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NUMERICAL ANALYSIS OF SELF-COMPACTED CONCRETE BEAMS REINFORCED WITH STEEL FIBERS UNDER TORSION

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Abstract: This study aims to numerically investigate the behavior of steel fiber-reinforced self-compacted concrete (SCC) beams subjected to pure torsional loading. A three-dimensional (3D) non-linear finite element analysis is carried out using the ANSYS software to predict the effect of steel fibers on the torsional behavior of SCC beams. A comprehensive validation study was conducted by adopting a multi-example validation approach to enhance the credibility and robustness of the conclusions drawn from the numerical investigation. Many variables were studied, including the compressive strength of SCC, the spacing between stirrups, the diameter of stirrups, the volume ratio of steel fibers and the beam width. The numerical model well captured the failure patterns, torque-angle of twist responses, stress distributions, and the ultimate load-carrying capacity of the SCC beams. The numerical results demonstrate that including steel fibers leads to enhanced mechanical properties and improved torsional resistance of the SCC beams. The effect of steel fibers is most significant at a volume ratio of 2%, which resulted in a 77.29% increase in the ultimate torsional capacity. Furthermore, the study proposes a rational approach in the form of an equation to predict the ultimate torsional capacity of SCC beams. The developed equation was compared against a range of experimental data and design codes to assess the accuracy and reliability of the predicted equation. The results of these comparisons demonstrate that the proposed analytical model provides acceptable predictions of the ultimate torsional capacity of SCC beams.

Keywords: Self-Compacting Concrete, torsion, finite element, concrete beams, steel fiber, ANSYS.

1. Introduction

The development of self-consolidated concrete (SCC) was initiated [1] in Japan. The self-compacted (SCC), possesses the ability to uniformly fill formwork solely by its weight without vibration [1]. This development emerged in response to the country's growing concerns regarding concrete durability, constructability, and productivity [2]. In recent decades, self-compacted concrete (SCC) has emerged as a significant advancement in the field of concrete technology [3-4]. In recent years, there has been a growing interest in SCC [5]. SCC has been employed in several commercial projects [6]. Numerous research studies have been conducted to establish the raw material requirements [7-8]. Self-compacted concrete and traditional vibrated concrete of similar compressive strength have comparable properties and if there are differences, these are usually covered by the safe assumptions on which the design codes are based [9].

The researchers developed analytical expressions to estimate significant mechanical properties of the SCC mixes. Moreover, a compressive stress-strain curve relationship was suggested [10-11-12] to model the mechanical behavior of SCC mixes. This proposed model was validated through comparisons with experimental data and values from existing literature [10-11-12].

The studies revealed that the torsional capacity of SCC beams was greater than that of conventional concrete (CC) beams. Additionally, the SCC models exhibited brittle behavior compared to the conventional concrete models. Furthermore, the SCC models demonstrated higher torsional moments and experienced first cracking at higher values compared to the CC models [13-14].

According to experimental studies [15-16], The results showed that adding steel fibers to self-compacting concrete improves cracking, angle of twist and ultimate torque for reinforced concrete beams. In addition, it significantly contributes to post-cracking ductility, toughness of beams with typical cracking patterns around the surface and smaller crack widths due to the bridging effect of the steel fibers [15-16].

The addition of steel fibers significantly improved the torsional properties of SCC compared to vibrated concrete (VC), [17-18].

2. Research Significance

This investigation presents a numerical study on the effect of the addition of steel fibers on the torsional behavior of self-compacted concrete (SCC) beams to develop a comprehensive understanding of the performance of self-compacted concrete under pure torsional loading. The current research also proposes a rational analytical approach in the form of an equation that can predict the magnitude of the torsional capacity of SCC beams, with and without the inclusion of steel fibers.

3. SCC Concrete Material Modeling in ANSYS

To accurately simulate SCC behavior, it is necessary to specify engineering properties such as compressive strength, modulus of elasticity, and Poisson's ratio. While there is a limited number of previous studies directly addressing this aspect, they provide useful relationships for determining the required geometric properties. **Table 1** shows the characteristics of SCC that were used. The stress-strain curve for SCC is established based on equations proposed by R. Kumar et al. [10], which describe the engineering properties with a high degree of accuracy.

Table 1. Characteristics of SCC in ANSYS modeling according to R. Kumar et al. [10].

Material Properties	**Material compressive strength (MPa)**			
	45	**50**	**55**	**60**
Linear Isotropic				
Modulus of elasticity (EX) (N/mm2)	30532	32048	33484.4	34852
Poisson ratio (PRXY)	0.2	0.2	0.2	0.2
Concrete Properties				
Open Shear-Coefficient	0.3	0.3	0.3	0.3
Closed Shear-Coefficient	0.8	0.8	0.8	0.8
Uniaxial Crushing Stress (fcu) (N/mm2)	45	50	55	60
Uniaxial Cracking Stress (fctr) (N/mm2)	4.2	4.5	4.76	5

4. Validation of Numerical Modeling

4.1 Elements Representation:

The beams were simulated with **ANSYS 17.2** [19], which presents a set of various solid nonlinear capabilities for analysis. A specific solid element **SOLID65** can be used. Concrete exhibits non-linear characteristics such as cracking, crushing, plastic deformation, and creep. SOLID65 addresses these complexities by considering cracking in three orthogonal directions, as well as the various modes of deformation experienced by concrete. SOLID65 can represent 3D conventional concrete and self-compacted concrete with or without reinforcing steel bars as shown in Figure (1). **Link 180** can be used to simulate steel reinforcement, Figure (2) show The LINK180. The LINK180 element accurately represents the uniaxial tension-compression behavior of the reinforcement steel and provides three degrees of freedom at each node. An eight-node solid element **Solid45** are shown in Figure (3), was used for the steel plates at the supports and loading areas in the beam models. The mesh size in the models is 25mm to confirm the model's accuracy.

