Flexural Behavior of Reinforced Concrete Beams under Eccentric Load

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ABSTRACT

Eccentric loading affects the structural behavior of all components in a system. While eccentric loading has been generally addressed, its direct impact on beams has not been thoroughly investigated. This study focuses on how eccentric loading influences the performance of Reinforced Concrete (RC) beams constructed with Normal Concrete (NC, C30) and High-Strength Concrete (HSC, C70). The experimental program included sixteen beams, each measuring 150 mm × 200 mm × 2000 mm and designed with identical reinforcement. The key variables examined were the type of concrete used, the inclusion of steel fibers, and the difference between centric and eccentric loading conditions. All beams were tested using two-point loading applied through a 100 mm diameter circular steel plate. For the centric loading, the plate was positioned at the center of the beam's top surface, while for the eccentric loading, it was shifted toward the edge along the x-axis. The results showed that eccentric loading did not negatively affect the flexural performance of the beams. HSC beams demonstrated an approximate 10% increase in ultimate load capacity compared to NC. Additionally, incorporating steel fibers improved the ultimate strength by 6% in NC and 10% in HSC. While these gains were modest, they played a significant role in enhancing the overall performance of the beams, especially regarding Absorbed Energy (AE).

Keywords-eccentric load; normal concrete; high-strength concrete; steel fiber

I. INTRODUCTION

Eccentric loading on beams is a critical factor in structural engineering, as it significantly influences the design and performance of structural elements. This phenomenon occurs when a load is applied out of the center, introducing additional bending moments and shear forces that affect the overall behavior and structural integrity of the beam. The eccentric load on concrete beams can occur in various scenarios, such as when cars are parked irregularly on bridges. In some structures, the columns may not be positioned in the center of the beams but rather on the sides. Analyzing eccentric loading is essential to ensure the safety and reliability of structures, such as buildings, bridges, and industrial frameworks. When a load is applied eccentrically, the beam experiences a combination of axial and flexural stresses, which can lead to complex stress distributions [1-4]. Advanced analytical methods enable engineers to evaluate how variations in beam geometry, material properties, and loading conditions influence structural performance. These insights contribute to optimized design solutions that ensure both safety and serviceability [5, 6]. Understanding the behavior of beams under eccentric loading is vital for accurate structural analysis and design. A major concern in structural integrity involves columns, which often experience eccentric loading due to their placement in high-stress areas, such as building edges and corners. It has been shown that RC columns are particularly susceptible to eccentric loads, which generate complex stress conditions, unlike those seen under concentric loading [7]. Thus, the behavior of RC columns under eccentric forces needs to be analyzed, as structural failures often stem from overlooking these effects. Similarly, eccentric loading in beams is a critical topic in structural engineering. When a load is applied away from the centroid of a beam's cross-section, it introduces an additional bending moment and creates a non-uniform stress distribution, making analysis and design more challenging. The way eccentricity affects various beam types has been investigated. Authors in [8] conducted three-point flexure tests on 50 pultruded Fiber-Reinforced Polymer (FRP) angle beams, a large sample size adding reliability to the findings. The study examined how different span-to-width ratios (L/b), ranging from 20 to 40, influence buckling behavior, revealing the significant role of geometric configuration in a beam's structural performance. The study assessed four levels of eccentricity (ranging from 0 to ±2e) to understand how such variations affect critical buckling loads and failure mechanisms in beams. The findings exhibited that eccentric loading can significantly reduce the load-bearing capacity by 9.9%-40.3%, depending on the load's magnitude and direction. These results offer important insights into how eccentricity influences the flexural-torsional buckling behavior of the FRP beams. Authors in [4] focused on wide RC beams, having examined how reinforcement layout and shear reinforcement spacing respond under eccentric loading. Using both experimental methods and finite element analysis, it was found that eccentric loads introduced additional torsional moments. Combined with bending and shear stresses, these forces created distinct cracking patterns. Moreover, increasing the concrete's compressive strength from 30 MPa to 40 MPa and 50 MPa improved the beams' ultimate load capacity by 25% and 46%, respectively. Authors in [10] studied deep beams subjected to varying eccentric distances, 15 mm, 30 mm, and 50 mm, alongside a reference beam under centric loading. The centric beam experienced shear failure, while the beam with 30 mm eccentricity failed through crushing under the applied load. The 50 mm eccentric beam showed a similar behavior to that of the centric beam, prompting further exploration of how eccentricity affects shallow beams. Hence, the eccentric loading effects not only on the columns, but also on the beams, especially the deep ones, need to be considered to improve design accuracy and ensure the structural safety under realistic loading conditions [11-22].

