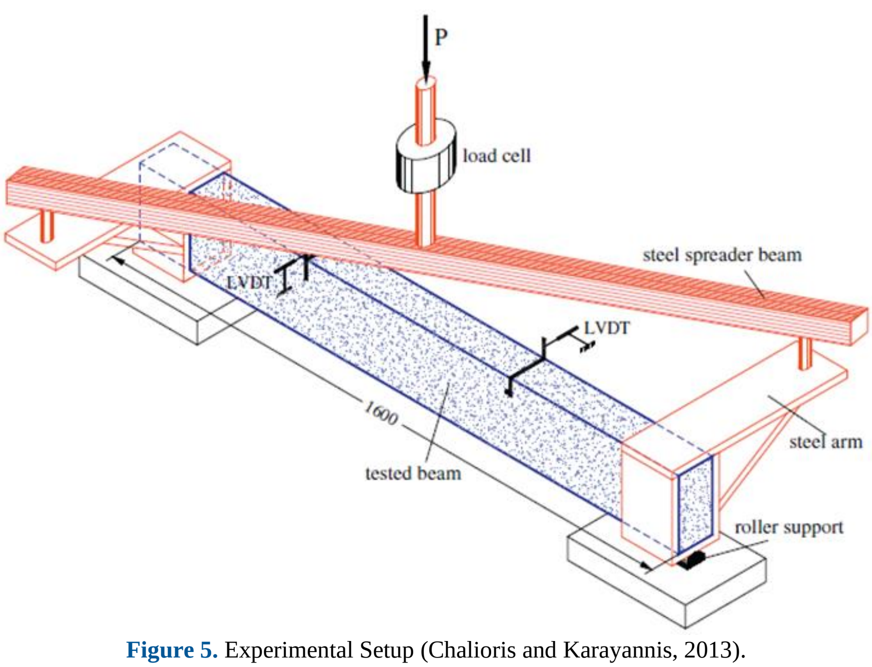

Figure 5. Experimental Setup (Chalioris and Karayannis, 2013).

4. Nonlinear finite element model

With the recent development of computer technology, numerical methods are preferred to produce solutions to complex engineering problems. Finite Element Method is one of the most preferred numerical solution methods. This method can be used in different engineering fields such as seismic analysis, stress analysis, dynamic and static elasticity-plasticity problems, and impact analysis (Ozturk, 2016).

Considering that the experimental studies are difficult, require skilled labor and high costs, it is very advantageous to obtain realistic solutions with the Finite Element Method (Demir, 2018). For this reason, ABAQUS (2018), a package program based on the 3D finite element model, which gives accurate results, is reliable and able to accurately reflect the nonlinear behavior of RC elements, was preferred.

4.1. Modeling of concrete

Material acceptances bear importance in order to reflect the nonlinear behavior of reinforced concrete elements realistically. In order to determine the numerical model of a brittle material such as concrete, its behavior under compressive and tensile stress should be well known. For this reason, in the study, the "Concrete Damaged Plasticity Model (CDP)" (Sinaei et al., 2012; Hibbitt, 2013) which is based on plasticity, was used as the stress-strain relationship of concrete under compressive stress in beam samples. The compressive stress strain diagram created in the light of the information given for the concrete used in the reference experimental study is given in Figure 6 (a) and concrete compression damage parameter (d_c) is shown in Figure 6 (b).

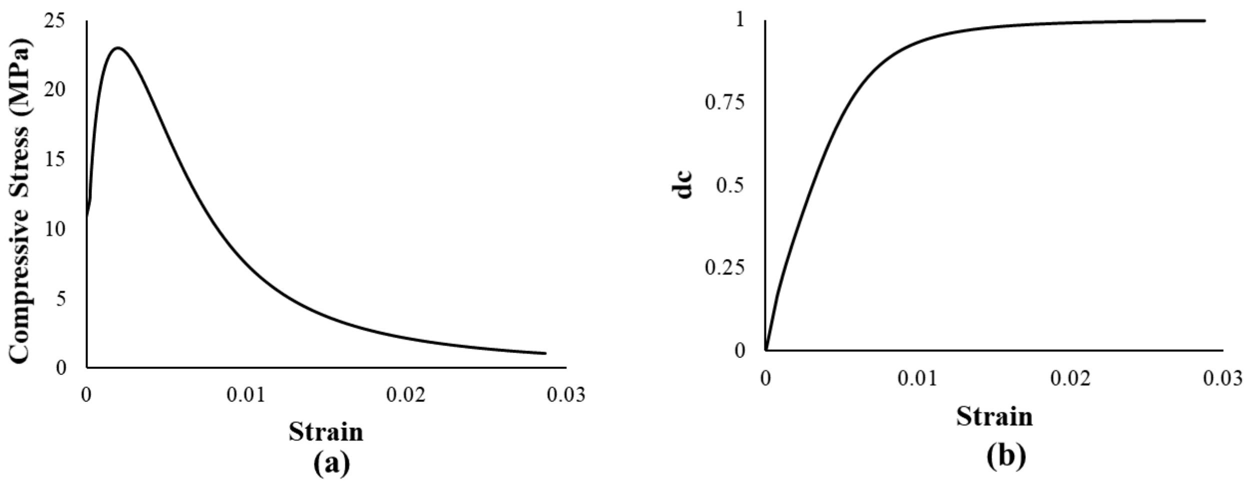

Figure 6. Compressive stress-strain relationship (a) and concrete compressive damage parameter (b) generated from the reference experiment (Sinaei et al., 2012; Hibbitt, 2013).

