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Numerical Analysis of Torsional Reinforcement of Concrete Beams in Unconventional by ANSYS Software

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Abstract

In this study, a finite element analysis is conducted to study the behaviour of RC beams with different configurations of transverse reinforcement under torsion. These configurations of stirrups are traditional closed stirrups, circular spiral stirrups, and inclined rectangular spiral stirrups. The numerical torsional load values are compared with the experimental torsional load values from previous research. The numerical analysis determined by the ANSYS software shows a reasonable agreement with the experimental torsional load values. The numerical results demonstrate that the use of continuous rectangular spiral stirrups improved the torsional response compared to using another type of beam stirrup. Thus, numerical results show that continuous spiral stirrups are effective at increasing torsional capacity. It is also noted that the behaviour of these beams with continuous spiral stirrups is better than the behaviour of the beams with traditional stirrups. The beams with helical reinforcement, which are TB2, TB3, and TB4 spiral reinforcements, greatly enhanced the toughness. The equivalent stresses are 13.709, 13.728, 14.72, and 15.894 MPa, while the equivalent elastic strains are 0.00421, 0.00377, 0.00347, and 0.00539 mm/mm for the beams TB2, TB3, and TB4, respectively. The beam TB4 had the highest stress and strain value, so its strength improved its ductility properties. As a result, the stirrups' configurations enabled the detection of beam failure mechanisms by improving torsional behaviour when compared to the beam's traditional stirrups. As a result, this research adds more knowledge to the literature on the most effective spiral stirrups for transverse reinforcement to improve the torsional behaviour of beams.

Keywords: Finite Element Analysis; RC Beam; Spiral Stirrups; Torsion.

1. Introduction

Concrete in which wire mesh or steel bars are embedded to increase tensile strength is called reinforced concrete (RC). It represents members of engineering structures that must be strengthened, with the existing design requirements checked and upgraded [1–3]. Recently, spiral transverse reinforcement was used to enhance the performance of the structure as a new promising technique. During this time, many researchers used spiral stirrups to study the shear reinforcement of different samples [4–11]. The shear reinforcement in spiral shape improved the effectiveness of the specimens in terms of failure mechanisms, ductility, and loading capacity. Thus, the performance of the structure is enhanced, so automatically the constructability is developed and the cost is lower [12]. In addition, Chalioris & Karayannis [13], and Askandar & Mahmood [14] found that using the spiral configuration as transverse reinforcement significantly improved the performance of torsional beams. Thus, the spiral stirrups used as transverse reinforcement in RC beams are considered a promising technique to improve both the torsional behaviour and the torsional capacity [15].

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For an experimental test, specific control is required in the testing equipment. The control indicates the time needed to prepare samples and conduct the tests, the cost of the test, and the numerical solutions that can offer approximate results of the specimen test that has been done in the previous literature. In general, many researchers used the numerical analysis of the concrete structure that is necessary to validate the experimental data. Furthermore, the results established that the numerical behaviour of strengthened beams was in good agreement with the strengthened beams tested under torsion [16–18]. Meanwhile, Mahmood (2007) analysed the six RC beams under torsion with the ANSYS-V10 software [19]. Moreover, the numerical results were in reasonable agreement with the experimental data. The ANSYS software could accurately predict the behaviour of RC beams and capture the occurrence of cracks in these beams [20]. The FE analysis is recommended due to excellent agreement with experimental tests [12]. The ANSYS software has correctly predicted the diagonal tension, shear, and compression failures as observed in the experimental beams by Thomas & Ramaswamy [22], and Bulut et al. [23]. The FE analysis can provide excellent solutions at a lower modelling cost [24]. With this, many researchers verify the experimental findings compared with the finite element by using the ANSYS program.

Nevertheless, through the previous literature, a few authors have studied the use of spiral reinforcement for beams under torsional loads. Therefore, it is necessary to study this area. While modern building construction continues worldwide with the strengthening of the building structures by steel, ANSYS, one of the software applications applied to collapse prediction, has been used in this paper. It is used to study the efficiency of spiral stirrups for improving the performance of beams under torsion. The FE analysis shows a numerical analysis that provides an explanation for issues that would otherwise be difficult or time-consuming to obtain. The finite element analysis involves three steps: pre-processing, solution, and post-processing [25]. This model effectively predicts the expected performance under the influence of loads. However, it requires good experience with the principles of accurate modelling and the actual representation of the element. This research is carried out with the help of ANSYS software that can predict behavior. This developed model was verified through a comparison with the results documented through a laboratory experiment.

Furthermore, the finite element analysis was done in various parts of the structure that are more detailed [26–28]. The nonlinear finite element analysis was performed to verify the torsional failure collected from the literature as compared to the results of the numerical models with experimental data [29]. Chen et al. showed that damage may occur at the column-end due to the effects of insufficient tie reinforcement and lateral confining, wherein a spiral reinforcement was used to improve the bearing capacity and ductility [30]. Also, there are a limited number of studies that deal with stirrups as an unconventional shape. The importance of this research is the use of stirrups in an uncommonly perfect manner for reinforcing concrete beams subjected to torsional moments by ANSYS software to get clear results of the behaviour of reinforced concrete beams under torque, thereby improving the strength and behaviour of RC beams under torque.

