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TORSIONAL BEHAVIOR IN SELF-COMPACTING AND CONVENTIONAL CONCRETE: FINDINGS FROM PAST RESEARCH AND EXPERIMENTS

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ABSTRACT

This study investigates the torsional behavior of reinforced concrete (RC) beams made with Conventional Concrete (CC) and Self-Compacting Concrete (SCC) under pure torsional loading. The primary variables considered are concrete type, concrete strength class, and web spacing. The torsional moment capacities, crack patterns, and failure mechanisms of the beams were experimentally evaluated and compared to theoretical predictions based on various standards and empirical formulas. The results revealed that SCC beams exhibited significantly improved torsional performance compared to CC beams, due to better adhesion between the cement paste and aggregates, resulting in narrower crack widths and higher torsional moment capacities. Additionally, the study found that decreasing web spacing increased torsional capacity and reduced crack width for both concrete types. The experimental results were compared with theoretical torsional moment values derived from ACI, EU, TS, AS3600, BS8110, Hsu's, and Rauch's formulas, with the closest correlation observed with the AS standard. The study highlights the importance of concrete type, concrete strength, and web spacing in enhancing the torsional behavior of reinforced concrete beams and suggests that existing empirical models should be refined to account for the unique characteristics of SCC.

Keywords: Civil Engineering, Self-Compacting Concrete, Web Spacing, Concrete Beam, Torsional Capacity, Experiment

1. INTRODUCTION

Concrete is a complex material made up of different components and phases. Its widespread use is largely due to its affordability and flexibility in construction. However, one of the main challenges with concrete structures is ensuring they have enough resistance to shear forces. Reinforcement is essential for achieving this, especially in concrete members that need to withstand such stresses. To improve shear strength, additional reinforcement, such as in the web of beams, is often used. The way reinforcement is arranged plays a major role in how a structure performs. Advances in concrete technology have led to the development of special types of concrete, like self-compacting concrete (SCC), which can flow into molds without the need for vibration. These materials are still made from cement-based mixes, which remain uneven in structure and are often exposed to irregular loads and complex structural layouts. These factors contribute to torsional, or twisting, forces in buildings. While torsion usually appears alongside other types of loads like axial and shear forces, studying pure torsion is mainly of academic interest.

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Recently, more attention has been given to SCC, especially in terms of how it performs over time and under stress. Most earlier research looked at the behavior of SCC without reinforcement. However, there is growing interest in understanding how reinforced SCC behaves, particularly in structural elements like beams. In earlier studies, torsional behavior was mostly examined in beams made from conventional concrete. This study instead focuses on comparing the torsional behavior of beams made with both SCC and conventional concrete. An experimental program was conducted to explore how reinforced beams made from these two types of concrete respond to pure torsional loads. The research also examined the cracks that formed under torsion, and how well different international standards apply to these materials. These include standards used in the U.S., Europe, Turkey, Australia, and the U.K. The study also compared experimental results with theoretical predictions from well-known models, such as plastic theory and skew-bending theory. Key aspects like the maximum torsional strength and the relationship between torsional force and twisting angle were also explored.

2. SCC OR SELF-COMPACTING CONCRETE

Self-compacting concrete (SCC) is a special type of concrete designed to flow and fill formwork on its own, without the need for vibration. For it to perform effectively, SCC must remain uniform and resist segregation during placement. This is achieved through a carefully balanced mix, which includes a low water-to-powder ratio, the use of chemical admixtures like superplasticizers, and sometimes viscosity-modifying agents. These ingredients help SCC flow easily, pass through tight spaces, and fill forms completely, even around dense reinforcement. SCC was first developed in Japan during the 1980s and has since been widely adopted due to its unique properties. Unlike traditional concrete, SCC does not require mechanical vibration to settle, which makes it particularly useful in complex or hard-to-reach construction areas, such as deep structural elements or intricate formwork. Its use improves construction speed, reduces labor and equipment needs, and minimizes noise on construction sites. The composition of SCC is similar to conventional concrete (CC), but there are notable differences. SCC typically includes a greater volume of paste, uses a lower water-cement ratio, and may incorporate mineral additives like silica fume, fly ash, or limestone powder. These changes influence both the fresh and hardened properties of the concrete. Although SCC and CC may use similar raw materials, their behavior during mixing, placing, and curing can vary significantly. Much of the earlier research on SCC has focused on its basic mechanical properties in unreinforced forms.