$$\sigma_c = (1 - d_c).E_0.(\varepsilon_c - \tilde{\varepsilon}_c^{pl}) \quad (1)$$

$$\varepsilon_c^{in} = \varepsilon_c - \frac{\sigma_c}{E_0} \quad (2)$$

$$\tilde{\varepsilon}_c^{pl} = \varepsilon_c^{in} - \frac{d_c}{(1 - d_c)}.\frac{\sigma_c}{E_0} \quad (3)$$

$$d_c = 1 - \frac{\sigma_c/E_0}{\sigma_c/E_0 + \varepsilon_c^{in}(1 - b_c)} \quad (4)$$

σ_c is the concrete compressive strength, E_0 is the presents the initial modulus of elasticity, ε_c is the concrete compressive strain, is the $\tilde{\varepsilon}_c^{pl}$compression plastic strain, ε_c^{in} is the implies the compression inelastic strain, $b_c = \tilde{\varepsilon}_c^{pl}/\varepsilon_c^{in}$.

The force value that causes the first crack formation in RC beam elements is called the critical force, and the torsional moment corresponding to this force is called the critical torsional moment (Ozturk, 2016). When the formulas given in TS500 (2000) for the calculation of these values are examined, it is seen that the most important parameter is the tensile strength of the concrete. For this reason, the stress-strain diagram of concrete under the tensile stress impact is important in order to reflect the behavior of the element under the torsional effect in a realistic way. The tensile stress-strain relationship used in this study and included in the literature is given in Figure 7. The tensile stress-strain diagram created with the information given for the concrete used in the referenced experimental study is shown in Figure 7 (a) and concrete tensile damage parameter (d_t) is shown in Figure 7 (b).

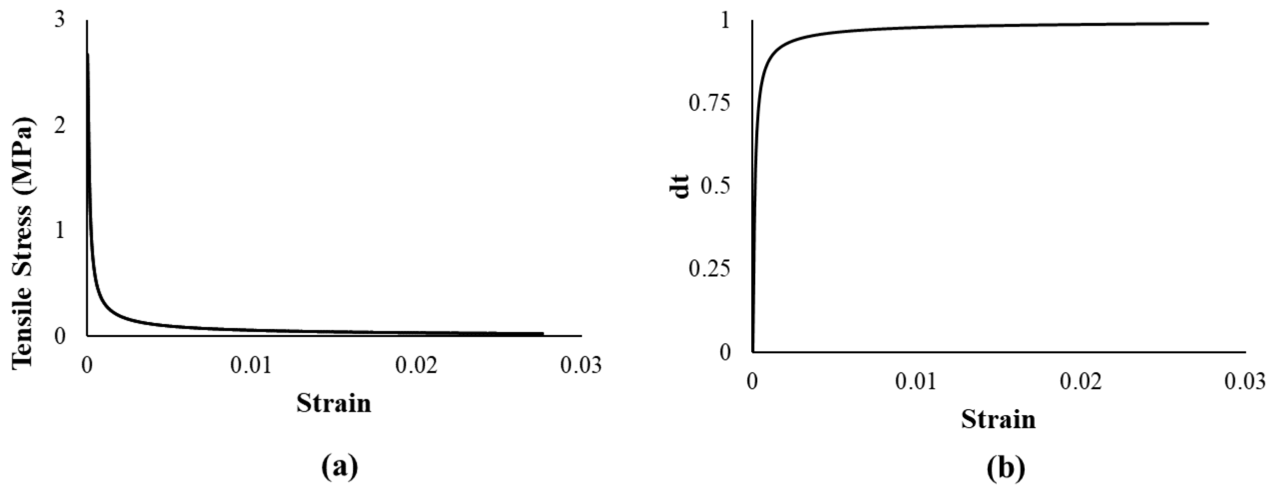

Figure 7. Tensile stress-strain relationship (a) and concrete tensile damage parameter (b) generated for the reference experiment (Cao et al., 2012).

$$\sigma_t = \frac{f_t * (\varepsilon/\varepsilon_t)}{(\alpha_t * \left(\frac{\varepsilon}{\varepsilon_t} - 1\right)^{1.7}) + (\varepsilon/\varepsilon_t)} \quad (5)$$

$$d_t = 1 - \frac{\sigma_{t0}/E_0}{\sigma_{t0}/E_0 + \varepsilon_c^{ck}(1 - b_t)} \quad (6)$$

$$\varepsilon_t^{ck} = \varepsilon_t - \frac{\sigma_t}{E_0} \quad (7)$$

σ_t is the concrete tensile strength, f_t is the maxsimum tensile strength of concrete, ε_t is the corresponding f_t is the concrete tensile strain, $\alpha_t = (0.312 * f_t{}^2)$, $\tilde{\varepsilon}_t^{pl}$ is the tensile plastic strain, ε_t^{ck} is the cracking unit strain.