II. STUDY OBJECTIVES

This study aims to explore the effects of eccentric loading on RC beams constructed with both NC (C30) and HSC (C70).

III. METHODOLOGY

A total of 16 RC beams were cast and divided into two main groups based on the type of concrete used. Group 1 included beams made with NC, while Group 2 consisted of beams made with HSC. Each group contained four different beam types, and for each type, two identical specimens were tested to allow averaging and minimize experimental variability. The details of the beam classifications are provided in Table I.

TABLE I. BEAM SPECIMEN DESCRIPTION

Beam name	Group	Concrete type	Fiber type	Load type
NC	Group 1	NC		Centric
NC-e		NC		Eccentric
NC-SF		NC	Steel with a hook	Centric
NC-SF-e		NC	Steel with a hook	Eccentric
HSC	Group 2	HSC		Centric
HSC-e		HSC		Eccentric
HSC-SF		HSC	Steel with a hook	Centric
HSC-SF-e		HSC	Steel with a hook	Eccentric

TABLE II. MIX PROPORTIONS (kg/m^3) FOR NC AND HSC

Mixture name	Cement	Silica fume	Sand	Gravel	Water	Superplasticizer
NC	339		900	944	173	3.4
HSC	510	90	681	944	173	12

TABLE III. PROPERTIES OF STEEL REINFORCEMENT

Bar diameter	Yield strength	Maximum strength	Elongation
10 mm	510	560	11%
12 mm	530	600	10%

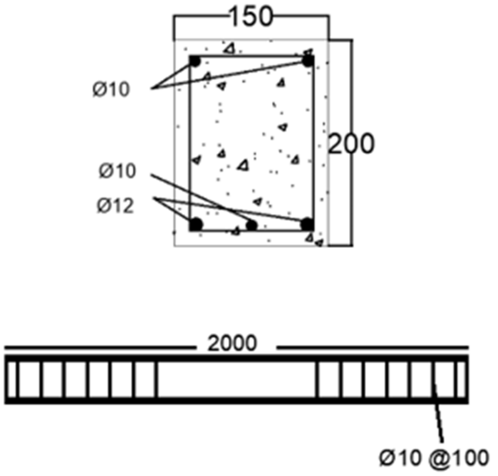


Fig. 1. Details of reinforcement and beam dimensions.

The concrete mix for all beams included locally sourced crushed aggregate with a maximum size of 12 mm and a specific gravity of 2.67 combined with Zone 3 sand, in compliance with [23]. Ordinary Portland cement was provided by the AL-Mass Company, meeting the specifications outlined in [24]. To enhance workability and prevent segregation and bleeding, a high-performance superplasticizer (Master Genium 54) was used. Steel fibers were incorporated into both NC and HSC mixes at a dosage of 1.5% by volume to study their impact on beam performance. The fibers had a length of 23.98 mm and a diameter of 0.26 mm, measured using a digital vernier caliper. The mix designs for both concrete types followed the guidelines provided in [9], with the mix proportions being detailed in Table II. The mechanical properties of the reinforcing steel are listed in Table III. Figure 1 displays the steel fibers utilized, demonstrating the beam geometry along with reinforcement details.

Fig. 2. Testing device.

