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NUMERICAL INVESTIGATION OF TORSIONAL BEHAVIOUR OF REINFORCED CONCRETE ELEMENTS WITH DIFFERENT SECTION SHAPES

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Highlights

- When the design codes are examined, it is seen that the reinforced concrete design under the effect of torsion is not sufficiently emphasized.
- Reinforced concrete elements with circular, square and rectangular cross-section shapes were modeled in accordance with the cross-section and reinforcement conditions specified in TEC-2007.
- The finite element model of the elements was created in ANSYS program.
- Torsional moment-curvature relationships, torsional capacities, and moment curvature graphs were obtained and used to determine the torsional stiffness of reinforced concrete elements based on the slope of these graphs.

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ABSTRACT: When torsional cracks occur in the RC element as a result of torsion effects occurring in the structure, the cross-section stiffness decreases by 1/10-1/30 of the stiffness before cracking. When the design codes are examined, it is seen that the reinforced concrete design under the effect of torsion is not sufficiently emphasized. In the study, it is aimed to determine the cross-sectional properties of reinforced concrete elements that will be exposed to torsion effects in accordance with the behavior of the RC element.

In this study, reinforced concrete elements with circular, square and rectangular cross-section shapes were modeled in accordance with the cross-section and reinforcement conditions specified in TEC-2007 and analyzed by ANSYS program. The torsional capacities of the elements increase as the cross-sectional area increases. Circular sections exhibit a highly ductile behavior in terms of rotation. Rectangular sections have more stiffness than circular and square sections to torsion.

Keywords: *ANSYS, Numerical Study, Reinforced Concrete, Torsion, Section, Structural Element*

1. INTRODUCTION

The majority of buildings in Turkey are constructed using reinforced concrete. Most of the existing building stock was built according to outdated codes, without engineering services, and without proper project management and quality control, resulting in irregularities [1]. Torsional effects occur, particularly in structures with plan irregularities, due to the eccentricity between the mass and the center of rigidity during an earthquake [2]. Under the effect of torsional moment, principal tensile stresses occur on both sides of the section, resulting in the formation of shear cracks [3]. The effect of damage on the structure is greater than that of bending due to the compliance caused by shear cracks occurring throughout the entire cross-section as a result of torsion[4]. The research findings indicate that the stiffness of the cross-section decreases by approximately 1/10-1/30 of its original stiffness upon the formation of shear cracks [1, 5, 6].

In structural elements subjected to torsional effects, the torsional moment varies depending on the magnitude of the earthquake force, material properties, cross-sectional size, and position and shape of the structural element in the structure [3, 7-9]. Furthermore, when torsion occurs in non-circular sections, the behaviour of the reinforced concrete member becomes more complex. This is due to the deviation of the member from the plane of the bar, the occurrence of 'section distortion' and sudden and brittle damage to the section. Circular sections remain as planes and circles without any distortion effects after torsion [6] (Figure 1). Evaluating the moment effect is crucial as it significantly alters and complicates the behaviour of the element, depending on changes in section shapes and dimensions. Additionally, it is important to consider torsion effects when designing reinforced concrete elements.

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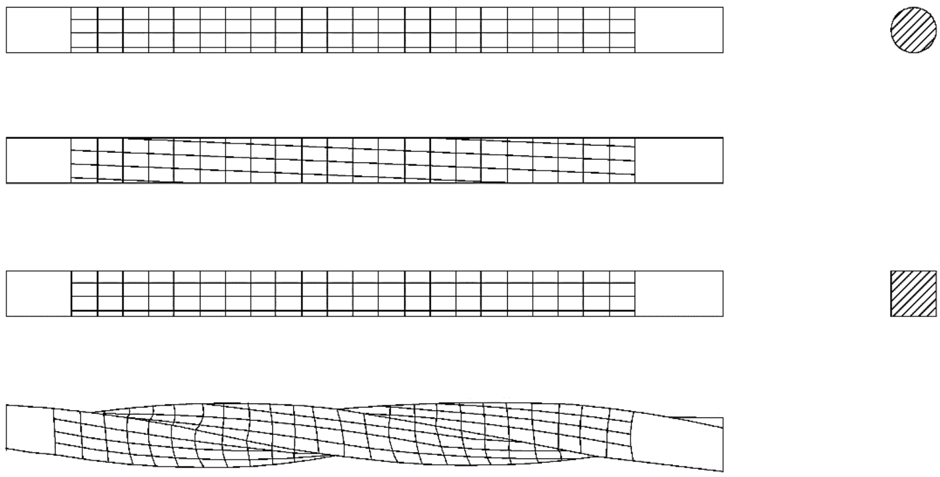