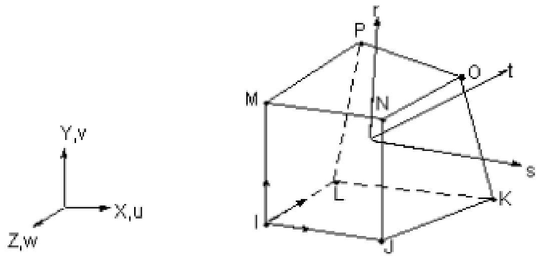

Fig. (1) Solid 65 element 3-D Reinforced Concrete in ANSYS [19].

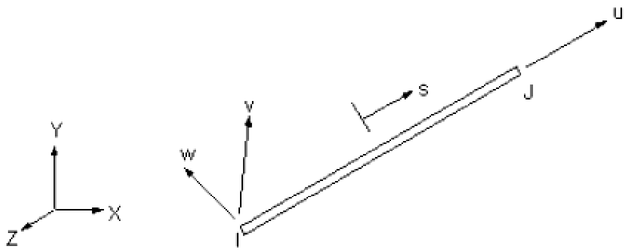

Fig. (2) Element Link 180 (Steel Reinforcement) in ANSYS [19].

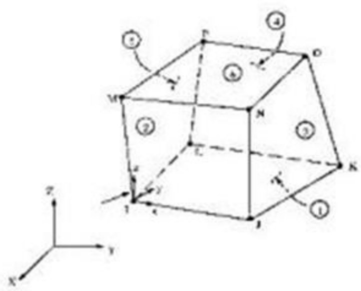

Fig. (3) Element Solid 45 3-D Steel plates at supports in ANSYS [19].

4.1.1 Modelling steel fibers inside reinforced SCC in ANSYS:

To simulate the behavior of steel fibers in reinforced concrete using the ANSYS [19] software program, specific modeling techniques must be employed. The steel fibers are represented as discrete elements within the concrete matrix, accounting for their characteristics and interaction with the surrounding concrete material.

This includes specifying the volume fraction and orientation of the fibers, which are critical parameters that influence the mechanical properties of the concrete. Furthermore, the relevant mechanical properties of the steel fibers, such as Young's modulus, Poisson's ratio, and tensile strength, are specified in the steel fibers simulation. The general properties of steel fiber are provided in Table 2.

Table 2. The general properties of steel fiber according to Syed S. Raza et al. [20].

Tensile strength (GPa)	**Elastic modulus (GPa)**	**Sp. gravity**	**Poisson ratio (PRXY)**
1.7	210	7.78	0.3

4.2 Validation

A thorough investigation was conducted on three different models reported in the literature [16, 20] to ensure the efficiency of the present modeling using the ANSYS model and the use of the program to obtain accurate results.

4.2.1 First verification example:

The first verification example used in the present study is an experimental study conducted by Khaled S. et al. [16]. The control beam (B11) in the study was used as the verification beam in the present study, the control beam was constructed using conventional concrete. **Fig 4** shows the Tested control beam geometry, beam reinforcement and section details. The simulation of the ANSYS model with meshing is shown in **Fig 5**.

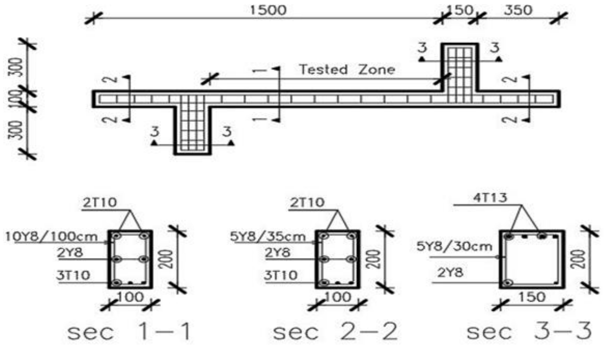

Fig. 4 Geometry, beam reinforcement and sections details of verification model, Khaled [16].

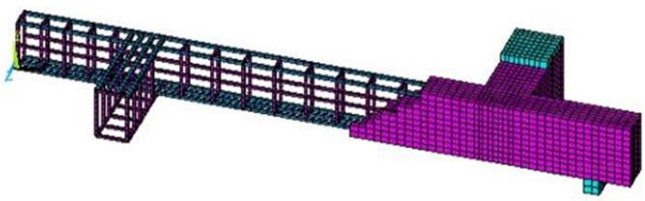

Fig. 5 ANSYS model of concrete and reinforcement meshing of present verification model.

The output results for the nonlinear finite element modeling analysis are shown in **Fig 6**. This figure shows the comparison between the current study verification model and the experimental results reported by Khaled S. [16]. Moreover, **Fig 7** displays the failure modes and crack patterns observed in the experimental study [16] with the present FEM simulation of the verification model, demonstrating striking similarities to the experimental results.

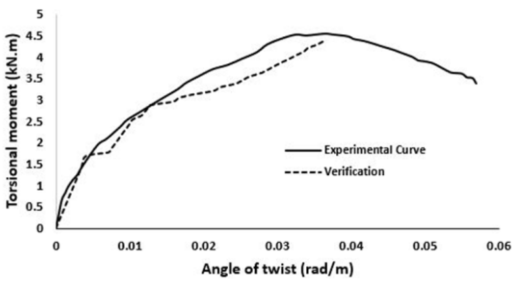

Fig 6 Comparison between the current study verification model and the experimental by Khaled S.[16].

Fig 7 Comparison between The FEA Failure modes and crack patterns of the verification model with experimental results by Khaled S. [16].

Based on the current investigation using the finite element analysis, it is demonstrated that the maximum torque is slightly lower than the maximum torque obtained in the experimental testing by 3%. Thus, the numerical results presented good agreement with the experimental results in all aspects of the comparison.

4.2.2 Second Verification Example:

The second verification example is the control beam from an experimental and analytical study conducted by Khaled F. et al. [21]. The experimental investigation was undertaken to enhance the torsional resistance of reinforced concrete (RC) beams. To complement the experimental investigation, a finite element method (FEM) modeling was employed using ANSYS-19 software. The FEM results were subsequently compared with the experimental findings. **Fig 8** shows the Tested control beam geometry, beam reinforcement and section details. The simulation of the present ANSYS model with meshing is shown in **Fig 9**.