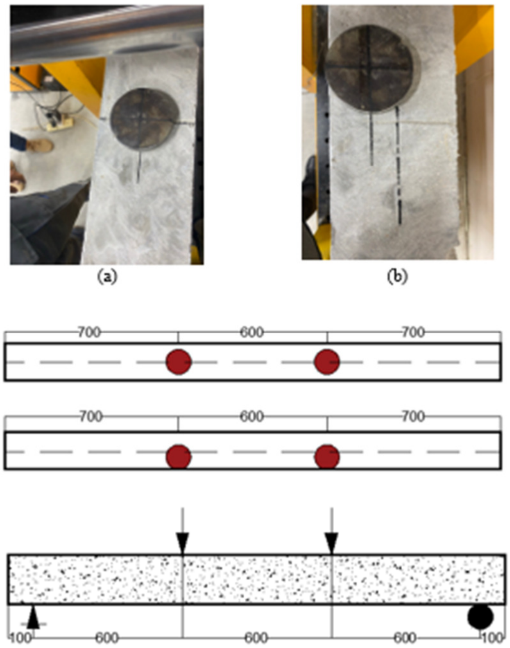


Fig. 3. (a) Centric loading, (b) eccentric loading.

The simply supported beams were tested under two concentrated loads. The test speed was 1 kN/s with a device maximum capacity of 600 kN (Figure 2). The applied load was transferred via a 100 mm diameter circular steel plate. For the centric loading, the plate was centered on the beam's top surface, while for the eccentric loading it was shifted toward the edge (X-direction), as illustrated in Figure 3.

IV. RESULTS AND DISCUSSION

A. Load and Deflection Curve

Under centric loading, the NC beams exhibited a typical three-stage load-deflection response. In the first stage, the elastic phase, the load-deflection relationship was linear until the appearance of the first crack, as shown in Figure 4. When steel fibers were added to the mix (NC-SF), the beam performance improved. After the initial cracking, the load-deflection curve became more stable, indicating better crack control. In the post-yielding phase, the deflection continued to increase steadily while the applied load remained nearly constant. This behavior reflects the enhanced ductility provided by the steel fibers. The load-deflection response for fiber-reinforced NC beams is portrayed in Figure 5.

Under eccentric loading, the overall behavior of the beams was slightly different compared to that under centric loading. The differences in deflection were minimal, particularly in the beams without fibers. However, the beams containing steel fibers demonstrated a more stable and ductile response under eccentric conditions. Figures 6 and 7 exhibit the load-deflection comparisons between centric and eccentric loadings for the NC beams, both with and without fibers.

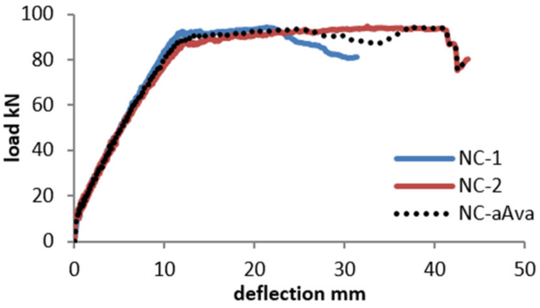


Fig. 4. Load-deflection for the NC beams.

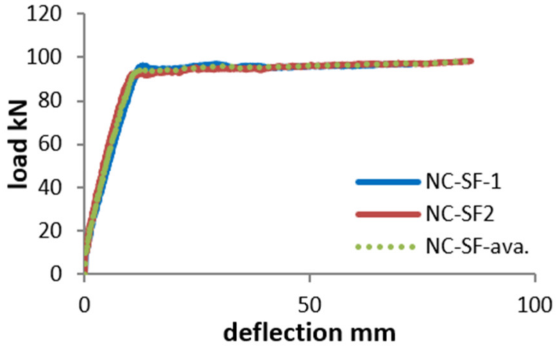
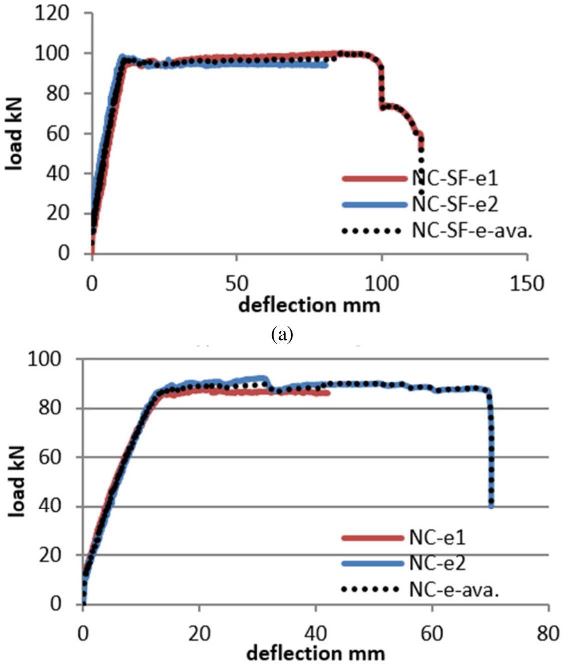