Figure 1. Section distortion [10]

Numerous experimental and numerical studies have been conducted in the literature on pure torsion in columns and beams [11-19]. Researches has shown that stress in the transverse reinforcement increases as the b/h ratio changes in the beam section [20-22][15]. If the cross-sectional area remains constant but the cross-sectional edge dimensions change, the torsional capacity is not significantly affected [15]. Increasing the shear reinforcement in rectangular sections enhances the torsional strength, irrespective of the section properties. After the formation of the first torsional crack, hollow section rectangular beams demonstrated higher torsional strength than solid section beams in pure torsion [17]. The torsional stiffness of L-shaped beams increases with the size of their projections in the cross-section [16]. For circular section elements, the torsional capacity and rotational ductility of the section decrease as the element length increases [22]. Furthermore, the torsional capacity of the section decreases as the spacing of the spiral reinforcement increases [21]. Previous studies have investigated the capacities of members subjected to torsion both experimentally and numerically. It is important to consider the cross-sectional properties of such members in detail.

The objective of this study is to examine the impact of section properties and shapes on the torsional behaviour of reinforced concrete members. The investigation will ascertain how the stiffness and behaviour of these elements change when subjected to torsion. The aim is to determine the section shape more readily for the sections that are expected to be subjected to torsion in design.

2. MATERIAL AND METHODS

This study investigates the effects of section shapes, dimensions, and concrete cover thickness on torsional behaviour. All sections are assumed to be subjected to torsional moment only and anchored at one end. Figure 2 shows that all members were tested under 0.35 radians of rotation. The torsional capacities and rotational ductility of the sections were analysed.

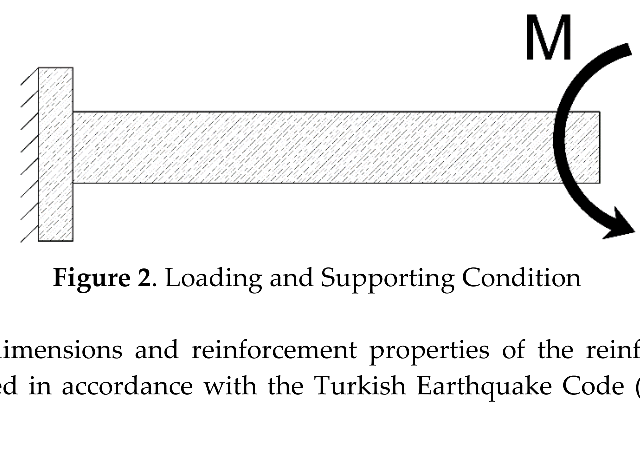

Figure 2. Loading and Supporting Condition

The cross-sectional dimensions and reinforcement properties of the reinforced concrete elements analysed were determined in accordance with the Turkish Earthquake Code (TEC-2007)[23]. This was done to represent structures built in previous years and to enable comparison with existing literature [24]. The code specifies a minimum width of 250 mm for high ductility beams and columns. For elements with circular cross-section, the regulation determines a minimum column diameter of 300 mm. The longitudinal reinforcement ratio in all sections was chosen to be greater than 1%. To compare the torsional behaviour, sections of different shapes with similar reinforcement ratio and arrangement will be used in all elements. Table 1 presents the cross-sectional properties and reinforcement ratios of all specimens analysed in the study.

Table 1. Section and reinforcement properties of reinforced concrete elements analysed in the study

Section Shape	Specimen	Section Dimensions (mm)	Longitudinal Reinforcement	Stirrup Spacing	b/h ratio	Concrete Cover (d')(mm)
	C25-B	Φ250			1	25
	C30-A	Φ300			1	20
	C30-B	Φ300			1	25
Circular	C30-C	Φ300	6Φ14	Φ8/100	1	30
	C30-D	Φ300			1	35
	C35-B	Φ350			1	25
	C40-B	Φ400			1	25
	S25-B	250x250			1	25
	S30-A	300x300			1	20
Square	S30-B	300x300	6Φ14	Φ8/100	1	25
	S30-C	300x300			1	30
	S30-D	300x300			1	35
	S40-B	400x400			1	25
	R25-30-B	250X300			1.2	25
Rectangular	R25-40-B	250X400	6Φ14	Φ8/100	1.6	25
	R25-50-B	250X500			2	25