2. Materials and Methods

When the designed engineer needs to know the nonlinear behaviour in reinforced concrete structures, there are two options: the first is based on tests in laboratories (laboratory tests), and the second is a representation and modelling with the help of a computer in the office (structural modeling). Although the first option gives results that reflect realistic reality, the application of this option is limited to special cases of dimensions and sizes. Moreover, there are the shapes, a limited loading model, and ideal dependence conditions. As for the second option, the applications have no limits or restrictions. However, the reliability of the representation and results depends mainly on applying the nonlinear laws of the material's structure, the correctness of building the studied finite element model, and the ability of the program used.

The current study attempts to study the behaviour of specimens with spiral reinforcement configurations under torsion. The finite element analysis software is applied as a methodology using famous engineering applications. According to the experimental results [15], spiral stirrups as transverse reinforcement in RC beams are a promising technique for improving torsional behaviour and capacity. In the 3D finite element analysis method, the unconventional torsional reinforcement behaviour of concrete beams was analyzed analytically using ANSYS Workbench, so it was assumed that there would be a complete correlation between the concrete and steel reinforcement. ANSYS Workbench uses virtual element types and other elements to idealize the contact areas (see Figure 1). Concrete was represented in the program by steel element 65, which is defined as an eight-node homogeneous structural rigid that causes cracking in tension and crushing in compression. As for the armature as a 180-degree coupling, the 3D SPAR may represent the uniaxial stress on the steel element. Steel plates were applied, and those for support were represented by the steel element 185.

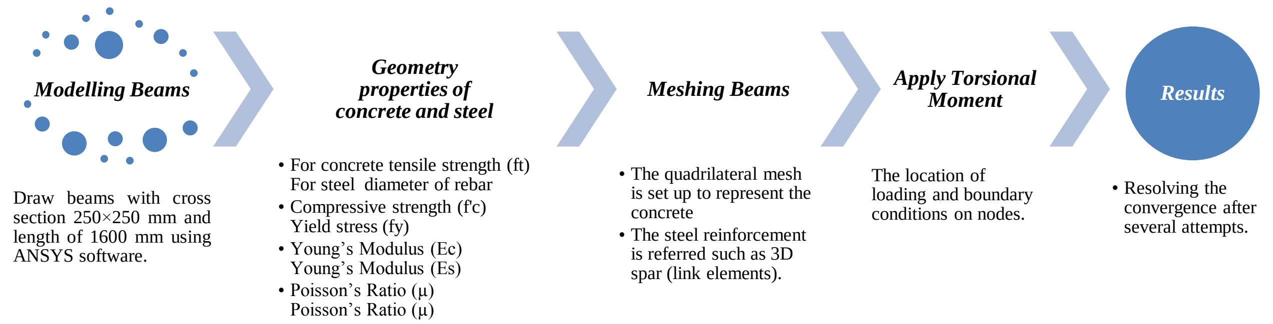


Figure 1. A flowchart that briefly shows the process of the methodology

2.1. Modeling, Meshing and Loading of Specimens

The finite element analysis consisted of four RC beams with a cross section of 250×250 mm and a length of 1600 mm, using the ANSYS scheme. These experimental beams from previous research by Katkhuda et al. [15] had different patterns of transverse reinforcement. The control beam has closed stirrups, while other beams have different patterns of spiral stirrups (see Figure 2). The diameter of the stirrups is 5.5 mm, with a spacing of 200 mm between them. Meanwhile, the four longitudinal steels were kept at the corner, with a diameter of 14 mm for each one. Table 1 shows the geometric properties of all beams.

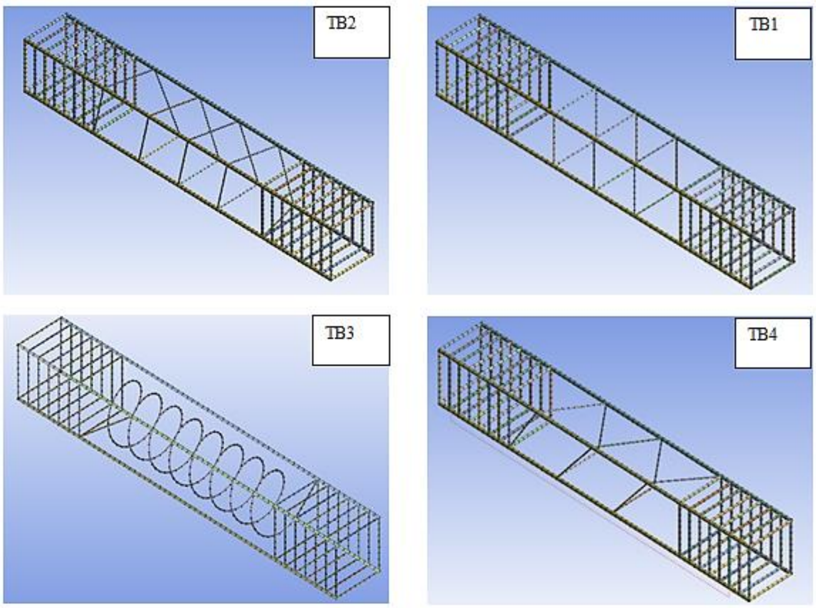


Figure 2. Link elements of stirrups configurations of beams

Table 1. Geometry properties of concrete and steel (Katkhuda et al. 2019 [15])

Concrete		
Tensile Strength (ft)		2.5 (MPa)
Compressive Strength (f'c)		25 (MPa)
Young's Modulus (Ec)		23500 (MPa)
Poisson's Ratio (μ)		0.2
Steel reinforcement		
Stirrup steel	Diameter of rebar	5.5 (mm)
	Yield Stress	394 (MPa)
Longitudinal steel	Diameter of rebar	14 (mm)
	Yield Stress	521 (MPa)
Young's Modulus (Es)		200000 (MPa)
Poisson's Ratio (μ)		0.3

The quadrilateral mesh was set up to represent the concrete (see Figure 3). Meanwhile, the steel reinforcement was referred to as 3D spar (link elements).