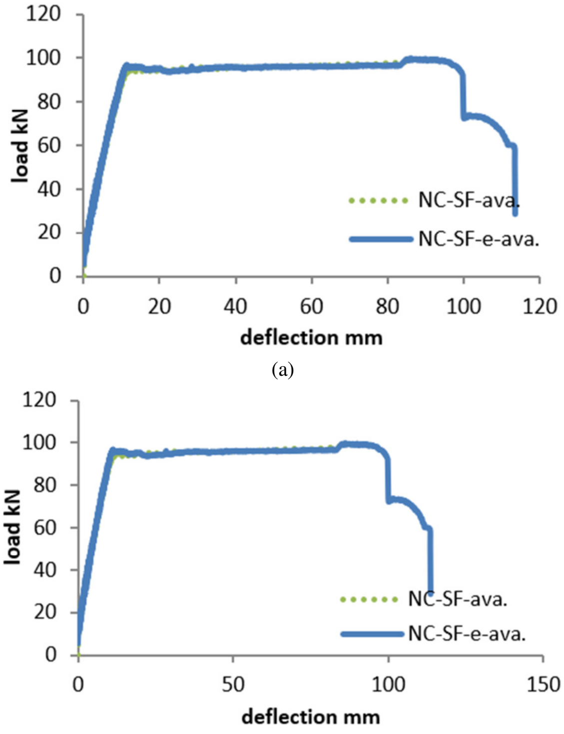
Fig. 5. Load-deflection for the NC beams with fibers.



(a)

(b)

Fig. 6. Load-deflection under eccentric loading of NC beams (a) with and (b) without fibers.



(a)

(b)

Fig. 7. Difference between NC beams under centric and eccentric loading.

HSC beams, similarly to their NC counterparts, displayed three distinct stages in their load-deflection behavior. However, two key differences were noted. First, the slope of the second stage, between initial cracking and yielding, was more gradual in HSC beams. This is attributed to HSC's higher compressive strength, which allows it to sustain greater loads before failure [16]. Additionally, the use of transverse reinforcement enhances the ductility of the HSC beams, enabling them to deform more before reaching the peak stress. This behavior is particularly evident during the transition from elastic to plastic deformation in the stress-strain curve. Second, after yielding, the HSC beams exhibited a more pronounced increase in the load capacity, which may be due to a stronger bond between the reinforcing steel and the surrounding concrete. Figure 8 presents the load-deflection response of the HSC beams.

