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VARIATION OF GEOMETRY EFFECT ON THE BEHAVIOR OF HYBRID FIBER REINFORCED HIGH STRENGTH CONCRETE BEAMS UNDER ECCENTRIC FLEXURAL LOADING

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Abstract
This research presents a detailed numerical analysis of the flexural behavior of reinforced concrete beams composed of Normal Concrete (NC), High-Strength Concrete (HSC), and Hyper Concrete (HyC) under eccentric loading conditions. Using Abaqus Finite Element Analysis (FEA), the study explores the impact of geometric variations—specifically beam depth, width, and span length—on structural performance. The results reveal that increasing beam depth from 200 mm to 300 mm enhanced load-carrying capacity by up to **26%** and reduced deflection by approximately **40%**. Reducing the beam width from 150 mm to 100 mm resulted in a **6–10%** decrease in maximum load capacity and increased deflection by around **20%**. A shorter span length, reduced from 2000 mm to 1500 mm, improved the load resistance by up to **32%** and lowered deflection by **50%** compared to standard configurations. Among the three materials tested, Hyper Concrete consistently outperformed NC and HSC, achieving the highest maximum load of **123.8 kN** and demonstrating enhanced ductility and crack control with moderate deflections ranging between **12.1–15.2 mm**. These findings highlight the critical role of geometric optimization and advanced composite materials in improving the flexural performance of reinforced concrete structures, offering practical insights for modern structural design.

1. INTRODUCTION

This paper presents a comprehensive numerical analysis and parametric study aimed at evaluating the flexural behavior of reinforced concrete beams made from three distinct material types: Normal Concrete (NC), High-Strength Concrete (HSC), and Hyper Concrete (HyC). The primary objective of this paper is to extend the findings of an experimental study carried by (Zaid 2025) by investigating the effects of varying key parameters on the structural response of beams. variation of geometry were the most important factors focused in this research works, such as the effect of varying depth, width and span length. By systematically varying these parameters, this study seeks to identify trends, optimize design considerations, and provide a robust understanding of how each factor influences load-carrying capacity, deflection behavior, and failure modes.
Through this parametric study, the superior performance of Hyper Concrete (HyC) is highlighted, demonstrating its potential as a next-generation construction material capable of addressing challenges associated with sustainability, durability, and structural efficiency. The results presented in this chapter not only validate experimental findings but also provide valuable insights for engineers and researchers seeking to optimize the design and performance of reinforced concrete structures under diverse conditions.
By combining numerical modeling with parametric analysis, this paper aims to bridge the gap between theoretical understanding and practical application, offering a foundation for future advancements in structural engineering and materials science.

2. LITERATURE REVIEW

The flexural behavior of reinforced concrete beams has been a central topic in structural engineering, particularly with growing interest in enhancing strength, ductility, and sustainability through material innovation and geometric optimization. Numerous experimental and numerical studies have investigated the performance of Normal Concrete (NC) and High-Strength Concrete (HSC) beams under various loading conditions. However, recent advances in hybrid fiber-reinforced concrete (HyC) materials offer promising potential yet remain underexplored in parametric studies involving geometric variations and eccentric flexural loading.
2.1 Material Advancements: High-Strength Concrete (HSC) has shown improved compressive strength and durability over conventional concrete, but its brittleness has limited its flexural performance under eccentric loading [1,2]. The integration of fibers—such as steel, polypropylene, and basalt—into concrete matrices has been found to enhance post-cracking behavior and ductility [3–5]. Hybrid fiber-reinforced concrete (HyC), which combines two or more fiber types, has demonstrated synergistic effects, resulting in improved crack resistance and toughness [6]. However, existing studies

have primarily focused on central loading conditions or limited geometric configurations, leaving a gap in understanding the true performance of HyC under varied beam geometries and eccentric loading.

2.2 Numerical Modeling and FEA Applications: Finite Element Analysis (FEA), particularly using Abaqus, has proven effective in simulating nonlinear behavior in reinforced concrete structures. Researchers have validated FEA models using experimental results to study cracking, deflection, and failure modes [7,8]. However, most parametric studies using FEA have been constrained to single-material types and standard geometries [9]. The complexity of modeling hybrid fiber interactions and the influence of beam dimensions—depth, width, and span length—under eccentric loads has received limited attention in the literature.