Important parameters that need to be defined in the CDP model are defined as in the Table 1. (σ_{b0}/σ_{co}) is the ratio of biaxial compressive strength to uniaxial compressive strength and the default value 1.16 in ABAQUS. The $K_c$value is used to define the shape of the failure surface in the deviatoric plane which is the ratio of the second stress invariant for compression and tension at the same hydrostatic stress. μ is the viscosity parameter which allows the stresses to go outside the yield surface. ψ is the dilation angle measured in the p–q plane at high confining pressure and this parameter was determined by sensitivity analysis, ϵ is a parameter, referred to as the eccentricity, that defines the rate at which the function approaches the asymptote (Abaqus, 2018).

Table 1. CDP model parameters.

Parameter	Value
Dilation angle (ψ)	50
Eccentricity (ϵ)	0.10
σ_{b0}/σ_{co}	1.16
Kc	0.667
Viscosity parameter (μ)	0.0001

4.2. Modeling of reinforcement

For the longitudinal reinforcement and stirrups used in the test samples, the stress-strain relationship of the reinforcement steel has been defined in the program so as to define the strain-hardening elastoplastic material behavior (Figure 8).

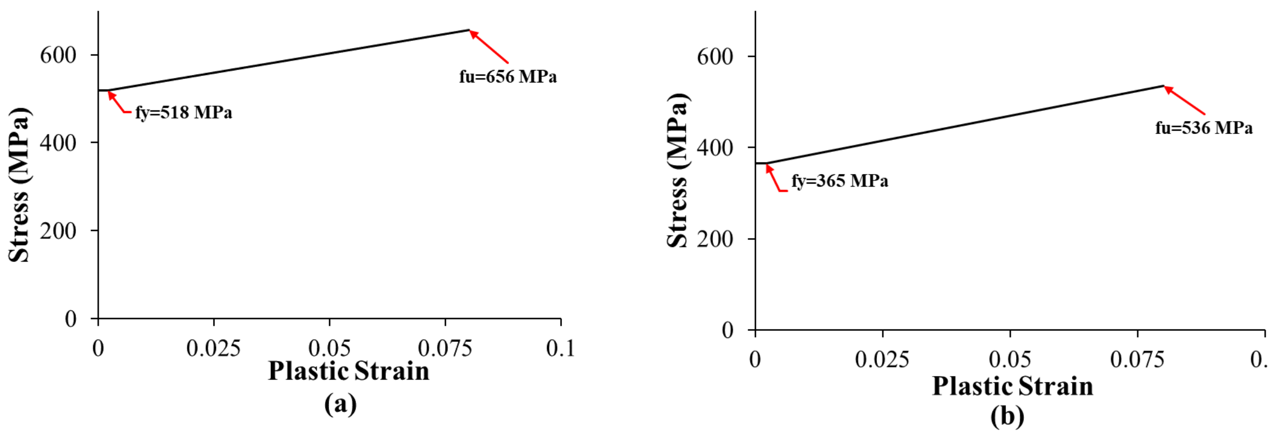

Figure 8. Stress-strain diagram for (a) longitudinal reinforcement and (b) stirrups.

4.3. Geometry and boundary conditions of finite element models

Reference beam elements were created in the ABAQUS program. Concrete and reinforcement are modeled as two separate finite elements. The concrete is formed as an 8-node, linear cubic element (C3D8R) with three degrees of freedom; for the reinforcement, it is formed as a two point, linear, three dimensional bar element (T3D2). The effect of mesh refinement on fem results was examined by mesh sensitivity analysis for various different mesh sizes such as 100 mm, 50 mm, 25 mm and 10 mm. The optimum mesh size in terms of analysis time and approximation to experimental data was found to be 50 mm with an aspect ratio of one. Since the beams are given freedom of movement in the horizontal direction in the experimental setup, both supports are modeled as roller. The numerical model created is given in Figure 9.