C: Circular, **S**: Square, **R**: Rectangle
A: 20 mm stirrup spacing, **B**: 25 mm stirrup spacing, **C**: 30 mm stirrup spacing, **D**: 40 mm stirrup spacing

The LINK180 material model is used to reinforce the finite element model. For concrete, the SOLID65 element is employed, which has eight nodes with three degrees of freedom at each node, including translations in the x, y, and z directions. This model element is also capable of exhibiting cracking behaviour in three vertical directions and plastic deformation by crushing, as illustrated in Figure 3 [25]

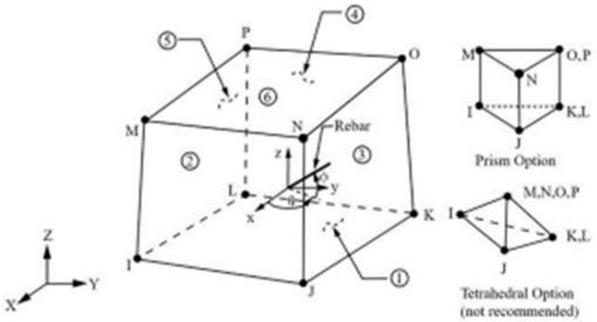

Figure 3. SOLID65 geometry [25]

The concrete compressive strength results used in the numerical analysis modelling were selected as C25/30, a value commonly found in literature. The yield strength of the reinforcement was taken as 379 MPa for stirrups and 409 MPa for longitudinal reinforcement, in accordance with a previous study [21]. The Hognestad model (Formula 1) was used to define the concrete model, based on the multilinear isotropic stress-strain curve and modulus of elasticity [26]. Figure 4 shows the stress-strain graph obtained from the formula.

$$\sigma_c = f_c\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \tag{1}$$

Poisson's ratio was assumed to be 0.2 for concrete and 0.3 for reinforcement. The structural model used for the crack analysis was 'Structural model for triaxial behaviour of concrete'. The model suggests that the open crack shear transfer coefficient is 0.3, the closed crack shear transfer coefficient is 1.0, and the uniaxial crushing coefficient is 1.0 [20, 27, 28].

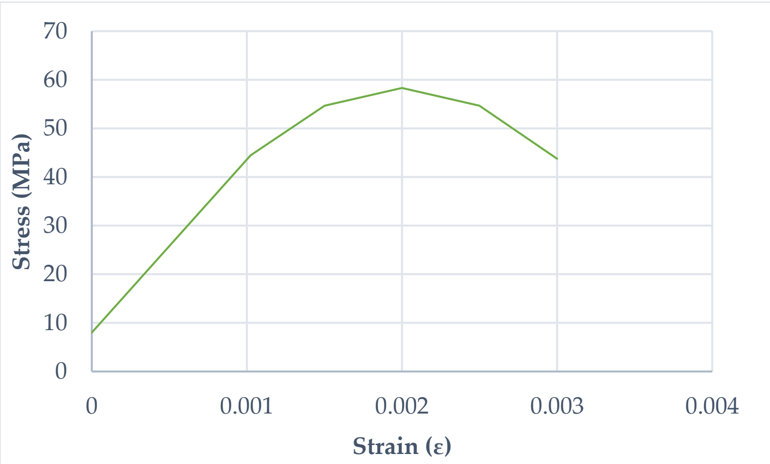

Figure 4. Stress-Strain graph for concrete

To verify the analyses and determine the appropriate mesh sizes, we modelled a reinforced concrete model with a circular cross-section and a diameter of 250 mm, following Soley's study [21]. The appropriate mesh spacing was determined by verifying the moment curvature relationship with experimental results. [18, 21].

In all models, the mesh dimensions and analysis properties were verified to be compatible with the experimental studies in the literature [18, 21] (Figure 5). The moment effect on the sections was investigated in all elements by controlling the rotation until a rotation angle of 0.35 rad was reached at the end. The rotation value was determined based on the maximum rotation angles found in similar cross-sectional elements in the literature [29].