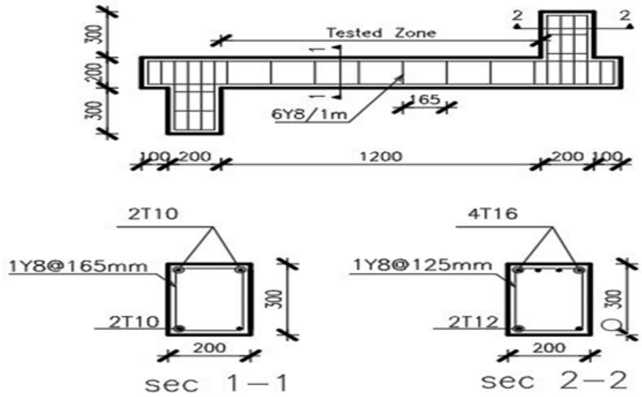

Fig 8. Geometry, beam reinforcement and section details.

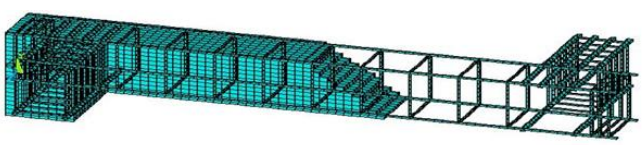

Fig 9. Present verification model simulation with steel reinforcement and meshing.

A comparison was carried out between the reported experimental and analytical results with the present ANSYS modelling. **Fig 10** shows that the results from the ANSYS model are in good correlation with the results from the experimental work. It was observed that the ANSYS model verification analysis was conservative by 1.4%; slightly lower than the maximum torque obtained in the experimental test. Failure mode and crack patterns of the tested control beam in the experimental work are compared with the results of the ANSYS model in **Fig 11**. Good correlation was observed between the experimental and analytical work.

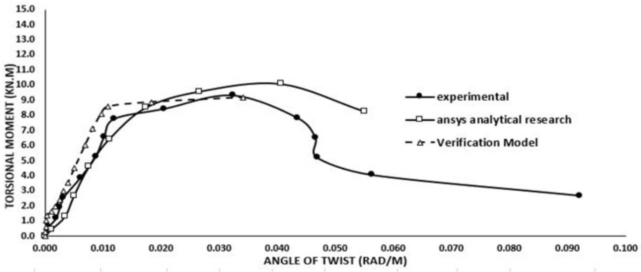

Fig 10 Comparison between the torque–angle of twist relationship reported in the experimental study [21] and the verification model

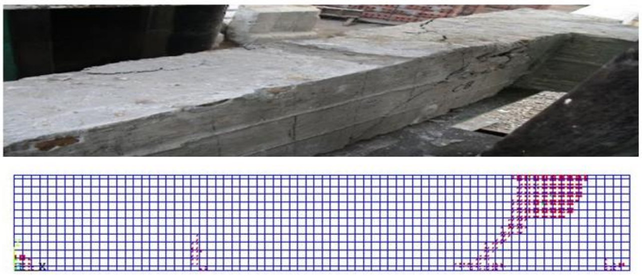

Fig 11 Comparison between The FEA Failure modes and crack patterns of the verification model with experimental results.

4.2.3 Third Verification Example:

The third verification example is another model conducted on a different component of the experimental work carried out by Khaled S. [16], specifically focusing on examining and analysing beam [B5]. This beam [B5] consisted of self-compacted reinforced concrete beam with steel fibers. The material properties used in the experimental investigation were as follows: a self-compacting concrete compressive strength of 90.0 MPa reinforced with Glass Fiber Reinforced Polymer (GFRP) bars. Steel fibers were incorporated at a volume ratio of 0.75%. **Fig 12** presents the comparison between the load-angle of twist curves of both the experimental results [16] and the results of the present nonlinear finite element modeling analysis.

The comparison reveals a significant resemblance between the outcomes obtained through the finite element method (FEM) and those obtained from the experimental work. This similarity is particularly evident in the failure modes and crack patterns exhibited by beam (B5) as depicted in **Fig 13**.

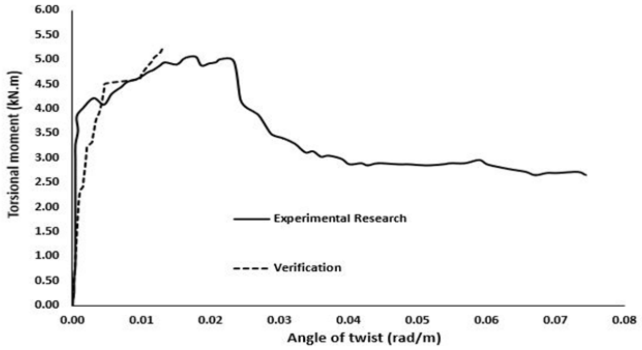

Fig 12 The torsional-twisting comparison between the experimental [16] and current verification model.

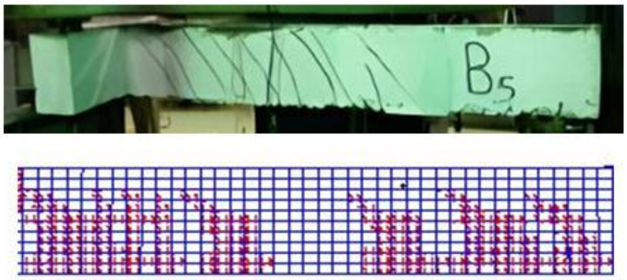

Fig 13 Comparison between The FEA Failure modes and crack patterns of the verification model with experimental results.

These comparisgons lead to the conclusion that the finite element models used in the current verification process are dependable. Consequently, the experimental model described in the study by Khaled S. [16] will be adopted to investigate the factors that govern and impact the behavior of self-compacting concrete beams under torsion.