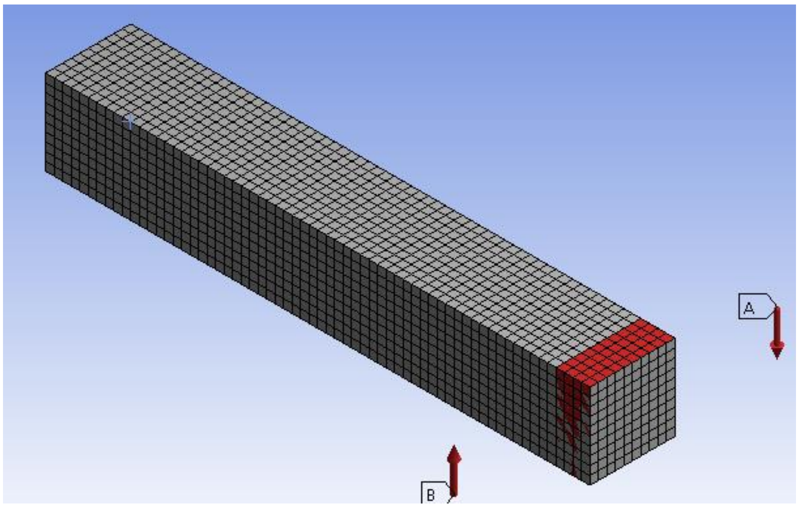


Figure 3. Quadrilateral mesh of specimens

The torsional moment is modelled by the location of the loading and boundary conditions on nodes (see Figure 4). The incremental rate of loading was equal to 0.025 kN [15] and led to convergence after several attempts.

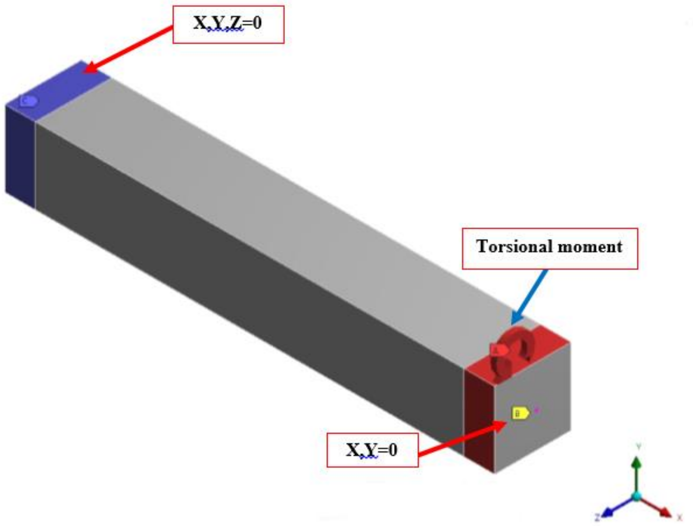


Figure 4. Location of loading and boundary conditions on nodes

3. Test Results

For the purpose of verification using the finite element results, the cracking torque (Tcr) and the ultimate torque (Tu) obtained from the FE analysis were compared with the experimental torque values from the previous literature.

3.1. Effect of Stirrups Configurations on Torsional Behavior

Table 2 illustrates the comparison between the numerical torque and the experimental torque of beams with different stirrup configurations. The finite element Tcr is equal to 9.1, 10.5, 10.5, and 9.1 kN.m for specimens TB1, TB2, TB3 and TB4, respectively. Meanwhile, these torque values are less than the torque values obtained by the experimental results of Katkhuda et al. [15]. This indicates that the finite element analysis has a considerable occurrence of the first cracking and the determination cracking torque from the experimental test. Meanwhile, the FE ultimate torque values were higher than the experimental ultimate torque values. Hence, the FE ultimate torque (Tu) was equal to 12.3, 15.6, 15.8 and 14.1 kN.m for specimens TB1, TB2, TB3 and TB4, respectively. This means that the FE result has more stiffness as compared to the experimental result because in the FE analysis, there is evidence of the perfect bonding between the concrete and steel reinforcement.

Table 2. Comparison between FE and experimental results of Katkhuda et al. [15]

No.	Beam	Cracking torque		Ultimate torque		Difference	
		Tcr EXP (kN.m)	Tcr ANS (kN.m)	Tu EXP (kN.m)	Tu ANS (kN.m)	Tcr EXP / Tcr ANS	Tu EXP /mTu ANS
1	TB1	10.9	9.1	12.6	13.2	1.198	0.955
2	TB2	13.7	10.5	14.7	15.6	1.305	0.942
3	TB3	13.8	10.5	15.6	15.8	1.314	0.987
4	TB4	13	9.1	13.8	14.1	1.429	0.979
				Mean		**1.311**	**0.966**
				Standard deviation		**0.094**	**0.021**

In general, there is a good match in the maximum torsional values between the experimental specimens and FE analysis for different stirrup patterns (see Figures 5 and 6). Nevertheless, it also reveals the improvement in the maximum torsional capacity of the beams after using the inclined spiral as transverse reinforcement. Therefore, the amount of increase is proportional to the pattern of spiral stirrups used. Considering the finite element results, the torsional behaviour for the RC beams with continuous spiral stirrups is enhanced as compared with the RC beam with rectangular traditional stirrups. Furthermore, the torsional strength of the RC beam with spiral stirrups is the best with respect to the same RC beam with traditional rectangular stirrups.