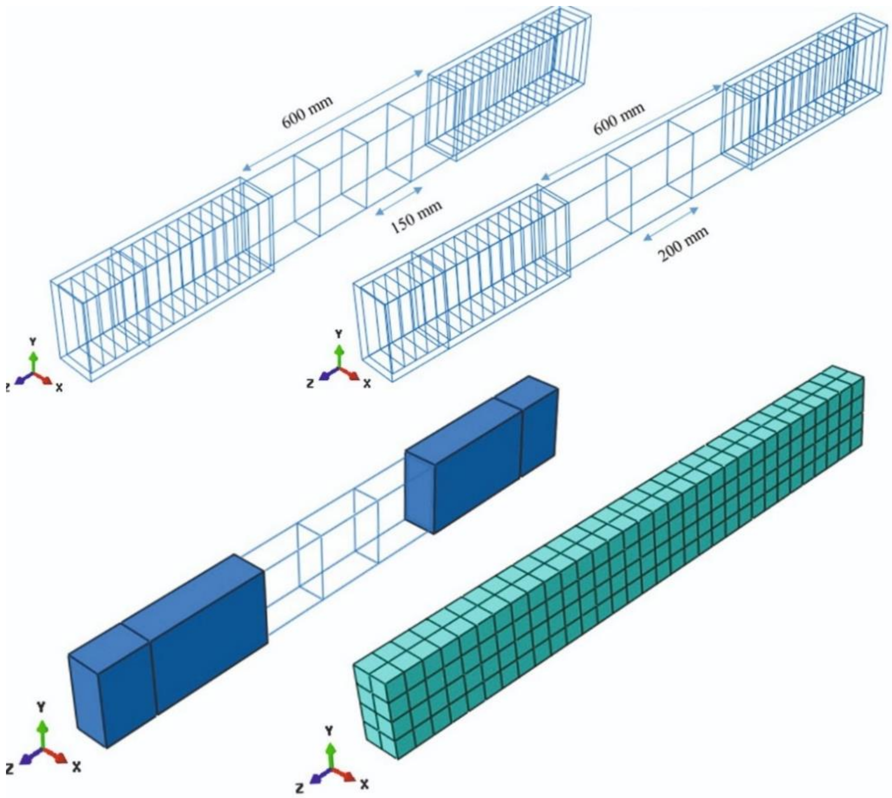

Figure 9. Numerical model generated

4.4. Loading conditions

The steel arms in the experimental setup are modeled as infinitely rigid. A displacement-controlled loading protocol was applied to these arms in accordance with the experimental conditions. Thus, torsional moment in the beam is created. The point where the LVDTs placed in the experimental setup are located was determined on the numerical model, and the deformations that may occur at those points and the reaction forces that may occur on the supports during loading were recorded (Figure 10).

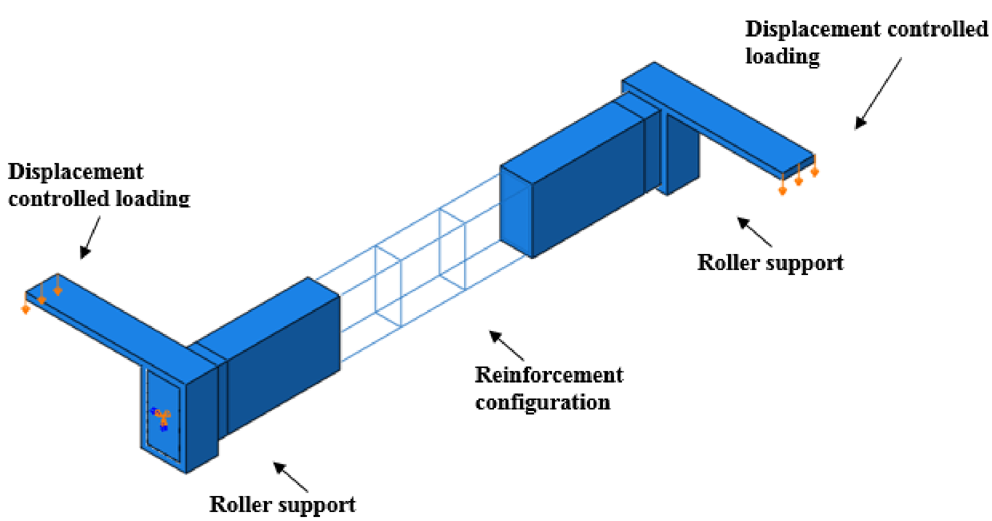

Figure 10. Finite element model developed.

5. Confirmation of finite element model

By using ABAQUS software program, a nonlinear numerical model was constituted to simulate the response of the RC beams subjected to torsion. A nonlinear numerical model validation was performed with experimental samples ST150 and ST200, which were included in the experimental study by Chalioris and Karayannis (2013). All of the parameters used for nonlinear FE model of ST150 and ST200 are kept same. The only difference between ST150 and ST200 is the space of stirrups. Numerical analysis and experimental results are given in Figure 11.