The aim of the current work is to study how the specific characteristics of SCC, beyond just its compressive strength, affect the torsional behavior of reinforced concrete beams. Torsion refers to the twisting of a structural element around its axis due to applied forces that act off-center. In real structures, torsion usually appears alongside other forces like bending and shear. While pure torsion (torsion acting alone) is mostly theoretical, understanding it helps to predict how elements will behave under more complex loading conditions. This study explores how reinforced concrete beams made with SCC respond under torsional loading and compares them to beams made with traditional concrete. Various design theories and structural standards are used to calculate and analyze critical and ultimate torsional capacities. These include principles based on elastic and plastic behavior, as well as specialized theories that consider how cracks form and propagate under torsion. In elastic theory, the highest shear stress appears along the longer sides of the beam cross-section. However, real concrete doesn't behave in a purely elastic or plastic manner, which means these theories often either overestimate or underestimate actual torsional strength. Plastic theory assumes uniform stress across the section, while skew-bending theory describes the diagonal cracking patterns that typically form under torsional stress. According to this view, cracks start on the large faces of the beam and extend toward the top and bottom surfaces. Other models also assume the concrete and steel reinforcement behave elastically until all the reinforcement reaches its yield point.

3. FINDS FROM PAST RESEARCH/EXPERIMENTATION

The experimental setup for testing torsional behavior in reinforced concrete (RC) and self-compacting reinforced concrete (SCRC) beams is designed to evaluate their performance under torsion. The beams are tested using a rigid steel frame, with a vertical load applied at the center of the beam. To measure the deflection and rotation of the beams, sensors are placed at various points along the length of the beams. The load is gradually increased until the beam fails, and key parameters such as the critical torsional moments, cracking torque, and ultimate torsional moments are recorded. The rotation angles at different stages of loading, including initial cracking and maximum torque, are also observed. The study focuses on comparing beams made from different types of concrete with varying compressive strengths and web spacings. The specimens are grouped by their concrete type, strength and reinforcement spacing. The materials used for preparing self-compacting concrete include fine aggregates, coarse aggregates, ordinary Portland cement, silica fume, and superplasticizers. The goal of this study is to investigate how different concrete types, such as conventional concrete (CC) and self-compacting concrete (SCC), affect the torsional behavior of reinforced concrete beams. The beams are tested using a hydraulic pump with a capacity to apply high vertical loads. The load is increased gradually, and the vertical deflections of the beams are measured at multiple points using displacement sensors. The concrete mixtures are prepared in a laboratory mixer, and the process involves mixing the dry ingredients first, then gradually adding water while continuing to mix until the desired consistency is reached. Mixing time for SCC is longer compared to conventional concrete due to its specific properties.

To evaluate the workability of SCC, several tests are performed, including the slump flow test, L-box test, and V-funnel test. These tests measure the ability of the concrete to flow, pass through reinforcement, and resist segregation. The test results help determine the quality of the SCC mix and its suitability for the beams. For each beam tested, three cubes are cast for measuring compressive strength after 28 days of curing. The beams are then tested for torsional behavior after curing for 27 days. The compressive strength target for the concrete mixes is set at 20 MPa and 40 MPa, with the characteristic strength being 26.7 MPa. A total of twenty beams are tested in the experimental program, with twelve beams made from conventional concrete and eight made from self-compacting concrete. All beams have the same cross-section dimensions and reinforcement details, in line with the requirements of structural standards. The beams are designed with both longitudinal and transverse reinforcement, with specific diameters and reinforcement ratios chosen based on common practice and previous research. The main objective of the experiment is to evaluate how the type of concrete and the spacing of reinforcement affect the torsional behavior of the beams. By testing different combinations of concrete and reinforcement spacing, the study aims to provide valuable insights into how these factors influence the performance of reinforced concrete beams under torsional loading.

4. FURTHER DISCUSSIONS AND INSIGHTS

The failures of the models observed in this study were of the abruption type, occurring once the beams exceeded the critical torsional moment. Cracks first appeared on the top side of the beams, forming at an angle of approximately 45 degrees relative to the horizontal axis. This behavior can be attributed to the shear stress being minimal or nearly zero when the tensile force affects the shear plane in parallel or perpendicular directions, allowing shear stress to reach its maximum. The initial crack was observed on the lateral surface of the beams. The gradation of the Self-Consolidating Concrete (SCC) resulted in narrower crack widths compared to Conventional Concrete (CC). The maximum aggregate size for CC was 32 mm, while for SCC, it was 16 mm. A decrease in the maximum aggregate size reduces the distance between the concrete grains, which affects the crack formation, particularly at the interface between the cement paste and the aggregates. This interface has the lowest strength, making it the most likely site for crack initiation. As the load increased, the crack width also grew, with the first crack exhibiting the widest width in all models. The results showed that cracks in the SCC series were narrower by about 70% compared to the CC series. In addition, increasing the concrete strength class and reducing the web spacing both contributed to narrower crack widths. The cracks exhibited complex propagation patterns. After the first crack appeared, it advanced downward and diagonally, with subsequent cracks forming in the mid-point of the beam. These cracks often branched off from the initial one, creating multiple fracture paths.