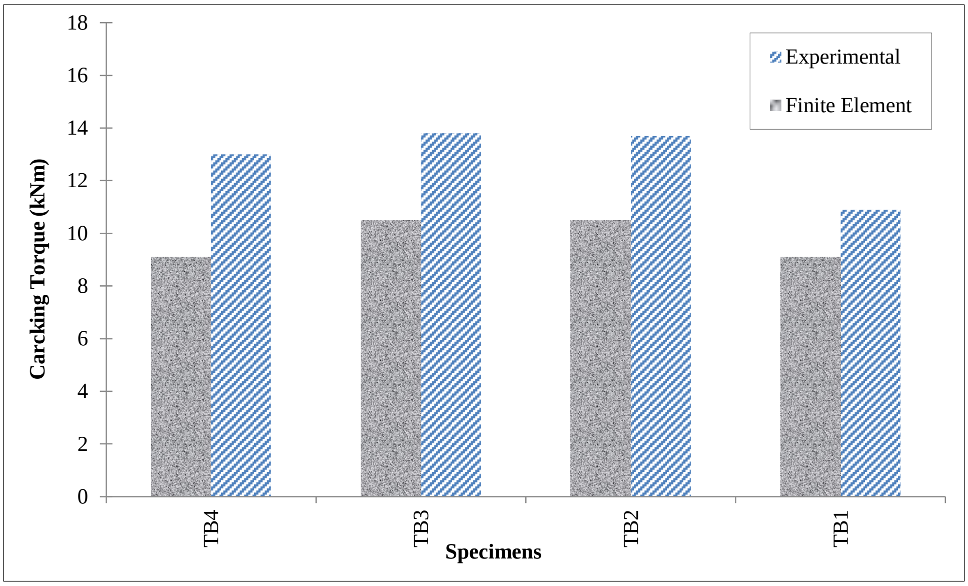


Figure 5. Finite element cracking torque compared to experimental cracking torque

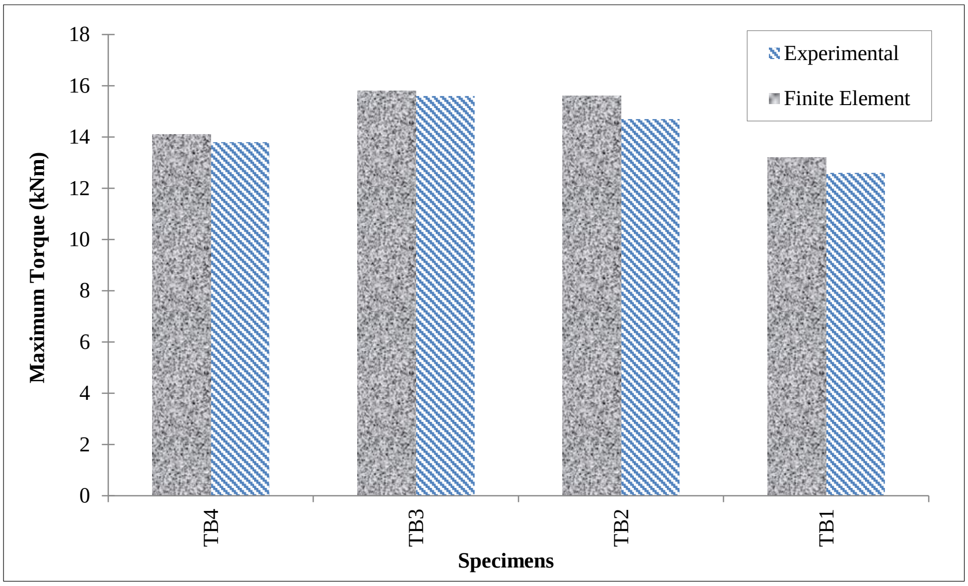


Figure 6. Finite element maximum torque compared to experimental maximum torque

The torsional moment for beams with different styles of spiral stirrups is compared to the same beam with rectangular closed stirrups. For better visualisation and understanding, the effect of the stirrup configurations on torsional stiffness and approximate toughness has been studied. The FE results indicated that the beams with helical reinforcement have the highest torsional stiffness (see Figure 7). Meanwhile, the finite element toughness explained the torsional behaviour under the cracking area. Beams, particularly TB2 and TB3 spiral reinforcement, significantly improved toughness. Figure 8 takes note of the approximate toughness that it calculated for different patterns of beam stirrups subject to torsion.