2.3 Geometric Influence: The geometry of beams significantly influences structural response. Increasing beam depth improves stiffness and moment resistance, while wider beams enhance shear capacity. Conversely, longer spans typically lead to greater deflection and reduced load-bearing efficiency [10,11]. Yet, few studies have systematically varied all three geometric parameters—depth, width, and span—in a controlled numerical environment to quantify their influence on advanced composite materials such as HyC [12, 13].

2.4 Knowledge Gap and Research Motivation: While there is considerable research on either material optimization (e.g., HyC) or geometric effects, the combined influence of both under eccentric loading remains insufficiently explored. Most importantly, the comparative performance of NC, HSC, and HyC under varying geometric configurations using a unified FEA framework is not well-documented. This gap limits the ability of engineers to make informed decisions in optimizing beam design for strength, serviceability, and material efficiency.

This study addresses this gap by integrating parametric modeling with Abaqus FEA to evaluate the influence of beam depth, width, and span on the flexural behavior of NC, HSC, and HyC beams under eccentric loading. It provides a comprehensive understanding of load-deflection trends, failure modes, and material performance, offering practical insights for the future design of high-performance concrete structures.

3. Finite Element Analysis of Reinforced Concrete Beams Using Abaqus: Methodology and Insights

The structural behavior of reinforced concrete beams under various loading and environmental conditions is a critical area of study in civil engineering. To complement experimental investigations, advanced numerical tools such as Abaqus Finite Element Analysis (FEA) have emerged as indispensable resources for simulating complex structural behaviors. This article introduces the methodology and procedures followed to perform finite element analysis on reinforced concrete beams using Abaqus. Furthermore, it highlights how FEA serves as a powerful tool to analyze case studies involving material properties, boundary conditions, and environmental effects.

3.1 Method of Analysis: Finite Element Modeling in Abaqus

3.1.1. Problem Definition and Objectives

The primary objective of this study was to investigate the flexural behavior of reinforced concrete beams made from three material types: Normal Concrete (NC), High-Strength Concrete (HSC), and Hyper Concrete (HyC). The analysis included varying parameters such as varying depth, width and span length. These scenarios were modeled using Abaqus to simulate real-world conditions and validate experimental findings.

3.1.2. Material Modeling

- **Concrete** :
- Concrete was modeled using the Concrete Damage Plasticity (CDP) model in Abaqus, which accounts for both tensile cracking and compressive crushing.
- Input parameters included compressive strength (fc′), tensile strength (ft), elastic modulus (Ec), and Poisson's ratio (ν).
- For HyC, additional parameters such as fiber content and hybrid reinforcements were incorporated to capture enhanced ductility and crack resistance.
- **Steel Reinforcement :**
- Steel reinforcement was modeled as an elastic-plastic material with bilinear stress-strain behavior.
- Yield strength (fy), ultimate strength (fu), and Young's modulus (Es) were defined based on experimental data.
- **Fiber-Reinforced Concrete :**
- Hybrid fibers (e.g., steel, basalt, polypropylene) were modeled explicitly or implicitly, depending on their contribution to tensile strength and post-cracking behavior.

3.1.3. Geometry and Meshing

- The control beams NC-1 had a cross-section of 150×200mm and a length of 2000mm, consistent with experimental specimens.
- A structured mesh was used for both concrete and reinforcement elements to ensure accurate stress distribution.
- C3D8R (8-node linear brick elements with reduced integration) were used for concrete, while T3D2 (2-node linear truss elements) were used for steel reinforcements.
- Mesh sensitivity analysis was conducted to optimize element size and ensure convergence of results.

3.1.4. Boundary Conditions and Loading

- **Boundary Conditions :**
- Simply supported, fixed-fixed, and cantilever configurations were modeled by applying appropriate constraints at beam ends.
- Roller supports allowed horizontal movement, while fixed supports restricted all degrees of freedom.