Table 3 shows the comparison between the results obtained from the verification models and the research findings. This comparative analysis provides a comprehensive overview of the key parameters and their corresponding values.

Table 3 compares between results of the current study and the results of the research findings

Ex. no	reference	Experimental results in research	ANSYS results in research	ANSYS results for verification model in the present study
		Ultimate torque (kN.m)	Ultimate torque (kN.m)	Ultimate torque (kN.m)
1	Khaled S. [16]	4.5	-	4.375
2	Khaled F. [21]	9.31	10.08	9.177
3	Khaled S. [16]	5.04	-	5.21

5. Parametric study

The number of experimental specimens is often limited due to the high costs associated with conducting torsional tests on concrete beams. Additionally, the small number of variables that can be examined in a single study restricts the depth of understanding that can be gained from experimental investigations alone. To overcome these limitations, finite-element analysis has emerged as a more economical and efficient method for studying the torsional behavior of concrete elements, including self-compacting concrete beams, enabling a more comprehensive exploration of the various parameters affecting torsional resistance. A comprehensive parametric study has been carried out to study the effect of different parameters on the torsional behavior of reinforced concrete beams.

5.1 Effect of compressive strength

The influence of varying the compressive strength of self-compacting concrete on the Torque- Angel of twist relation is illustrated in **Fig 14**. The control beam in this study represents self-compacting concrete with a compressive strength of 45 MPa and achieved a maximum torque of 4.0 KN.m. The findings indicate that increasing the compressive force to 50, 55, and 60 MPa leads to a respective increase in maximum torsional moments by 7.5%, 15%, and 22.5%. This demonstrates that higher compressive forces positively impact the torsional behavior of self-compacting concrete beams. The observed enhancement in the torsional capacity of SCC beams due to increased compressive strength is consistent with the findings reported in previous studies [13-14-16], which have also demonstrated the positive effect of increased compressive strength on the torsional capacity of SCC members.

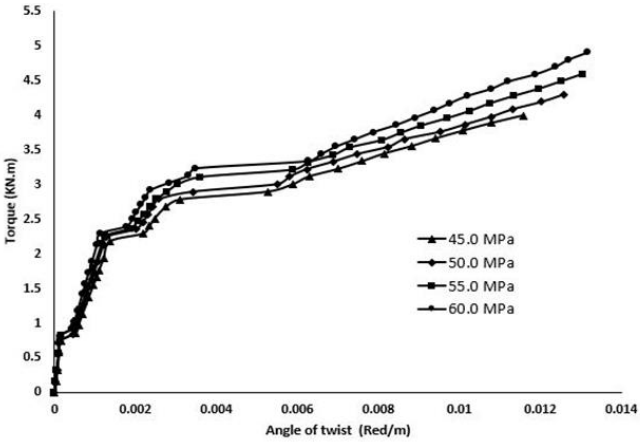

Fig 14 Effect of compressive strength on Torque- Angel of twist relation

5.2 Effect of spacing between the stirrups

When the spacing of the transverse reinforcement is decreased from 200 mm to 150 mm, the maximum torque for the specimens having compressive strengths of 45 MPa, 50 MPa, 55 MPa, and 60 MPa increased by 25.75%, 17.61%, 23.22% and 21.66% respectively. Similarly, when the spacing is further reduced from 150 mm to 100 mm, the maximum torque for the afore-mentioned specimens increased by 14.32%, 14.69%, 16.42% and 15.70% respectively. The findings in **Fig 15** indicate that decreasing the stirrup spacing leads to a further enhancement of the torsional capacity. The observed enhancement due to the decreasing spacing between the stirrups is consistent with the findings reported in previous studies [13-14]. Decreasing the stirrup spacing increases the control over the length of cracks, reduces the width of cracks, and distributes the torsional stresses more evenly across the entire cross-section, rather than concentrating them around a specific area.

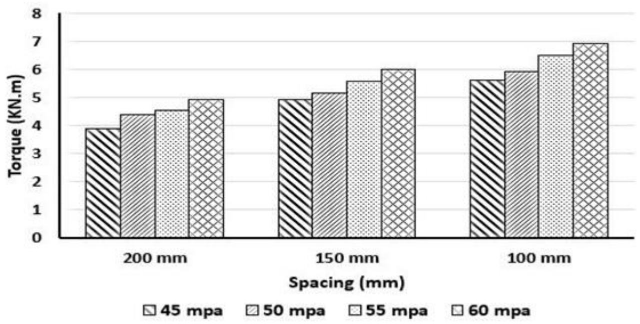

Fig 15 Effect of spacing between stirrups.

5.3 The effect of stirrup diameter

In this section, the effect of changing the transverse reinforcement ratio on self-compacted concrete beams was examined. Fig 16 shows that when a compressive strength of 45 MPa was used, the maximum torque increased by 11.68% and 27.76% when the diameter increased from 6 mm to 8 mm and 10 mm, respectively. For the same stirrup spacing, when a compressive strength of 50 MPa was used, the torque increased by 14.60% and 34.76% when the diameter increased from 6 mm to 8 mm and 10 mm, respectively. When a compressive strength of 55 MPa was used, the torque increased by 20.81% and 32.41% when the diameter increased from 6 mm to 8 mm and 10 mm, respectively. When a compressive strength of 60 MPa was used, the torque increased by 24.74% and 36.74% when the diameter increased from 6 mm to 8 mm and 10 mm, respectively.

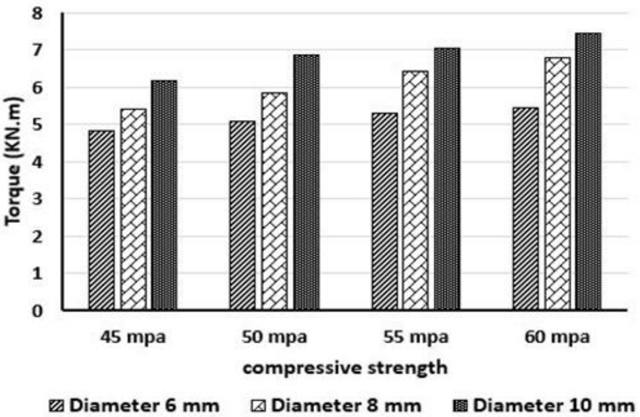

Fig. 16 The effect of stirrups diameter on the torque of the SSC beam.