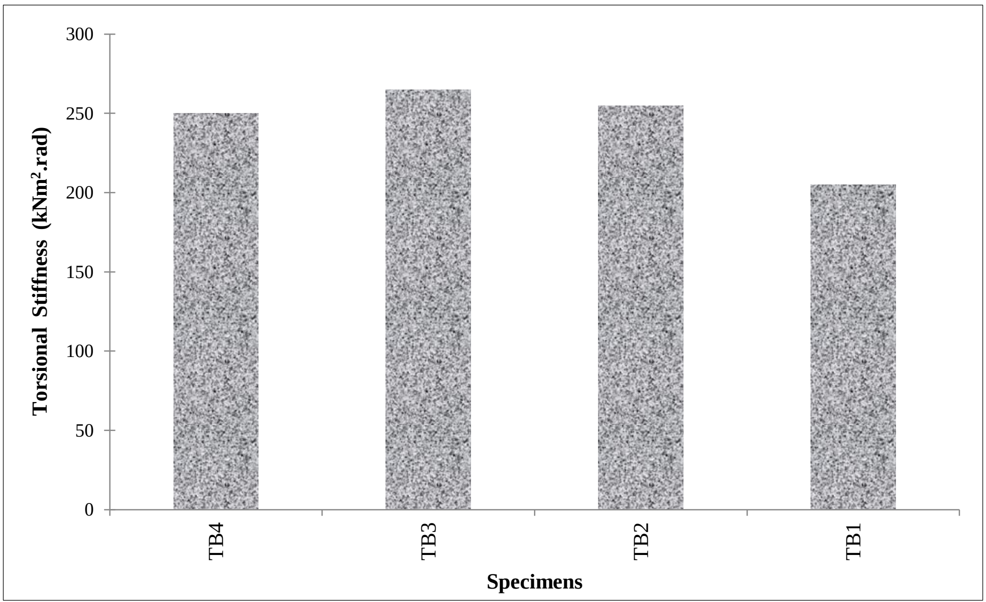


Figure 7. Finite element torsional stiffness of specimens with different styles stirrups

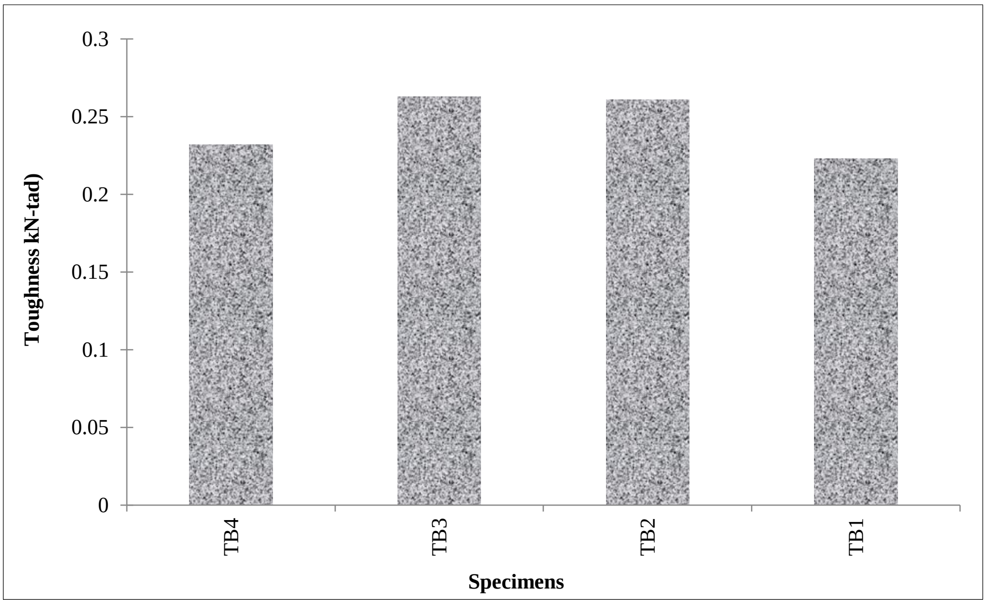
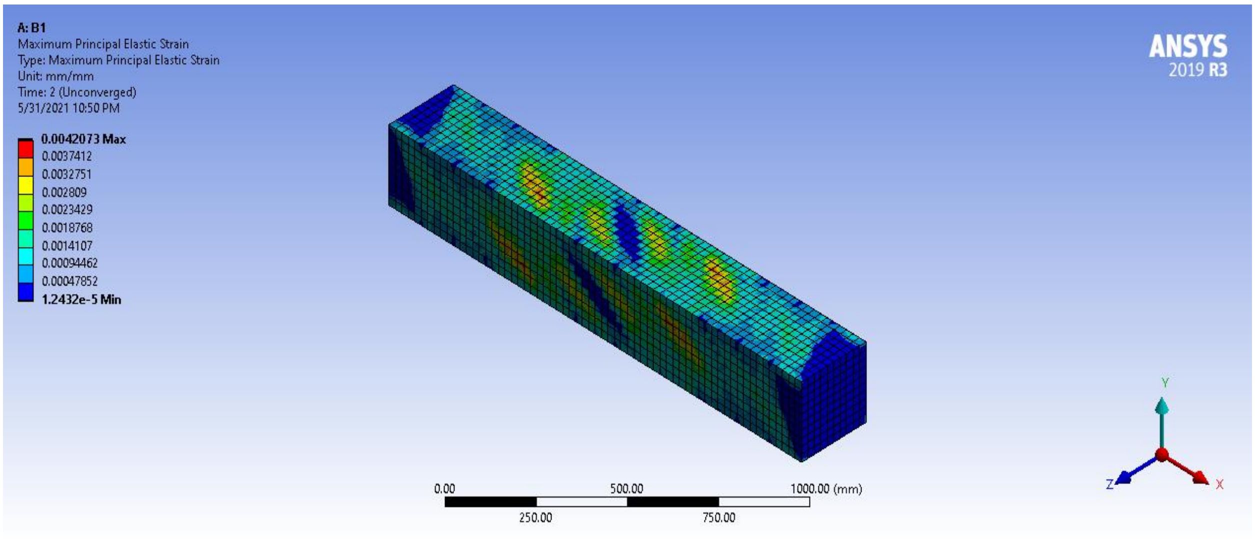
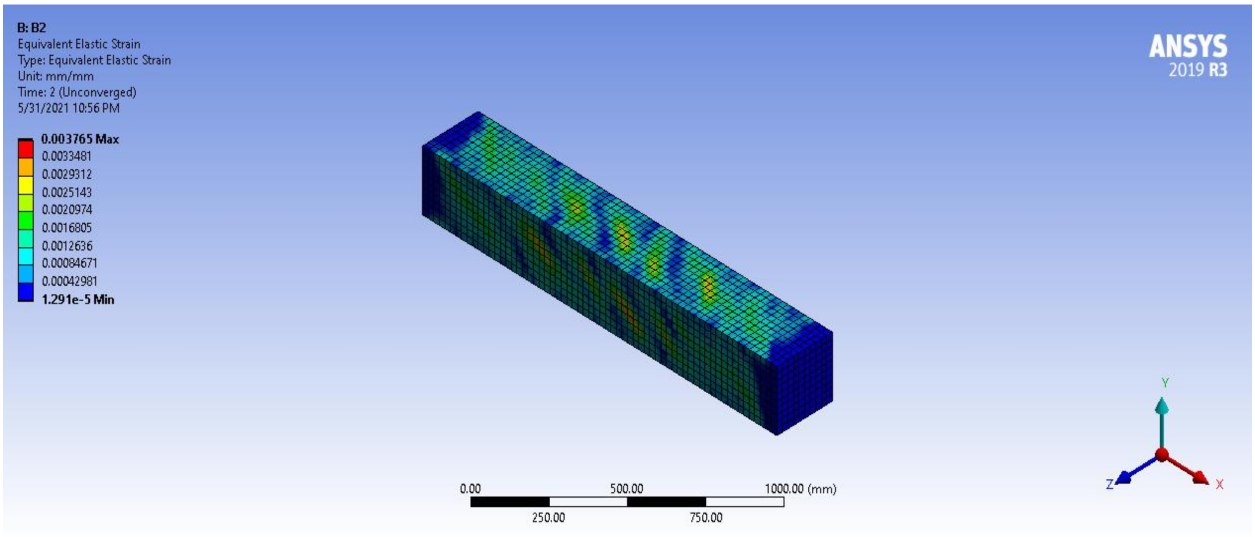