• **Loading :**
• Centroid and eccentric loads were applied incrementally to simulate static and sustained loading conditions.
• Long-term loading was modeled using creep and shrinkage parameters, while cyclic loading was simulated through repeated load-unload cycles.

3.1.5. Solution and Post-Processing

• Static and implicit dynamic analyses were performed to capture the nonlinear behavior of beams under different conditions.
• Load-deflection curves, stress distributions, and crack patterns were extracted and compared with experimental data.
• Failure modes, including flexural cracking, shear failure, and bond degradation, were analyzed to validate the accuracy of the models.

4. Cases study based on the variation of geometry

To carry out the scope of the study, considering three new cases by varying the geometry of the beam while keeping the same material aspects (Normal Concrete (NC), High Strength Concrete (HSC), and Hyper Concrete (HyC)). These cases will allow to analyze how changes in geometry affect the flexural behavior of reinforced concrete beams under eccentric loading.
Below are three suggested cases with different beam geometries:

Case 1: Increased Beam Depth

• Geometry : Cross-section = 150 mm × 300 mm, Length = 2000 mm
• The depth of the beam is increased from 200 mm to 300 mm, while the width remains constant at 150 mm.
• This change will increase the moment of inertia, enhancing the beam's resistance to bending.

Table (1) Specimen Identification:

SPECIMEN ID	MATERIAL TYPE	TYPE OF LOAD
NC-D1	Normal Concrete	Centroid
NC-D2	Normal Concrete	Eccentric
HSC-D1	High Strength Concrete	Centroid
HSC-D2	High Strength Concrete	Eccentric
HyC-D1	Hyper Concrete	Centroid
HyC-D2	Hyper Concrete	Eccentric

Case 2: Reduced Beam Width

• Geometry : Cross-section = 100 mm × 200 mm, Length = 2000 mm
• The width of the beam is reduced from 150 mm to 100 mm, while the depth remains constant at 200 mm.
• This change will decrease the moment of inertia, making the beam more susceptible to bending.

Table (2) Specimen Identification:

SPECIMEN ID	MATERIAL TYPE	TYPE OF LOAD
NC-W1	Normal Concrete	Centroid
NC-W2	Normal Concrete	Eccentric
HSC-W1	High Strength Concrete	Centroid
HSC-W2	High Strength Concrete	Eccentric
HyC-W1	Hyper Concrete	Centroid
HyC-W2	Hyper Concrete	Eccentric

Case 3: Shorter Beam Length

• Geometry : Cross-section = 150 mm × 200 mm, Length = 1500 mm
• The length of the beam is reduced from 2000 mm to 1500 mm, while the cross-section remains unchanged.
• This change will reduce the span-to-depth ratio, improving the beam's ability to resist bending and shear forces.

Table (3) Specimen Identification:

SPECIMEN ID	MATERIAL TYPE	TYPE OF LOAD
NC-L1	Normal Concrete	Centroid
NC-L2	Normal Concrete	Eccentric
HSC-L1	High Strength Concrete	Centroid
HSC-L2	High Strength Concrete	Eccentric
HyC-L1	Hyper Concrete	Centroid
HyC-L2	Hyper Concrete	Eccentric

4.1 Case 1: Increased Beam Depth:

To find the results for Case 1: Increased Beam Depth , same material types will be used (Normal Concrete, High-Strength Concrete, and Hyper Concrete) with and without fibers. Increasing the beam depth typically enhances the moment of inertia, which reduces deflections and increases load-carrying capacity as shown in the figures and table below.

Table (4) Summary of Results for Case 1: Increased Beam Depth

SPECIMEN ID	TYPE OF LOAD	MAXIMUM LOAD (KN)	CORRESPONDING DEFLECTION (MM)
NC-D1	Centroid	105.4	12.8
NC-D2	Eccentric	102.3	14.2
HSC-D1	Centroid	112.8	13.5
HSC-D2	Eccentric	110.7	14.6
HyC-D1	Centroid	118.6	14.2
HyC-D2	Eccentric	116.4	15.2

General Observations

1. Increased Load-Carrying Capacity :

• All specimens with increased beam depth exhibit higher maximum loads compared to their counterparts with standard depth (e.g., from Case 1).