5.4 The effect of area steel

The effect of changing the longitudinal reinforcement ratio on self-compacted concrete beams was examined. **Fig 17** shows that for a beam with a compressive strength of 45 MPa, the torque exhibited an increase of 11.18% as the reinforcement ratio was raised from 1.57% to 2.26%. Further increasing the ratio to 4% resulted in a torque increase of 35.53%. Similarly, with a compressive strength of 50 MPa, the torque increased by 8.93% when the reinforcement ratio was elevated from 1.57% to 2.26%, and by 35.80% when increased to 4%. At a compressive strength of 55 MPa, the torque demonstrated a more modest increase of 5.66% with a change from 1.57% to 2.26%, followed by a significant rise of 39.85% upon reaching a 4% reinforcement ratio. Finally, when the compressive strength of 60 MPa, the torque increased by 4.94% for the transition from 1.57% to 2.26%, and by 38.89% when the ratio was increased to 4%. The observed enhancement due to changing the longitudinal reinforcement ratio is consistent with the findings reported in previous studies [22-23].

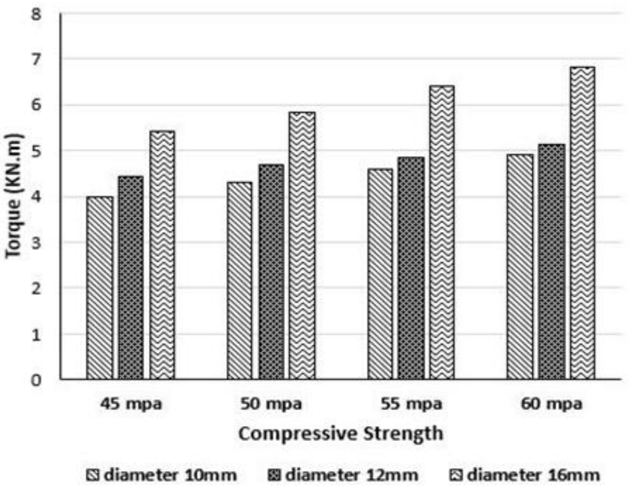

Fig 17 The effect of longitudinal reinforcement ratio on the torque of the SCC beam.

5.5 Effect of fiber volume ratio

Steel fiber is the most common type of fiber used to reinforce concrete with 7.78 specific gravity, modulus of elasticity equals 210 GPa and 1.7GPa tensile strength [20]. To assess the impact of fiber volume fraction on the torsional behavior of self-compacted concrete beams, ANSYS software was employed to investigate four distinct volume ratios. The results demonstrated that the maximum torque for the beams having a compressive strength of 50 MPa increased by 21.62%, 39.11%, 53.47%, and 77.29% compared to the control specimen when employing steel fiber ratios of 0.5%, 1%, 1.5%, and 2%, respectively, as depicted in **Fig 18**.

When the self-compacted concrete beams with a compressive strength of 50 MPa were subjected to 80% of the ultimate torque, the addition of 0.5% steel fibers resulted in a 27.16% decrease in the angle of twist compared to the control beam without any fiber reinforcement. Furthermore, with steel fiber ratios of 1%, 1.5%, and 2%, the angle of twist reduced by 43.35%, 66.64%, and 87.96% respectively, compared to the control beam as shown in **fig 18**.

The increase in steel fiber volume fraction appears to contribute to a more effective transfer and distribution of torsional stresses within the concrete matrix. This, in turn, leads to an enhancement in the ultimate torque capacity. This finding is consistent with the results reported in previous studies [15-16-18], which have also demonstrated the positive effect of increasing the steel fiber volume fraction on the torsional performance of self-compacting reinforced concrete beams.

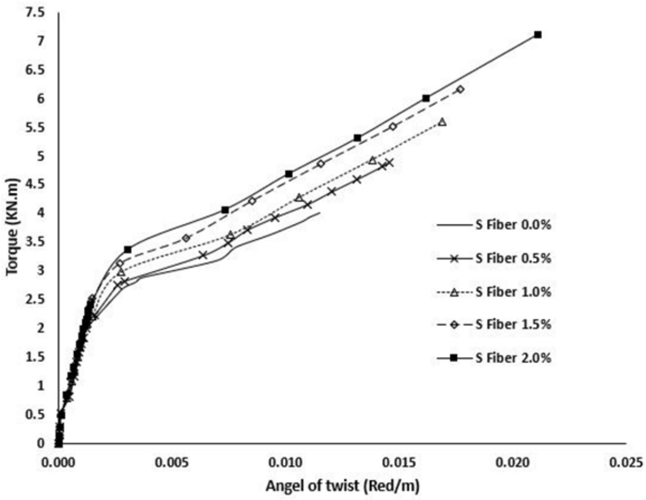

Fig. 18 Effect of steel fiber ratio on Torque- Angel of twist relation.

6. Theoretical Study

6.1 Energy absorption

The area beneath the torque-twist curve up to peak torque is defined as energy absorption [24] as illustrated in **Fig 19**. **Table 4** provides the calculated values of energy absorption for SCC beam reinforcement with steel fibers with different volume fractions.

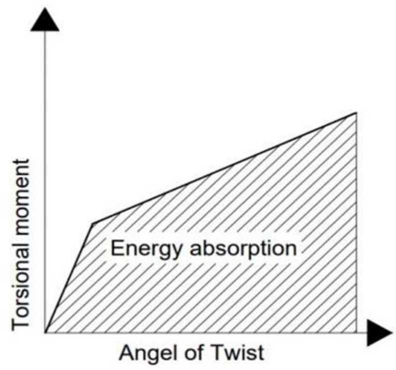

Fig. 19 Energy absorption in the torsional moment – the angle of twist curve**.**

Table (4) energy absorption for fiber addition to SCC beams with Fcu 50 MPa.