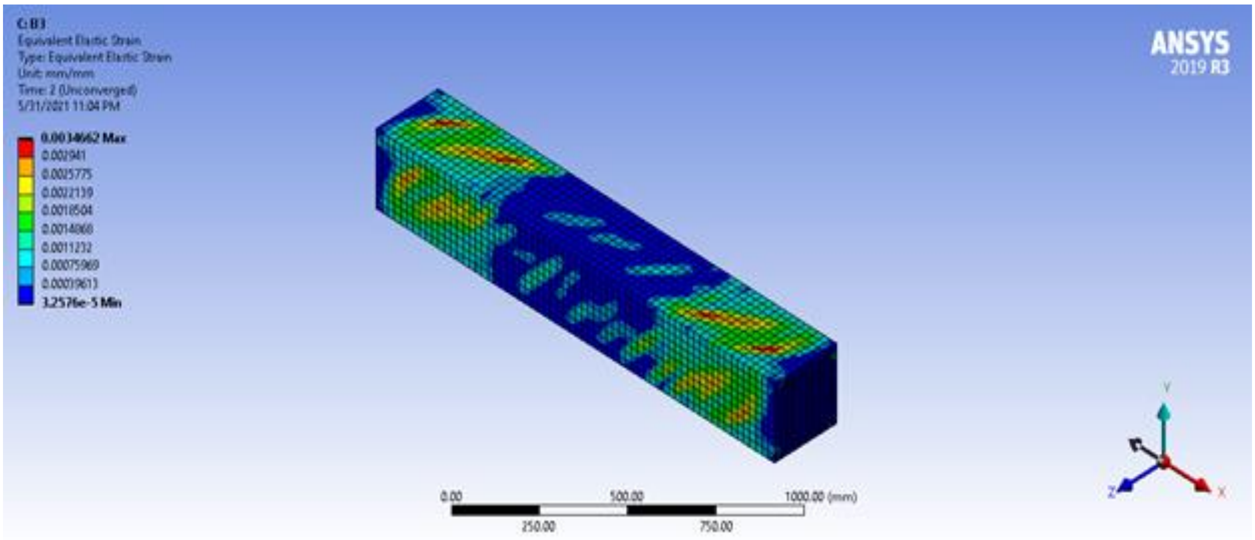
Figure 8. Finite element approximate toughness of specimens with different styles stirrup

3.2. Finite Element Results

FE results indicate that the specimen's failure was a torsional failure. The idea of the crack pattern on beams is that the initial cracking could be observed on the concrete, then a sudden increase in the number of cracks was observed until the peak torque. The beginning of the loading showed no cracks. The first crack was then discovered to be cracking diagonally in the concrete. Because of this, the principal stress has been distributed as diagonal tension and compression in a specimen. The new crack lines occurred in parallel with the first crack track. Finally, at the ultimate load, the spiral cracking was around the specimen. It is observed that the numerical analysis gives detailed results for the beams with different components. Figures 9 and 10 show the higher value and the lower value equivalent to the elastic strain and equivalent stress (von Mises), respectively. It was noted from the numerical results that the equivalent elastic strain is 0.00421, 0.00377, 0.00347, and 0.00539 mm/mm, whereas the equivalent stress (von-Mises) is 13.709, 13.728, 14.72, and 15.894 MPa for beams TB1, TB2, TB3, and TB4, respectively. It is found that the highest stress and strain values were observed for beam TB4, which means that its ductility properties and its strength have improved. Additionally, the stirrup configurations have limited the failure mechanisms of beams, so the torsional behaviour of beams is better as compared to that of conventional stirrups.