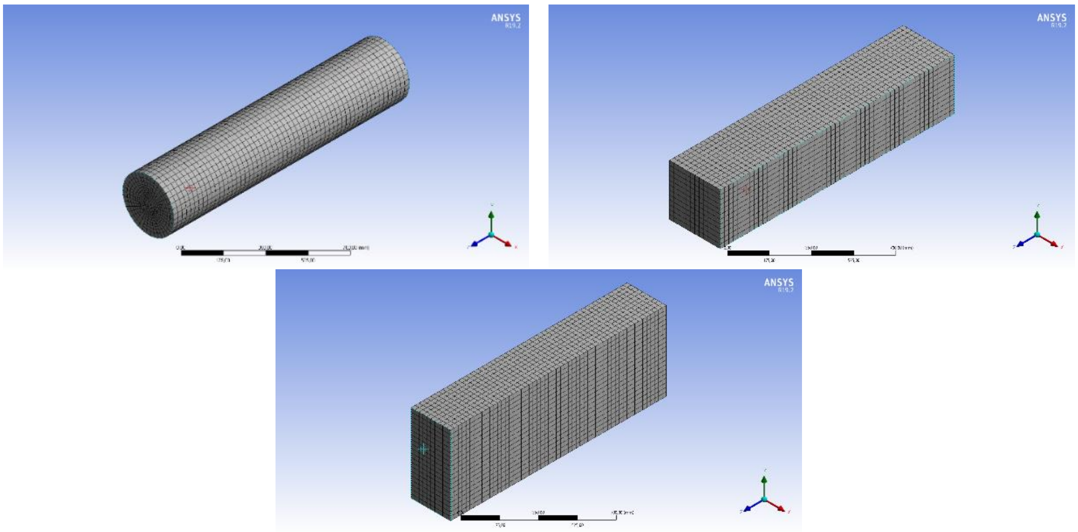

Figure 5. Reinforced Concrete Element specimens and mesh models

3. RESULTS AND DISCUSSION

This study investigates the analytical effect of changing section shapes and properties on the torsional moment capacity of reinforced concrete elements. Finite element analysis was used in ANSYS software to analyse circular, square, and rectangular sections. Torsional moment-curvature relationships, torsional capacities, and moment curvature graphs were obtained and used to determine the torsional stiffness of reinforced concrete elements based on the slope of these graphs. The moment and rotation values obtained from the specimens are given in Table 2. The study analysed stress and strain conditions that depend on changes in section dimensions, concrete cover thickness, b/h ratio, and section shapes. Figure 6 shows the shear stress distributions that occur in circular, square, and rectangular sections under torsion.

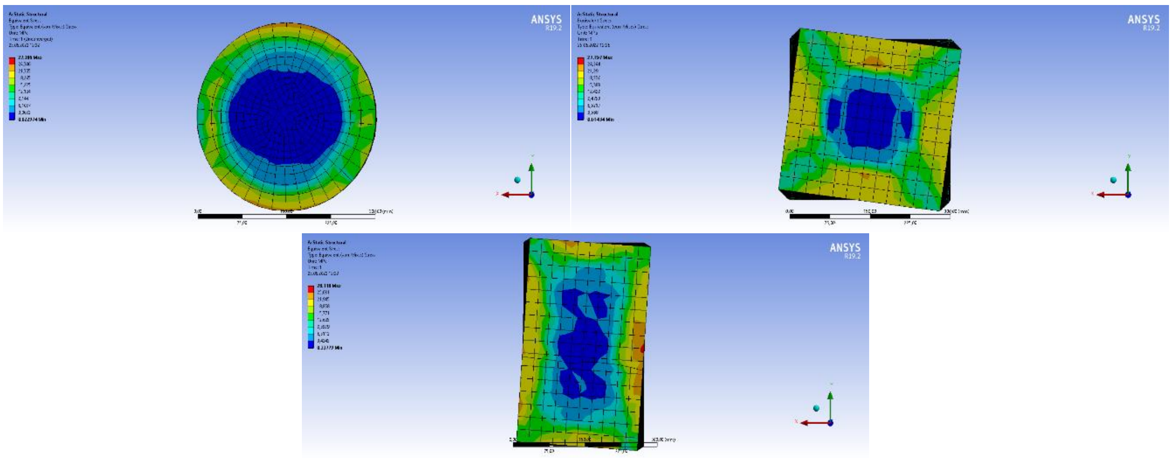

Figure 6. Stress Condition in Sections

In circular sections, the stresses are homogeneously distributed across the section and there is a large area of no stress in the center of the section. In square and rectangular sections, this area is smaller. In square and rectangular sections, it is observed that the stresses are concentrated near the edges and the stress increases as the edge length increases. As a result of the torsional effect in the circular section, the section remained on the same axis, whereas in the non-circular sections distortion occurred (Figure 7).