Fiber type	Fiber ratio %	Energy absorption
Steel fiber	0	0.0457
Steel fiber	0.5	0.0711
Steel fiber	1	0.089
Steel fiber	1.5	0.109
Steel fiber	2	0.133

Incorporating steel fibers into self-compacting concrete (SCC) beams improves the mechanical properties of the concrete, including its ductility, stiffness, toughness, and control over crack propagation. The cracking observed in steel fiber-reinforced self-compacting concrete (SF-SCC) beams is linked to the debonding and pullout of randomly distributed steel fibers within the concrete. Consequently, SF-SCC demonstrates a pseudo-ductile tensile response, allowing for enhanced energy dissipation compared to the brittle behavior characteristic of concrete.

According to the calculated values, adding fiber enhances the energy absorption of the self-compacted concrete beams. As shown in **Fig 20** the addition of steel fiber by volume fraction ratio 0.5%, 1%, 1.5% and 2% improves the energy absorption by 55.57%, 94.7%, 138.5% and 191.02% respectively. These results are in agreement with findings from earlier experimental studies [18-25-26], which similarly indicated that increasing the volume fraction of steel fibers positively influences the energy absorption capacity of self-compacting reinforced concrete beams.

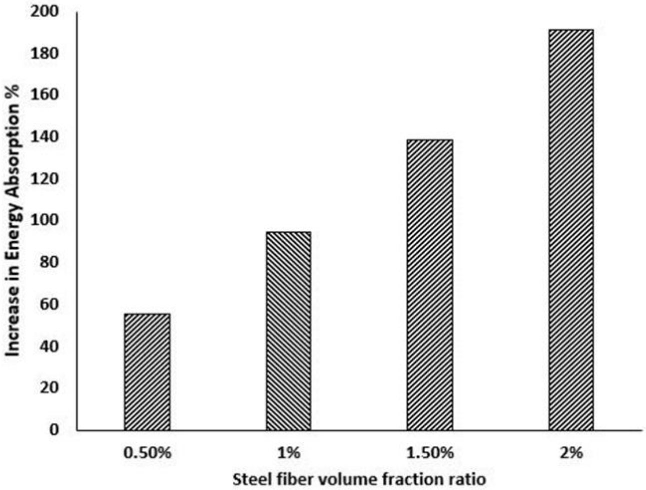

Fig. 20 Influence of adding steel fibers to SCC beams on energy absorption.

6.2 Ductility

The ductility factor (μ) is defined as the ratio between the angle of twist at failure and the angle of twist at the yield point [27]. This index could be defined as presented in Equation (1) and **Fig 21**:

$$\mu = \frac{\theta_f}{\theta_y} \quad (1)$$

In which: μ the indicates the ductility ratio, θ_f is the failure torsional curvature and θ_y is the curvature corresponding to the yield point.

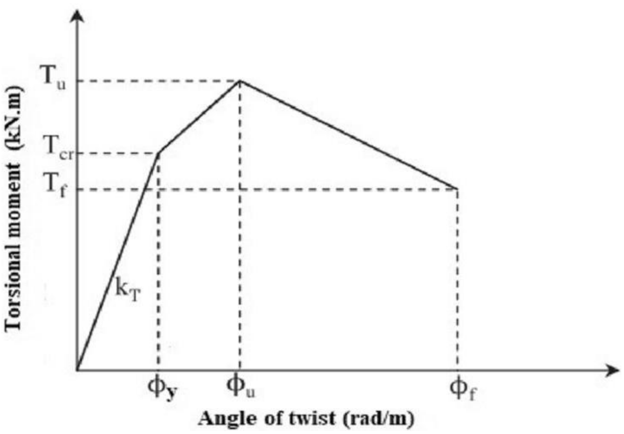

Fig. 21 Calculation of the ductility ratio.

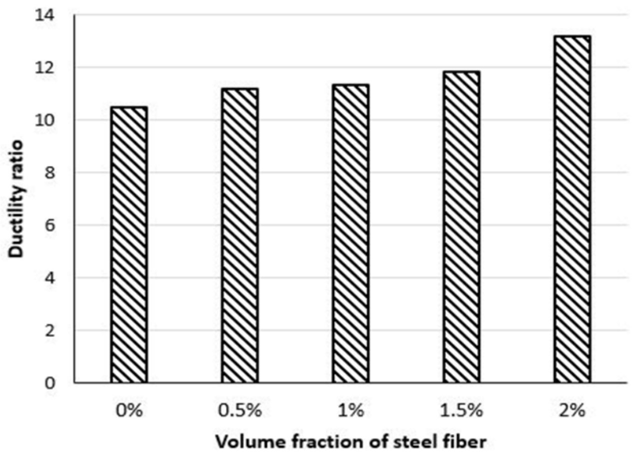

Fig. 22 Effect of steel fiber on the ductility ratio of specimens.

The crack-bridging behavior of fibers significantly enhances the ductility of the concrete matrix. One of the primary advantages of steel fiber-reinforced concrete (SFRC) is its exceptional resistance to cracking and crack propagation. The fibers effectively hold the matrix together, even in the presence of extensive cracking, due to their bridging effect.

According to the findings illustrated in **Fig 22**, the ductility ratio of the self-compacting concrete (SCC) beams was enhanced by increasing the steel fiber content. Specifically, the use of 0.5%, 1%, 1.5%, and 2% steel fibers led to improvements in the ductility of the SCC beams by 6.7%, 8.2%, 12.9%, and 25.8%, respectively. The enhancement of ductility is a crucial factor in the torsional performance of concrete beams and this finding aligns with the experimental results presented in earlier studies [26-28-29].

7. Proposed model for the torque of SCC beams

The design code provisions for torsional design are primarily focused on normal aggregate concrete and may not be entirely appropriate for the design of self-compacting concrete (SCC) structures. Additionally, the existing design codes do not account for the influence of fiber reinforcement on the torsional performance of concrete members.