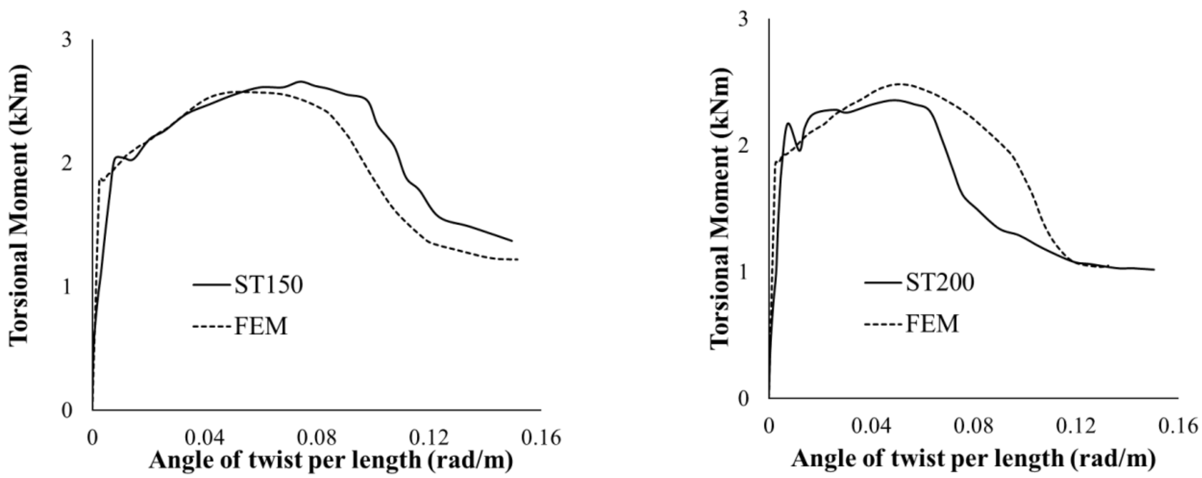

Figure 11. ST150 and ST200 test samples with the results of the nonlinear finite element model.

When the results given in Figure 11 are examined, it is seen that the experimental results and the nonlinear finite element model results are quite close to each other. It is seen that the nonlinear finite element model behaves more rigidly as expected until the first cracking moment, but the experimental results with the nonlinear finite element model are quite similar in terms of both torsional moment and angle of twist of per length. The numerical model can simulate the torsional moment-angle of twist of per length relationship quite successfully both for the linear region and for the nonlinear region after longitudinal reinforcement yields (Figure 11). It is clear from the results that the nonlinear finite element model can be used successfully to simulate the behavior of RC beams under the influence of torsional moment.

6. Simplified analytical approach

There are various theories for the analytical calculation of the torsional behavior of reinforced concrete structural elements. Space Truss Analogy (STA) provides the best analytical solution to the torsion problem in reinforced concrete beams. European codes and ACI (American Concrete Institute) code torsion calculation design rules are based on STA (Bernardo and Andrade ,2020). The contribution of concrete is neglected in the space truss model. After the crack caused by torsion, unconfined concrete will be spilled, so it will not carry a load. Therefore, the effective cross sectional area is used in STA (Engin, 2005). Simplified torsional analysis based on the space truss theory is shown in Figure 12.

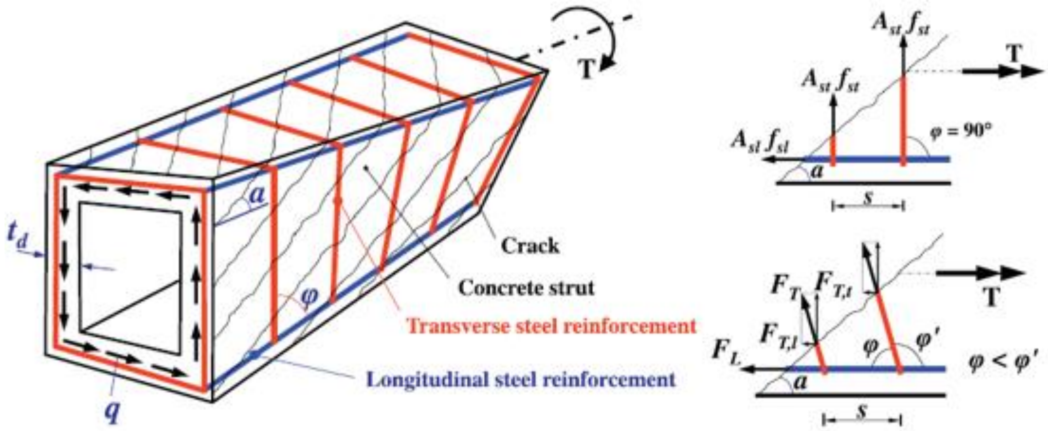

Figure 12. Simplified torsional analysis based on the space truss theory (Chalioris and Karayannis, 2013).

In STA, $\boldsymbol{T}$ is the torsional moment, $\boldsymbol{q}$ is an internal torque resulting from the shear flow, $\boldsymbol{\alpha}$ is cracking angle, $\boldsymbol{t_d}$ is the wall thickness of the equivalent thin-walled tube ($\boldsymbol{t} = {}^{\boldsymbol{A_{oh}}}/_{\mathrm{P}_h}$). Cracking angle calculation is given in Eq. 8 (Chalioris and Karayannis, 2013), torsional moment calculation of transverse and longitudinal reinforcement is given in Eq. 9-10 (Mahmood, 2007).