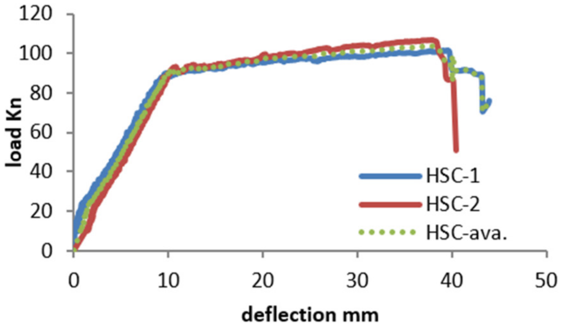
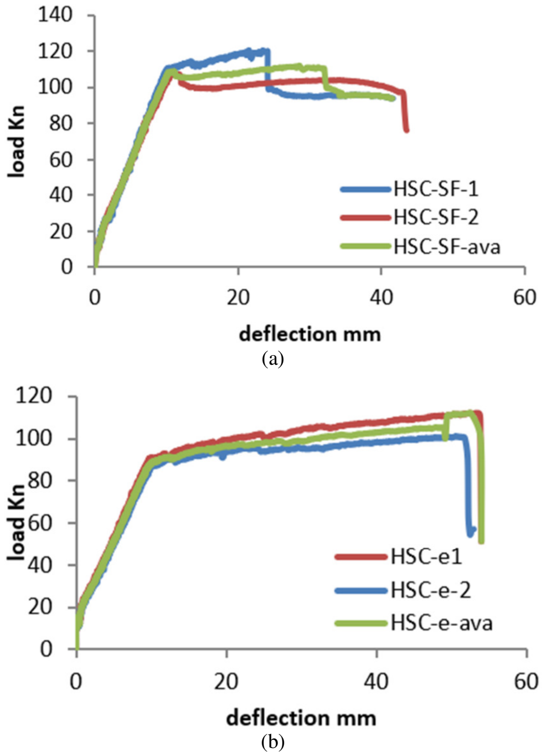


Fig. 8. Load-deflection for HSC beams.

HSC-SF beams exhibited improved ductility but varying results due to uneven fiber distribution as can be seen in Figure 9 and 10. Under eccentric load, the HSC beams behaved similarly to the centric ones, with slight reductions in ductility.



(a)

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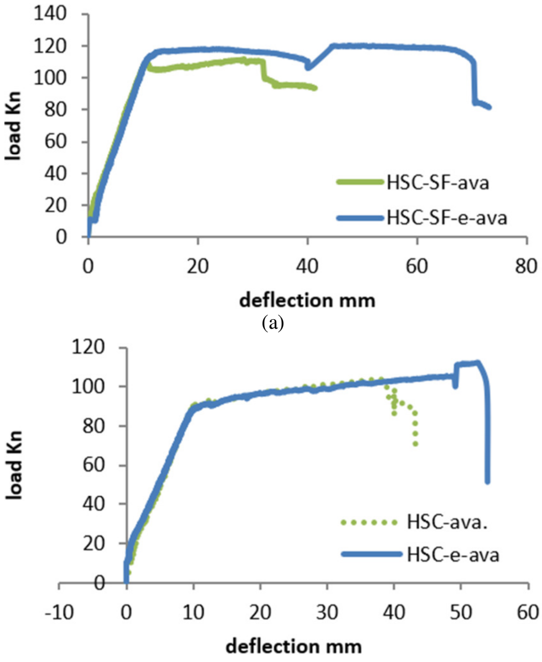
Fig. 9. Load-deflection graphs of HSC beams under eccentric load.



(a)

(b)

Fig. 10. Load-deflection graphs of HSC beams under centric and eccentric load.

B. Ultimate Load

After testing, it was found that eccentric loading increased the ultimate load in most cases. These results are in contrast with prior findings of tests conducted on slabs [17]. The addition of steel fibers also contributed to an increase in the ultimate capacity [18].

TABLE IV. ULTIMATE LOAD FOR TESTED SPECIMENS

Mixture name	**Ultimate load (kN) for beams under centric load ***	**Ultimate load (kN) for beams under eccentric load ***	**Increasing percentage (%)**
NC	92.3	92.4	0.11
NC-SF	98.3	113.5	15.46
HSC	101.8	112.3	10.31
HSC-SF	112.1	120.5	7.49