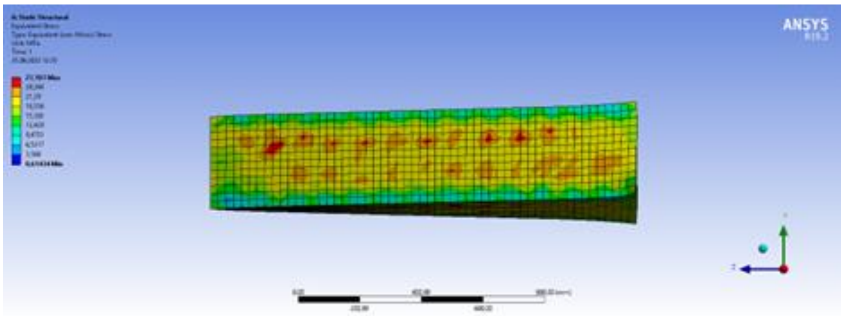

Figure 7. Warping in Non-Circular Sections

When analysing the torsional moment-curvature relationship of circular sections of different diameters, it can be seen that the section size has a large effect on the torsional capacity. As the cross-sectional area increases, the torsional moment that can be supported increases. When the circular section area is doubled, the torsional capacity in the section increases by approximately 2.25 to 2.50 times. In all sections, the reinforcement reaches its yield point at a curvature of approximately 0.5 rad/m. As the cross-sectional area increases, the rotational ductility of the element decreases. The torsional stiffness increases with increasing cross-sectional area (Figure 8).

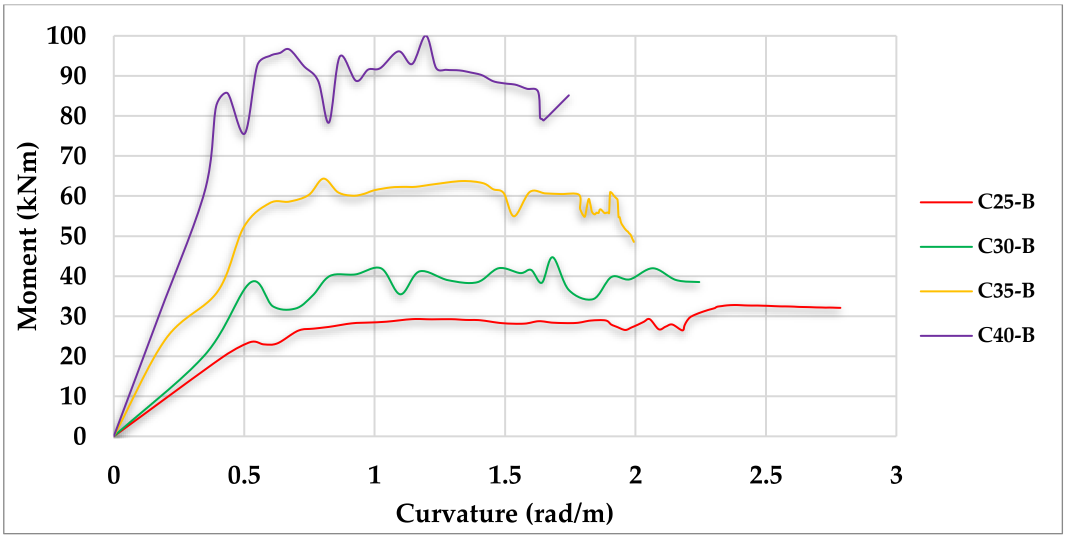

Figure 8. Moment-Curvature Relationship of Circular Sections

When analysing the torsional effects occurring in square sections, similar effects are observed with circular sections. As the cross-sectional area increases, the torsional capacity increases. However, unlike the circular sections, the flow of reinforcement in the square sections occurred at different angles of rotation. In the 250 mm side length section, yielding occurred at approximately 0.4 rad/m curvature, in the 300 mm side length section at 0.3 rad/m curvature and in the mm side length section at 0.12 rad/m curvature. As the dimensions of the sections increased, the rotational ductility decreased and the torsional stiffness increased significantly (Figure 9).