$$tan\alpha = \sqrt{\frac{A_t * f_{yt} * \mathrm{P}_h}{A_l * f_{yl} * s}} \qquad (8)$$

$$T_l = \frac{2 * A_l * f_{yl} * A_o}{\mathrm{P}_h} * tan\alpha \qquad (9)$$

$$T_t = \frac{2 * A_t * f_{yt} * A_o}{s} * cot\alpha \qquad (10)$$

$\boldsymbol{A_o}$is the cross sectional area bounded by the centerline of the shear flow (0.85$\boldsymbol{A_{oh}}$), in which ($\boldsymbol{A_{oh}}$) is the area enclosed by the outermost center line of the closed stirrups in the section, $\mathrm{P}_{\boldsymbol{h}}$ is equal to the perimeter of the centerline of the closed stirrups, $\boldsymbol{A_l}$ is the total area of steel longitudinal bars; $\boldsymbol{A_t}$ is the area of one legged steel stirrup; s is the spacing of steel stirrups; $\boldsymbol{f_{yl}}$ and $\boldsymbol{f_{yt}}$ are the stresses of the longitudinal and the transverse steel reinforcement, respectively.
α_{exp} values are given in the referenced experimental study (Chalioris and Karayannis, 2013). α_{calc} was calculated with the formula given in Equation 8. The analytically calculated cracking angle and maximum torsional moment values for beam samples ST150 and ST200 are given in Table 2.

Table 2. Analytical and experimental comparison of crack angle and maximum torsional moment values.

Specimens	α_{exp} (deg)	α_{calc} (deg)	α_{calc} /α_{exp}	$T_{max,exp}$ (kN.m)	$T_{max,calc}$ (kN.m)	$T_{max,calc}/T_{max,exp}$
TEST-ST150	43	43.6	1.014	2.649	2.635	0.995
TEST-ST200	38	39.53	1.040	2.385	2.283	0.957

When the results are examined, it is seen that the cracking angle and maximum torsional moment values are quite close to each other. This shows the accuracy and availability of the model.

7. Parametric study

A parametric study was carried out using the verified nonlinear numerical model and the contribution of DSR reinforcements to the torsional behavior was examined. The mechanical properties of the numerical models used in the parametric study are given in Table 3. It is assumed that the material properties of the diagonal shear reinforcement used are the same as the material properties of the transverse reinforcements. Front and 3D views of the numerical models of FEM-DSR 150(a), FEM-DSR 200(b) and FEM-DSR 300(c) are shown in Figure 13. Additionally, the spacing and inclination of the stirrups in the DSR beams are shown in Figure 13.

The analysis results of nonlinear finite element models and the experimental results are presented in Figure 14 comparatively. ρ_t is the ratio of steel transverse reinforcement. In addition, the effects of DSR reinforcement on torsional behavior are compared with continuous spiral reinforcement, which has been experimentally examined in the literature. In the experimental study conducted by Chalioris and Karayiannis (2013), the contribution of these reinforcements to torsion was analyzed by adding continuous spiral reinforcement to the test region of the beams SPL150 and SPL200. When the test results are examined, it is seen that the continuous spiral reinforcements increase the torsional strength. However, since the installation of continuous spiral reinforcement requires special workmanship, there are serious usage difficulties in applications. The application of DSR reinforcements proposed as an alternative within the scope of this study, on the other hand, is very easy.

Table 3. Data of numerical study.

Specimens	s (mm)	ρ_t (%)	ϕ_{DSR} (mm)	$f_{sd,y}$ (MPa)	$f_{sd,u}$ (MPa)
FEM-ST150	150	0.818	n/a	n/a	n/a
FEM-DSR150		1.903	8	365	536
FEM-ST200	200	0.613	n/a	n/a	n/a
FEM-DSR200		1.553	8	365	536
FEM-DSR300	300	1.231	8	365	536