*Average of two beams

C. Absorbed Energy

AE, calculated as the area under the load-deflection curve, represents the ductility and energy dissipation capacity of a beam before failure. In Group 1 (NC beams), eccentric loading significantly improved AE by 1.7 times in NC-e and 1.4 times in NC-SF-e compared to their centric counterparts. Additionally, the inclusion of steel fibers further enhanced AE, increasing it by 2.2 times compared to plain NC beams. This improvement is attributed to the fiber's ability to maintain a more stable, linear post-cracking response, allowing the beam to absorb more energy before failure. The ultimate load capacity in fiber-reinforced NC beams was achieved alongside a steady increase in deflection, indicating improved performance and enhanced ductility. In contrast, Group 2 (HSC beams) showed a slight decrease in AE under eccentric loading. The use of fibers did not significantly improve AE in HSC beams. For example, the AE of HSC-e was 79% of that in centric HSC beams. These findings confirm that while steel fibers are effective in increasing ductility and AE in NC beams, they have a limited impact on HSC beams, likely due to the inherent brittleness of HSC. Despite this, all beams exhibited similar areas under the curve during the elastic stage up to the yielding point, suggesting comparable initial strength and stiffness across all specimens. Figures 10 and 11 present the aforementioned AE comparisons.

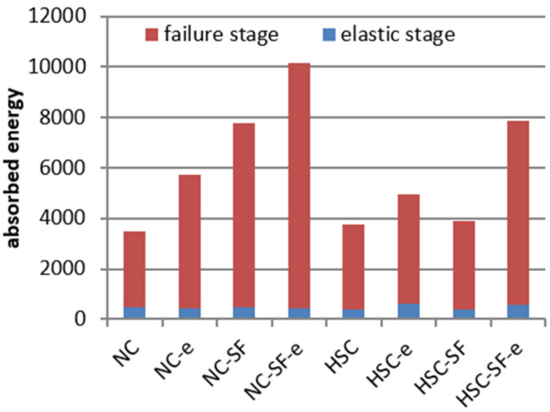


Fig. 11. AE in the elastic and failure stages.

V. CONCLUSIONS

This examined the flexural behavior of Reinforced Concrete (RC) beams under eccentric loads. The findings indicate that eccentric loading led to an increase in the ultimate load capacity for both Normal Concrete (NC) and High-Strength Concrete (HSC) beams. Under centric loading, the load is applied along the beam's axis of symmetry and bending occurs uniformly, resulting in a symmetric stress distribution. Failure in such cases tends to occur evenly once the beam exceeds its capacity to resist compressive or flexural stresses.

In contrast, when the load is applied eccentrically, offset from the beam's central axis, it introduces additional torque due to the distance between the load's line of action and the neutral axis. This added moment causes a redistribution of internal stresses within the beam's cross-section, which can improve the equilibrium between the tensile forces in the reinforcement and the compressive forces in the concrete. As a result, failure may be delayed, since the increased moment enhances the tensile performance of the steel and the compressive capacity of the concrete. This phenomenon is particularly relevant in reinforced beams, where the capacity for moment redistribution and structural flexibility contributes to an improved performance under eccentric loading. However, in unreinforced concrete beams, such eccentric forces typically reduce load capacity, as the asymmetrical bending can induce premature failure. Authors in [10] demonstrated that under specific conditions, eccentric loading can produce structural responses like those observed under centric loading. However, the present study focuses on standard-sized beams, raising awareness of their performance under eccentric loading. This broader perspective enhances the understanding of eccentricity effects across a wider range of structural elements, contributing to the current design and analysis practices:

- Load Capacity and Behavior: The beams reached their maximum load capacity under both centric and eccentric loading conditions, maintaining a stable behavior. This stability shows that fiber-RC can effectively handle both types of loads, supporting their overall structural integrity.
- Absorbed Energy (AE): The amount of the energy absorbed by the concrete beams is greatly affected by the type of loading and fiber reinforcement. Beams with fibers demonstrated improved AE characteristics, which enhances their structural performance and resilience under different loading conditions.

These findings contribute significantly to the theoretical understanding of beam behavior. This study uses innovative methods that improve the reliability and accuracy of the results. Compared to earlier research, which may have used less rigorous techniques, the approaches deployed in the present work establish a higher standard for future studies in this field. The conclusions indicate potential applications in related areas that previous research has not fully explored, opening new opportunities for interdisciplinary investigation.

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