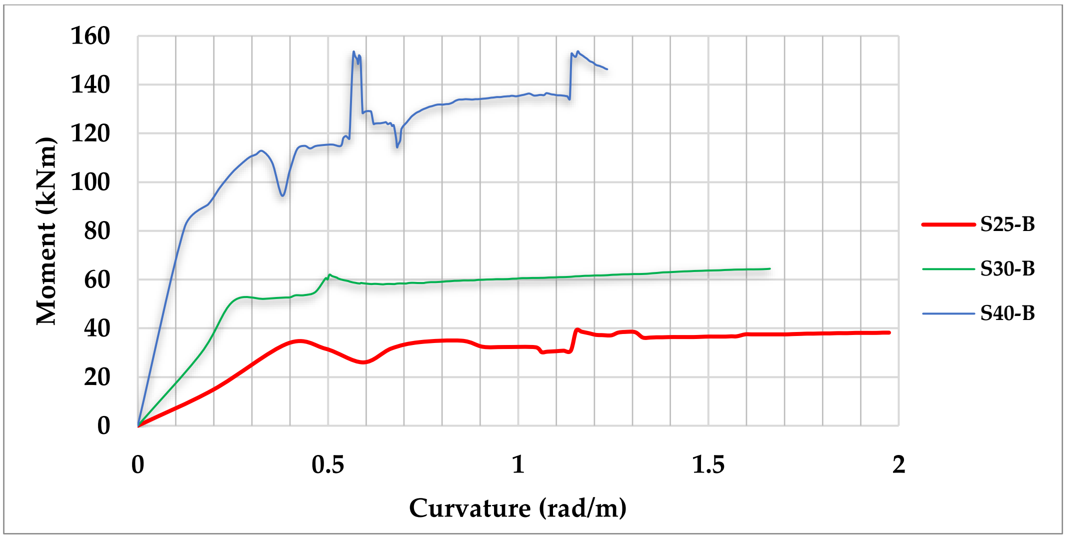

Figure 9. Moment-Curvature Relationship of Square Sections

The other parameter analysed in the models is the concrete cover thickness of the section. The letters A, B, C, D refer to the concrete cover of 20 mm, 25 mm, 30 mm and 35 mm respectively. Accordingly, when examining the results obtained from the models with the same cross-sectional dimensions in circular and square sections, it is clear that changing the concrete cover in circular sections has no noticeable effect on the torsional behaviour. For square sections, the angle of twist up to the point where yielding occurs after the elastic limit increases as the concrete cover are increased (Figure 10).

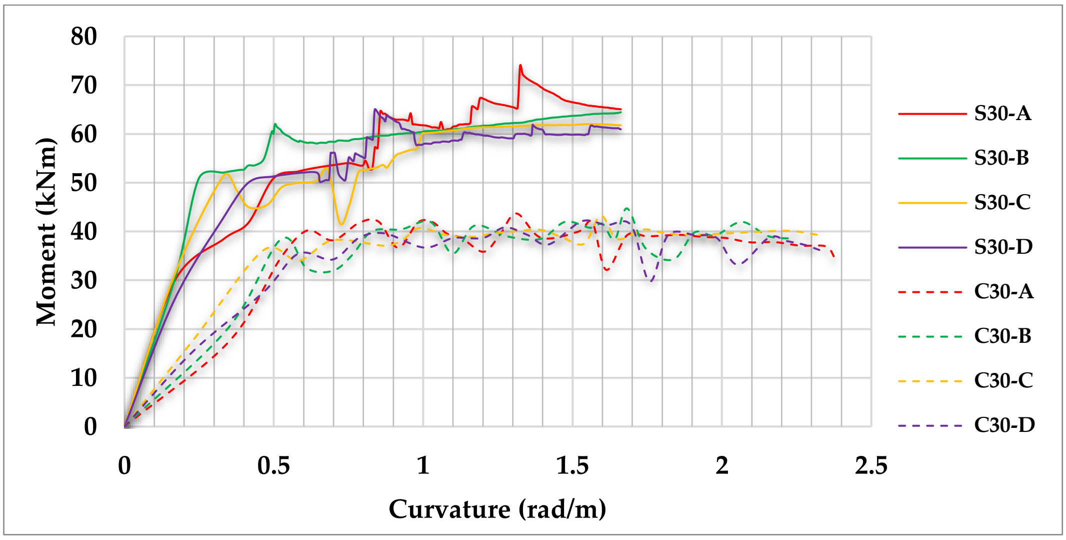

Figure 10. Moment-Curvature Relationship for Different Concrete Cover Thicknesses

The torsional moment and curvature curves of reinforced concrete elements are analysed with the variation of the b/h ratio, which is expressed as the ratio of the length of one side of the section to the other side. As the b/h ratio in the cross-section increases, the cross-sectional area increases and the torsional capacity increases accordingly by up to 3 times. However, as the b/h ratio increases, the sections start to move away from the circular state and larger shear stresses occur on the long sides. The rotational ductility of the sections decreases by more than 50% as the edge length increases (Figure 11).