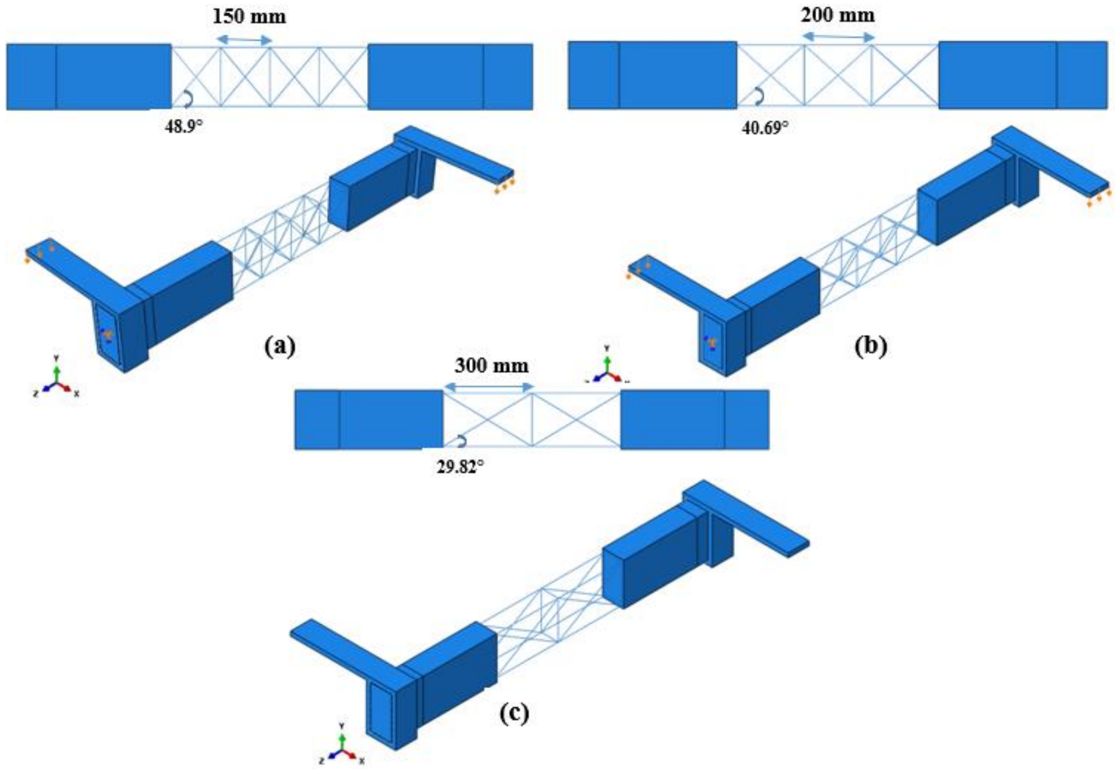

Figure 13. Front and 3D views of the numerical models of (a) FEM-DSR150 (b), FEM-DSR200, (c) and FEM-DSR300.

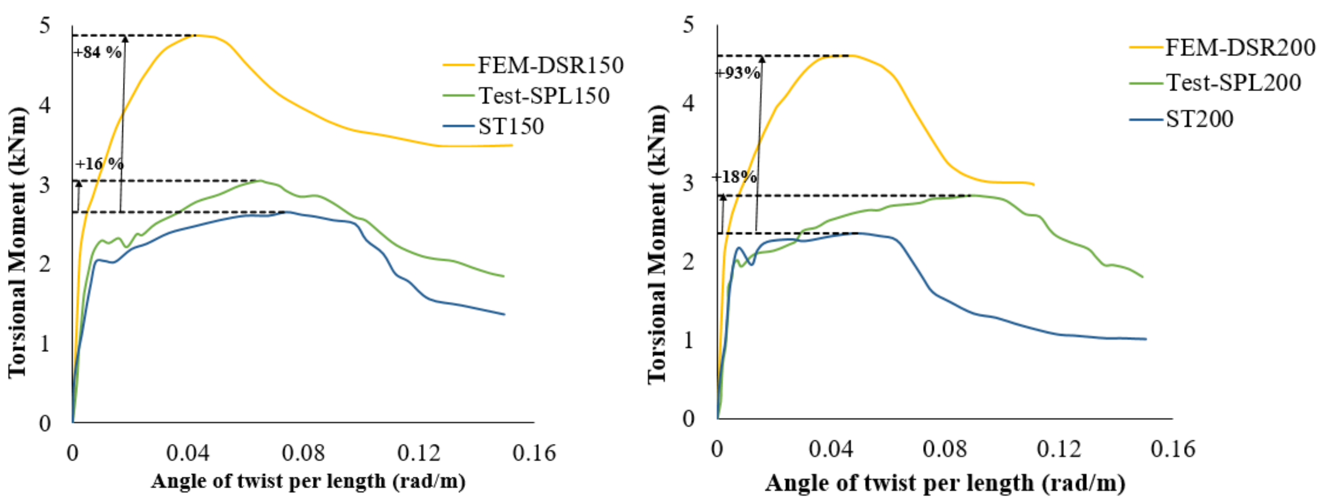

Figure 14. Comparison of numerical models FEM-DSR150 and FEM-DSR200.

When the test-SPL150 and test-SPL200 results are compared with the results of the diagonal shear reinforced FEM-DSR150 and FEM-DSR200 numerical models, it is seen that the use of DSR significantly increases the torsional moment capacity of RC beams. As can be clearly seen from the figure, the torsional moment capacity of RC beams increases by approximately 16-18% when continuous spiral reinforcement is used. In the case of using DSR reinforcement, an increase of approximately 84-93% occurs. Therefore, in case of using diagonal shear reinforcements, which are very easy and practical to apply, a significant improvement will be achieved in the torsional moment capacities of RC beams under the influence of critical torsional moment.

Since DSR reinforcements are supported by stirrups, they are also effective on the behavior of the reinforced concrete beam. Reinforced concrete beams show a more brittle behavior with increasing stirrup spacing. The most obvious effect of DSR reinforcements on behavior is improvements in torsional moment capacity. The results of the numerical models of FEM-DSR150, FEM-DSR200 and FEM-DSR300 with different stirrup pitch spacing in the examined region of RC beams are compared in Figure 15. The area examined in the parametric study was chosen as 600 mm since it was compared with the experimental results in the literature. The number of DSR applied regions is 4, 3 and 2 in FEM-DSR150, FEM-DSR200 and FEM-DSR300 models, respectively. Therefore, the number of DSRs applied increases as the number of steps decreases. As can be clearly seen from Figure 15, the model with the highest torsional moment capacity is FEM-DSR150.