According to ACI [30], equation (2) calculates the torsional moment of the concrete term as follows:

$$T_u = \varphi 0.33\, \lambda \sqrt{f'_c} \quad (2)$$

While φ= strength reduction factor, λ = modification factor reflecting the reduced mechanical properties of lightweight concrete. Acp and Pcp are the section area and perimeter respectively. The equation (3.a) and equation (3.b) calculate the torsional moment of transverse reinforcement and longitudinal reinforcement respectively according to ACI where Tn shall be the lesser of (a) and (b) is

$$T_n = \frac{2A_0 A_t f_{yt}}{s} \cot\theta \quad (3.a)$$

$$T_n = \frac{2A_0 A_l f_y}{\rho_h} \tan\theta \quad (3.b)$$

where Ao shall be determined by analysis except that it shall be permitted to take Ao equal to 0.85Aoh, θ shall not be taken less than 30 degrees nor greater than 60 degrees, A_t is the area of one leg of a closed stirrup resisting torsion within spacing s, A_ℓ is the area of longitudinal torsional reinforcement, and p_h is the perimeter of the centerline of the outermost closed stirrup.

Narayanan and Kareem-Palanjian [31] have proposed an equation (4) for the torsional design of steel fiber-reinforced concrete rectangular beams. Equation (4) for calculating the torsional moment is as follows:

$$T = 0.13x^2y\sqrt{F_{cu}} + k_2\frac{x_1y_1}{s}A_sf_{ty} + 0.22F\frac{x_0y_0}{x_0+y_0}xy\sqrt{F_{cu}} \quad (4)$$

Where: x and y are the smallest and largest dimensions of the concrete section respectively.

F is the fiber factor, which is taken as β (l_f/d_f) ρ_f.

β is the bond coefficient of steel fiber, it is related to the shape of fiber and it can be taken 1,0.75 and 0.5 for hooked, crimped, and straight fiber respectively [32].

(l_f/d_f) is the aspect ratio between the length and diameter of the steel fiber.

ρ_f is the fiber ratio.

x0 and y0 is (5/6)x and y-(1/6)x respectively,

x1 and y1 can be calculated by 0.9 x and 0.9 y respectively.

k_2 is the longitudinal reinforcement factor, which is calculated from the equation:

$$k_2 = [0.2m + \sqrt{m}(\frac{0.45y_1}{x_1} - \frac{s}{x_1+y_1})] \quad (5)$$

Where m is the ratio between the longitudinal and transversal reinforcement, which is taken as $\rho_l f_{ly}/\rho_t f_{ty}$,

ρl and ρ_t are the longitudinal and stirrups steel reinforcement ratios,

f_{ly} is the yield stress of the longitudinal steel reinforcing bars, f_{ty} is the yield stress of the transversal steel. S is the spacing between the stirrups.

Starting from the Kareem-Palanjian [31] equations and established on the numerical results obtained from the present study and considering the experimental results of several researchers, an empirical equation to calculate the torsional capacity of SCC beams is proposed as presented in equation (6). This proposed equation will enable the calculation of the maximum torsional moment for SCC beams, with or without the inclusion of steel fibers:

$$T = 0.17x^2y\sqrt{F_{cu}} + k_2\frac{x_1y_1}{s}A_sf_{ty} + 0.35F\frac{x_0y_0}{x_0+y_0}xy\sqrt{F_{cu}} \quad (6)$$

Table (5) and **Fig** 23 present a comparison between the results of the present analytical study and the results of the proposed equation (6). Also, a comparison between the current proposed equation (6) and the previous torsional behavior of SCC beams using numerical and/or experimental results [13-18-33] are presented in Table 6 and Fig 24.

The comparison between the current proposed equation (Eq. 6), the results from the present analytical study, the ACI equation, and the previous experimental research works [13-18-33] reveal the following:

- The proposed equation (6) yields slightly higher torque results than those reported in the present analytical study by 5.4%. These results are more closely aligned with the present analytical results than the results produced by the ACI equation which yields lower torque results by 16%, which exhibit a degree of conservatism as shown in **Fig** 23.
- Specifically, when compared with the experimental results from previous researches [13-18-33], the proposed equation (6) demonstrates an average deviation of 10% (either higher or lower) when compared to the results from previous tests of SCC beams reinforced with or without steel fibers. Furthermore, the ACI equation appears to adopt a conservative approach relative to the experimental results for self-compacting concrete (SCC) beams reinforced without steel fibers which gives lower values by 33% as shown in **Fig** 24. This conservatism may stem from the ACI's focus on structural safety considerations, In addition, the equation is basically for traditional concrete without steel fibers and SCC shows better torsional behavior from conventional concrete.

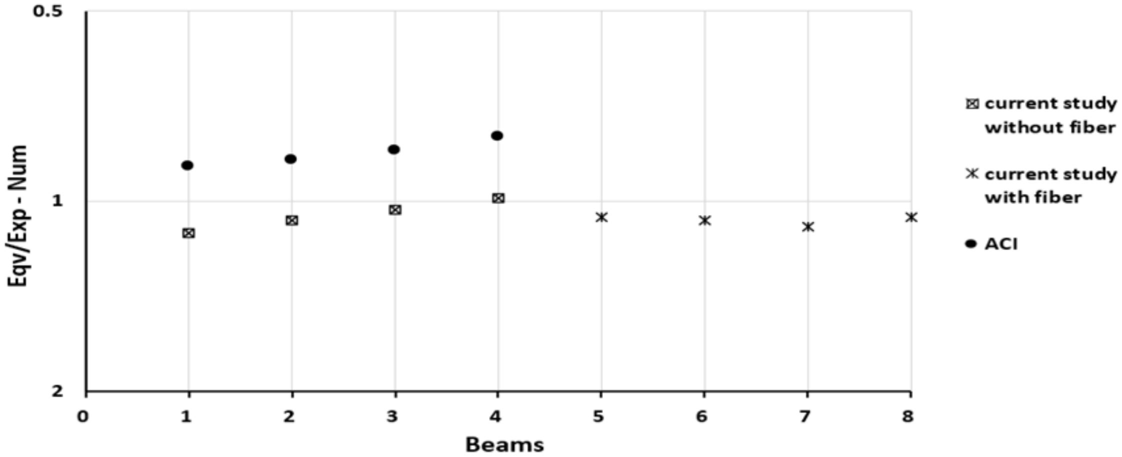

Fig 23 The application of the proposed equation with the results of the present analytical study for SCC beams with and without steel fiber addition

Table 5. Comparison between numerical results, proposed model results and ACI equations.