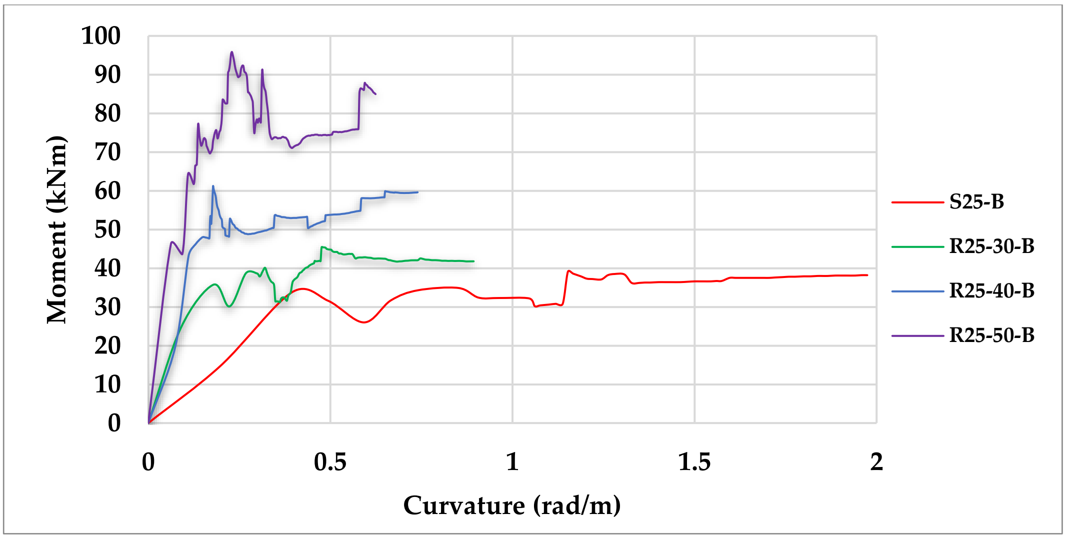

Figure 11. Moment-Curvature Relationship of sections with different b/h ratio

This study investigated the torsional effects of circular, square and rectangular sections with similar properties and similar cross-sectional areas. The reinforcement ratio of the sections was chosen to be same and the aim was to investigate only the effect of section shape on torsional behaviour. When analysing the torsional moment values at which yielding occurs in the sections, the circular section reaches the yield point at larger torsional values. However, the torsional stiffness of the rectangular section is higher than that of the circular and square sections. In addition, it can be seen that the rotational ductility of rectangular sections is lower than that of circular and square sections due to the effect of distortion occurring in the section (Figure 12).