The branching behavior was more pronounced in RC beams compared to SCRC beams, which could be attributed to differences in material gradation. As the load continued to increase, the cracks propagated downward along the beam's side surface, primarily in the areas near the braces. This propagation pattern followed the behavior expected from shear-induced failures, where diagonal cracks often occur due to the shear stress reaching critical levels. The torsional behavior of the beams was further examined by comparing experimental data with theoretical calculations based on various standards and empirical formulas. The experimental torsional moment capacity and the critical torsional moment, which corresponds to the load at which the first crack occurs, were compared with the values predicted by ACI, EU, TS, AS3600, BS8110, Hsu's, and Rauch's formulas. The results revealed a close correlation between the experimental and theoretical values, though some standards, such as AS, provided the most accurate predictions. Notably, the theoretical torsional moment values calculated using Rauch's formula deviated significantly from the experimental data, highlighting the limitations of this particular empirical approach. The relationship between torsional moment capacity and rotation angle was also explored. It was found that the maximum torsional moment capacity occurred in beams with higher concrete strength and reduced web spacing. This outcome aligns with previous studies indicating that both the web reinforcement and the concrete strength class play pivotal roles in improving the torsional capacity of beams. Furthermore, the results showed that both the torsional moment capacity and the rotation angle at the point of failure were closely related, with the critical torsional moment and the torsional moment capacity being nearly identical. This suggests that the failure behavior of the beams was brittle, as indicated by the abrupt changes in the rotation angle and torsional moment upon failure.

Another key observation was the impact of concrete type on torsional behavior. The beams constructed with SCC exhibited superior torsional performance compared to those made with CC, even when both had the same web spacing. This improvement was likely due to the enhanced bond between the cement paste and aggregates in SCC, which reduces the ease of crack formation and enhances the material's resistance to torsion. Despite the similar compressive strengths of both types of concrete, the finer gradation of SCC led to more elongated shear crack patterns and ultimately greater torsional capacity. Additionally, the web reinforcement was found to have a more significant effect on torsional characteristics than longitudinal reinforcement. Ductility, an essential factor in torsional failure, was also analyzed in the study. Ductility refers to a material's ability to deform without fracturing, and in structural engineering, it is a desired characteristic for preventing sudden and brittle failures. The experimental results demonstrated that the ductility of RC beams increased with greater web spacing, suggesting that increased shear reinforcement improves the beam's ability to absorb energy before failure. However, the SCRC beams exhibited more brittle failure behavior than the RC beams, even though they showed higher torsional moment capacities. This can be attributed to the differences in the concrete types and their respective crack propagation patterns. The study also highlighted the importance of web spacing in enhancing torsional performance. Beams with lower web spacing exhibited higher torsional moment capacities, and this trend was more pronounced in beams with higher concrete strength. For both the SCC and CC series, decreasing the web spacing led to an increase in the torsional moment capacity, which is consistent with the theory that more closely spaced webs provide greater resistance to torsional deformation.

Furthermore, the results showed that reducing the web spacing also led to smaller crack widths, particularly in lower-strength concrete models, which further emphasizes the role of web reinforcement in controlling crack formation. When comparing experimental and theoretical results for both the critical and ultimate torsional moments, the study found that the theoretical values based on empirical equations differed from the experimental results, especially for the models with SCC. The empirical formulas used to calculate the torsional moment capacity for conventional concrete beams (CC) seemed to provide better approximations than those used for SCC, which exhibited higher torsional moments than predicted by most standards. This discrepancy suggests that the empirical formulas based on conventional concrete properties may not fully capture the behavior of SCC under torsional loading. The results also pointed to the significant role of concrete strength in determining the critical torsional moment. For higher-strength concrete, the critical torsional moment increased by approximately 30%. Additionally, decreasing web spacing from 100 to 80 mm led to a substantial increase in the critical torsional moment for both the SCC and CC groups. These findings support the notion that both concrete strength and web reinforcement play crucial roles in enhancing the torsional performance of reinforced concrete beams.

5. IN CONCLUSION

This study provides valuable insights into the torsional behavior of reinforced concrete beams, emphasizing the importance of concrete type, strength, and web spacing. Beams made with SCC demonstrated improved torsional performance compared to those made with CC, primarily due to better aggregate-paste adhesion and finer gradation. The web reinforcement was found to significantly influence torsional capacity, with smaller web spacing contributing to increased torsional strength and reduced crack widths. While the experimental results were generally consistent with theoretical predictions, the study also highlighted the limitations of existing empirical formulas, particularly for beams constructed with SCC. Future research should focus on refining these empirical models to better account for the unique properties of SCC and their impact on torsional behavior.

CONFLICT OF INTERESTS

None.

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