	Parameter values					Ultimate torque (KN.m)		Equivalent Proposed model Equ. (6) /Numerical and or experimental	ACI equation application /Numerical and or experimental	Reference
	Fcu MPa	concrete dimensions mm		Fiber						
		W	H	%	Aspect ratio	Equivalent Proposed model	Proposed model Numerical and/or experimental			
1	45	100	200	-	-	4.49	4.0	1.1225	0.88	Current Study without steel fiber
2	50	100	200	-	-	4.61	4.3	1.072	0.86	
3	55	100	200	-	-	4.73	4.58	1.0327	0.83	
4	60	100	200	-	-	4.843	4.898	0.989	0.79	
5	45	100	200	0.5	55	5.2	4.9	1.061	-	Current Study with Steel Fiber
6	50	100	200	1	55	5.985	5.58	1.072	-	
7	55	100	200	1.2	55	6.765	6.16	1.098	-	
8	60	100	200	2	55	7.545	7.115	1.060	-	

Table 6. Comparison between experimental results, proposed model results and ACI equations.

	Parameter values					Ultimate torque (KN.m)		Equivalent Proposed model Equ. (6) /Numerical and or experimental	ACI equation application /Numerical and or experimental	Reference
	Fcu MPa	concrete dimensions mm		Fiber						
		W	H	%	Aspect ratio	Equivalent Proposed model	Proposed model Numerical and/or experimental			
1	30	150	250	-	-	7.5	8.25	0.91	0.64	Karim said [13] without fiber
2	30	150	250	-	-	8.9	9.75	0.913	0.718	
3	50	150	250	-	-	9.025	9	1.003	0.701	
4	50	150	250	-	-	10.422	11.25	0.9264	0.714	
5	35	150	300	-	-	10.695	10.5	1.0186	0.6066	Noha Y.E [33] without fiber
6	22.4	100	200	-	-	1.61	1.69	0.95	0.69	Sai Nitesh K.J.N [18] Without fiber
7	81	100	200	-	-	3.06	3.7	0.85	0.597	
8	22.4	100	200	0.5	50	2.065	1.93	1.069	-	Sai Nitesh K.J.N [18] With fiber
9	22.4	100	200	0.5	70	2.25	2.04	1.10	-	
10	22.4	100	200	0.5	100	2.33	1.87	1.246	-	
11	81	100	200	0.5	50	3.75	4.24	0.885	-	
12	81	100	200	0.5	70	4.025	4.38	0.919	-	
13	81	100	200	0.5	100	4.438	4.12	1.077	-	

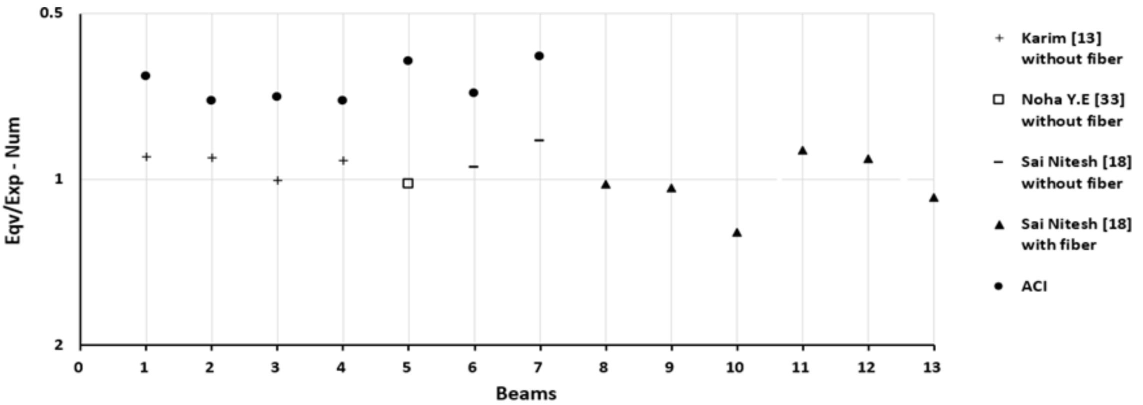

Fig 24 The application of the rational approach on previous studies [13-18-33] for SCC beams with and without steel fiber addition

8. Conclusions

Based on the analytical studies carried out in the present research work, the following conclusions can be drawn:

1. Torsional strength and angle of twist of self-compacting concrete (SCC) beams increase with the increase in concrete compressive strength.
2. Steel fibers effectively improve the mechanical properties, serviceability, and torsional capacity of self-compacting concrete beams.
3. The inclusion of steel fibers in SCC beams significantly enhances the ultimate torsional moment capacity. Specifically, the use of steel fibers with a volume fraction of 2% in self-compacting concrete resulted in a 77.29% increase in the ultimate torsional moment.
4. According to the findings, the addition of steel fibers by a volume fraction ratio of 2% significantly improve the energy absorption and the ductility of SCC beams by 191.02% and 25.8% respectively.
5. A new rational approach has been proposed for the prediction of ultimate torsional moments in self-compacting concrete beams, taking into consideration the addition of steel fibers.
6. A comparison was carried out for the efficacy of the proposed equation with previous studies and results from the parametric study. The results demonstrated good agreement between the results derived from the proposed equation and the experimental outcomes.
7. Furthermore, the results obtained from applying the proposed equation were greater than results from the ACI equation. This discrepancy may be due to the factors of safety considerations and design limits in the codes, which are often conservative in nature to ensure structural safety.

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