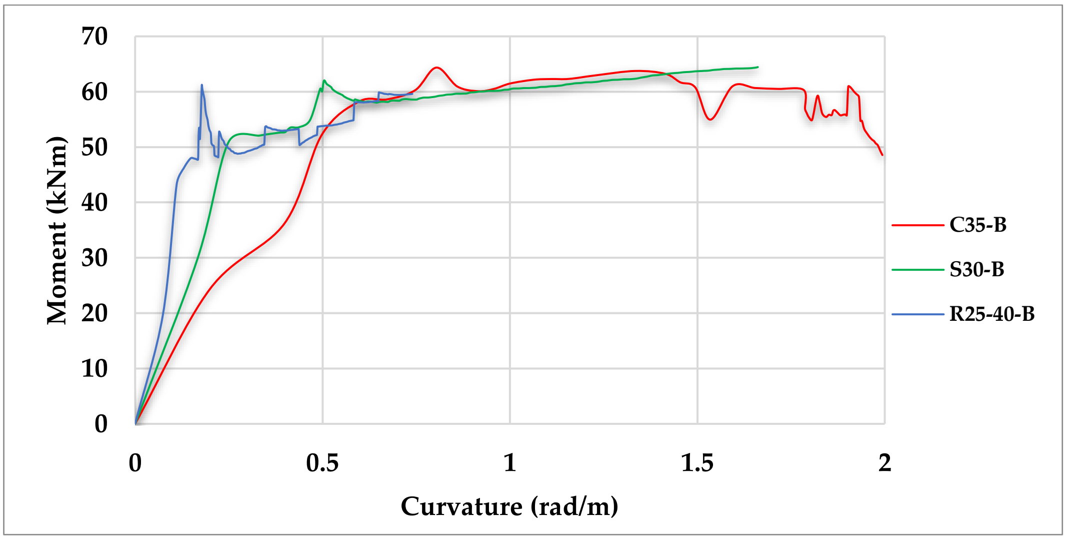

Figure 12. Moment-Curvature Comparison of Different Shaped Sections

Table 2. Moment and rotation values obtained from specimens

Specimen	Yielding Moment (kNm)	Max Moment (kNm)	Yield Rotation (rad)	Max Rotation (rad)	Ductility Ratio (μ)
C25-B	23.52	27.92	0.052	0.23	4.34
C30-A	40.17	41.87	0.091	0.234	4.64
C30-B	38.38	44.72	0.078	0.252	4.77
C30-C	36.14	37.48	0.069	0.231	5.56
C30-D	35.42	41.26	0.087	0.254	4.46
C35-B	58.24	64.35	0.104	0.268	4.23
C40-B	85.68	100.07	0.087	0.327	4.43
S25-B	33.8	38.60	0.069	0.35	5.79
S30-A	38.44	73.93	0.068	0.278	5.03
S30-B	50.89	61.38	0.052	0.348	7.54
S30-C	51.47	60.11	0.069	0.35	5.93
S30-D	50.03	63.87	0.087	0.35	4.25
S40-B	90.86	136.17	0.052	0.31	5.85
R25-30-B	35.73	45.38	0.069	0.35	5.56
R25-40-B	46.15	60.49	0.061	0.348	1.83
R25-50-B	61.32	94.45	0.062	0.167	2.30

The torsional ductility index of the elements analysed in this study is in the range of 2.0-7.0. In the experimental studies in the literature, it is observed that the torsional ductility index varies in the range of 1.0-5.0 [30]. In the existing literature, it is recommended that the minimum required ductility for beams made of normal strength concrete should be 3.32 [31]. It is thus concluded that all specimens, with the exception of R25-40-B and R25-50-B, can be considered ductile. While the theoretical ductility of columns with square cross-sections is greater, their behaviour is unstable due to the warping effect.

4. CONCLUSIONS

As a result of this study, the effect of the geometrical shape and properties of the section on the torsional behaviour was determined. Results of the study are shown below.

- The torsional capacity increases with increasing cross-sectional area for sections with the same reinforcement ratio and arrangement regardless of their shape. However, there is a decrease in rotational ductility.
- For circular sections, the yield strength of the reinforcement does not change with increasing diameter of the section in torsion.
- The effect of the concrete cover used in reinforced concrete elements on the torsional behaviour is negligible.
- The torsional strength and stiffness increase as the b/h ratio in the section increases.
- Larger warping effects are observed in the sections as the b/h ratio increases. The rotational ductility of the sections decreases significantly with increasing side length.
- Circular and square sections show more ductile behaviour in torsion.

• It has been observed that the results obtained from the study give results compatible with the literature, and the analytical investigation gives results compatible with the experimental studies. As a result of the comparison with the experimental results of C25-B specimen, an approximation ratio of approximately 7% of the maximum moment and yield moment was obtained. The numerical analysis results can be used to verify the experimental results with this approximation.

DECLARATION OF ETHICAL STANDARDS

The authors declare that they have carried out this completely original study by adhering to all ethical rules including authorship, citation and data reporting.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

A. SOLAK: Methodology, Conceptualization, Resources, Investigation, Modelling, Analyzing Writing, Review & Editing, Supervision.

S. CENGIZ: Methodology, Conceptualization, Resources, Review, Supervision.

A. UNAL: Methodology, Conceptualization, Resources, Writing -review & editing, Supervision.

M. KAMANLI: Methodology, Conceptualization, Investigation, Review, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declared that they have no conflict of interest

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DATA AVAILABILITY

Data supporting the findings of this study can be obtained from the corresponding author with reasonable requests to assist in scientific studies.

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