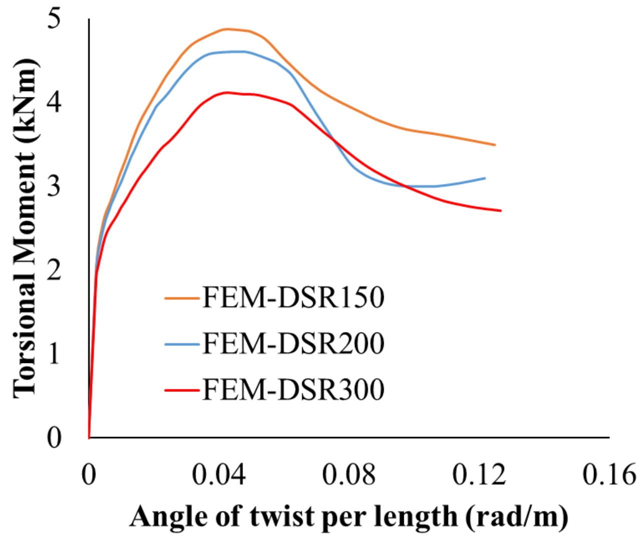

Figure 15. Comparison of numerical models FEM-DSR150 and FEM-DSR200.

When DSR is applied to RC beams under the impact of torsional moment, an improvement of approximately 90% is achieved in torsional moment capacities compared to conventional RC beams. In this study, DSR was applied only to the side surfaces of RC beams. Considering that torsional moment cracks occur on all surfaces of the beam and the application of DSR is very simple and practical, it is clear that DSR can be easily applied to all surfaces of the beam, resulting in a significant improvement in torsional moment capacity.

Maximum torsional moment values of FEM-DSR150, FEM-DSR200 and FEM-DSR300 models (considering the contribution of diagonal shear reinforcements) were calculated theoretically. The calculated analytical values were compared with the numerical model results (Table 4).

Table 4. Comparison of analytical values with numerical model results.

Specimens	$T_{max,FEM}$ (kN.m)	$T_{max,calc}$ (kN.m)	$T_{max,calc}/T_{max,FEM}$
FEM-DSR150	4.878	5.796	1.188
FEM-DSR200	4.607	5.394	1.170
FEM-DSR300	4.116	4.905	1.191

8. Conclusions

Numerous studies have applied the diagonal shear reinforcement (DSR) to increase the shear capacity and ductility of RC beams, columns and beam-column joints. However, the number of studies in which DSR is applied to increase the torsional capacity of RC members is quite low. In this study, a numerical study is performed to investigate efficiency of DSR reinforcement on the response of RC beams subjected to pure torsion. For this purpose, a nonlinear numerical model was constituted to simulate the response of the RC beams by using ABAQUS software program. The numerical developed model was verified with the selected experimental results from literature. The CDP model was used to constitute concrete material behavior. The numerical analysis results proved that the nonlinear numerical model is quite successful in simulating the nonlinear behavior of RC beams under torsion moment. A parametric study was carried out to examine the significant effect of DSR on the response of the RC beam subjected to pure torsion in terms of torsional moment and angle of twist per length. At the end of the parametric study, the following conclusions were derived.

- DSR makes very significant contribution to torsional moment capacity of the RC beam subjected to pure torsion.
- DSR reinforcements contribute to the torsional strength than continuous spiral reinforcements, which have been experimentally examined in the literature. The shear stresses due to the torsional moment reach their maximum values on the surfaces of the structural elements. Since DSR stirrups are applied by connecting, their contribution to the torsional strength is much more evident than spiral reinforcements as they are positioned on the outer surface of RC beams.
- Cracking angle and maximum torsional moment values obtained as a result of theoretical study and referenced experimental study (ST150, ST200) were compared. It was determined that the results were compatible with each other with an error margin of approximately 4%.
- When the finite element models using diagonal shear reinforcement are compared with the theoretical study results according to ACI code, it is seen that the maximum torsional moment values are compatible with each other at a rate of approximately 80%.
- When the theoretical study and the results of the analysis of finite element models are examined, it is clearly seen that diagonal shear reinforcement (compared stirrup and spiral reinforcement) increases the torsional moment capacity of reinforced concrete beams much more.
- Compared to continuous spiral reinforcements, which require special workmanship to assemble, DSR reinforcements are very easy to apply and do not require any special workmanship.
- Although torsional moment cracks occur on all surfaces of the RC beam, DSR reinforcement is applied only to the side surfaces of the RC beam in numerical analysis. As can be seen from the numerical results, the torsional strength of the beam increased obviously as crack propagation was prevented on the surfaces where DSR was applied. If DSR is applied to all surfaces of the beam, including the lower and upper surfaces, the torsional moment capacity will increase further as crack propagation is prevented.

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