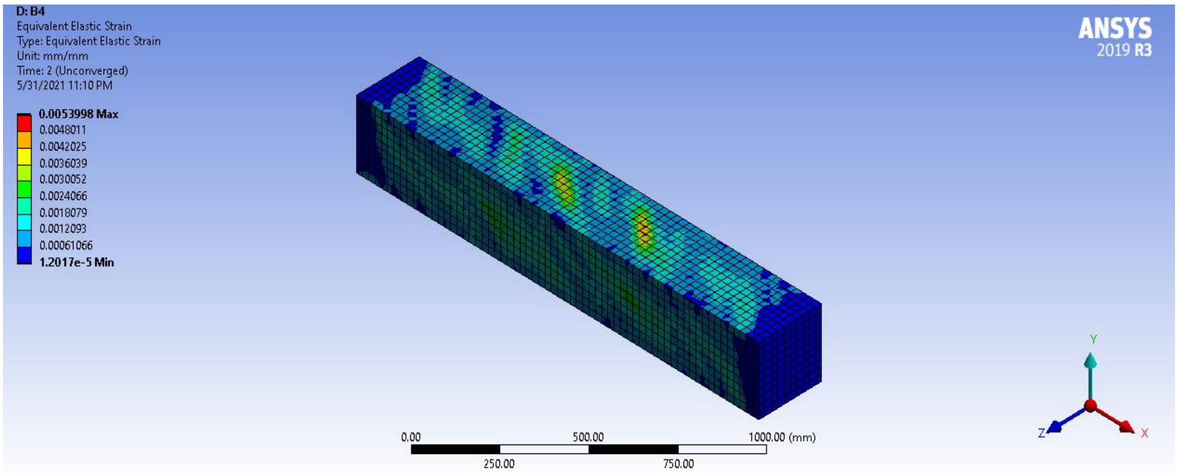
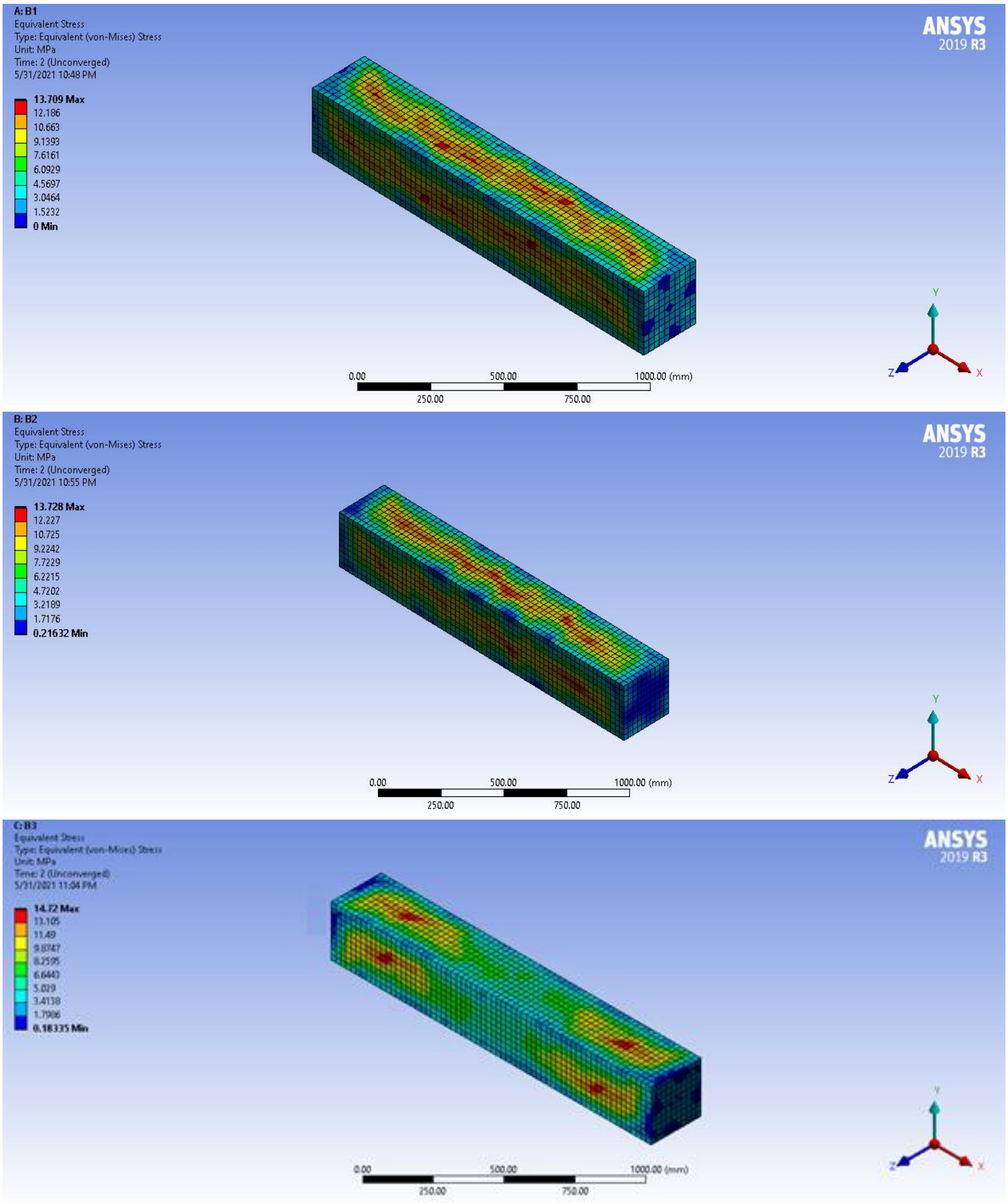


Figure 9. Equivalent elastic strain of beams



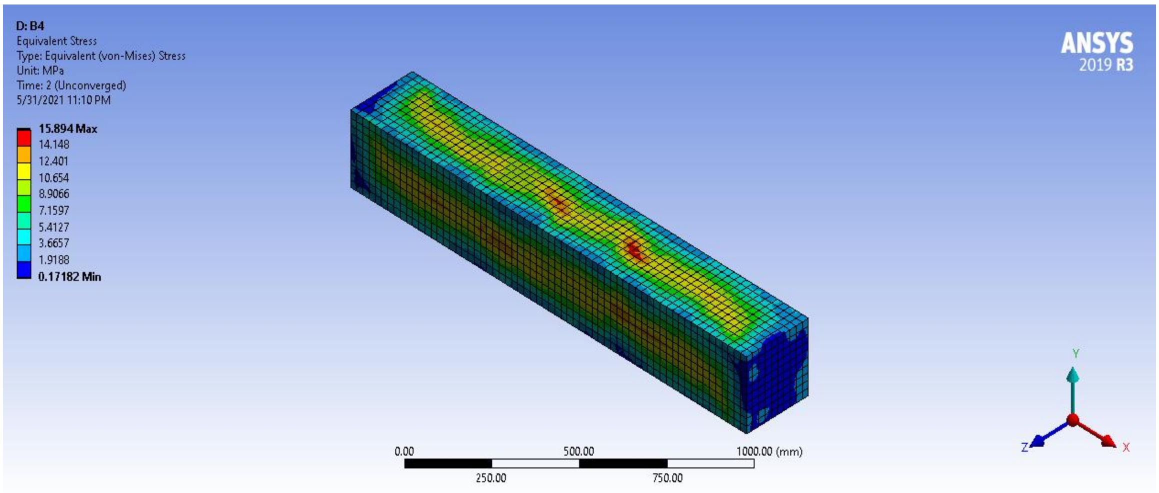


Figure 10. Equivalent stress (von -Mises) of beams

4. Conclusion

In this research, the results were obtained using ANSYS software to analyse RC beams for the experimental test done in previous research. Then, the effectiveness of these beams was discussed with different styles of helical reinforcement as a promising technique before it was compared with the well-established conventional stirrups. In sum, the torsional moment of the beams with helical stirrups is higher than that of closed stirrups. In addition, the helical reinforcement shows a higher torsional moment for TB2 and TB3 beams, while the TB4 beam has a lower torsional moment among the various styles of helical reinforcement. For specimens TB1, TB2, TB3, and TB4, the FE cracking torque (Tcr) is 9.1, 10.5, 10.5, and 9.1 kN.m, while the FE ultimate torque (Tu) is 12.3, 15.6, 15.8, and 14.1 kN.m. As a result, the maximum torsional capacity of the beams after using the inclined spiral as transverse reinforcement was enhanced. The spiral reinforcement enhanced the torsional stiffness and approximate toughness of the beams. The equivalent stresses (von Mises) are 13.709, 13.728, 14.72, and 15.894 MPa for beams TB1, TB2, TB3, and TB4, respectively. The high values of equivalent stress lead to the improved ductility properties of these beams compared with the control beam. Meanwhile, beam TB4 had the highest stress and strain value, so it improved its ductility properties along with its strength. Finally, the stirrup configurations are important to limit the types of failure mechanisms for beams under torsion. Generally, this paper adds to the knowledge in the literature; the most effective torsional behaviour of beams is achieved by using helical stirrups as the transverse reinforcement.

5. Declarations

5.1. Author Contributions

Conceptualization, T.J.M., K.M.B. and A.F.H.; methodology, T.J.M., K.M.B. and A.F.H.; validation, T.J.M. and K.M.B. ; formal analysis, T.J.M. and K.M.B.; investigation, T.J.M., K.M.B. and A.F.H.; resources, T.J.M., K.M.B. and A.F.H.; data curation, T.J.M., K.M.B. and A.F.H.; writing—original draft preparation, T.J.M. and K.M.B.; writing—review and editing, T.J.M. and K.M.B.; visualization, T.J.M., K.M.B. and A.F.H.; supervision, T.J.M., and K.M.B.; project administration, T.J.M., K.M.B. and A.F.H.; funding acquisition, T.J.M., K.M.B. and AF.H. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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