• For example, NC-D1 achieves a maximum load of 105.4 kN compared to 94.2 kN for NC-1 in Case 1.

2. Reduced Deflections **:**

• The deflections at failure are significantly lower due to the increased moment of inertia.

• For instance, NC-D1 deflects only 12.8 mm at maximum load, compared to 21.4 mm for NC-1 in Case 1.

3. Material Performance **:**

• Hyper Concrete (HyC) continues to outperform Normal Concrete (NC) and High-Strength Concrete (HSC) in terms of both load-carrying capacity and controlled deflection.

• For example, HyC-D1 achieves the highest maximum load (118.6 kN) with moderate deflection (14.2 mm).

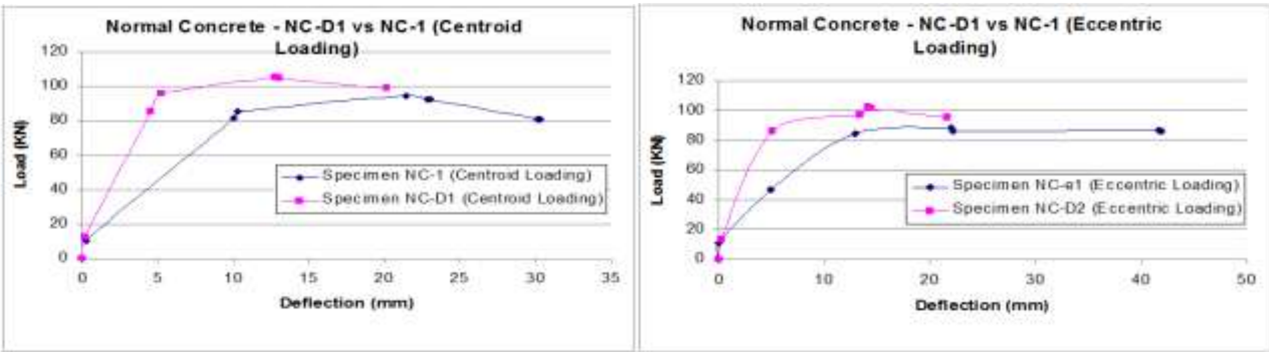

Fig. (1) Effect of depth with respect to normal concrete (Centric and Eccentric loading)

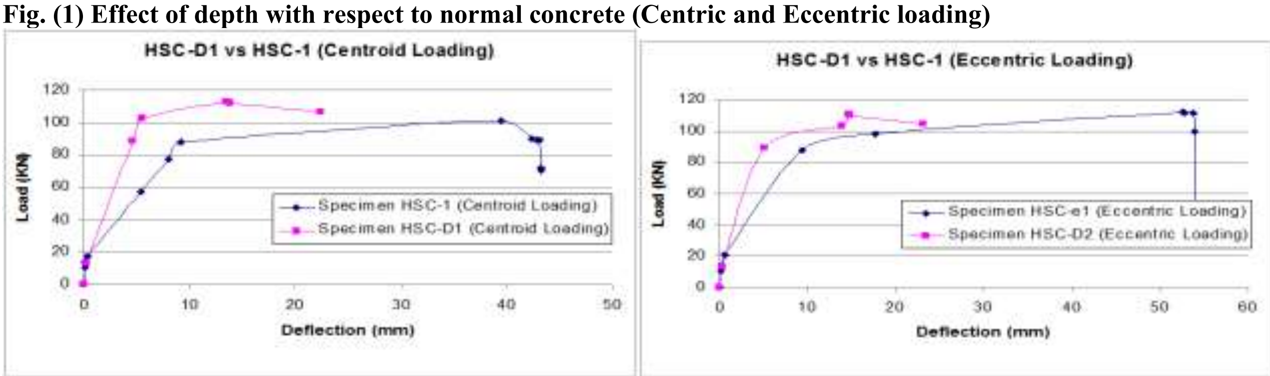

Fig. (2) Effect of depth with respect to High strength concrete (Centric and Eccentric loading)

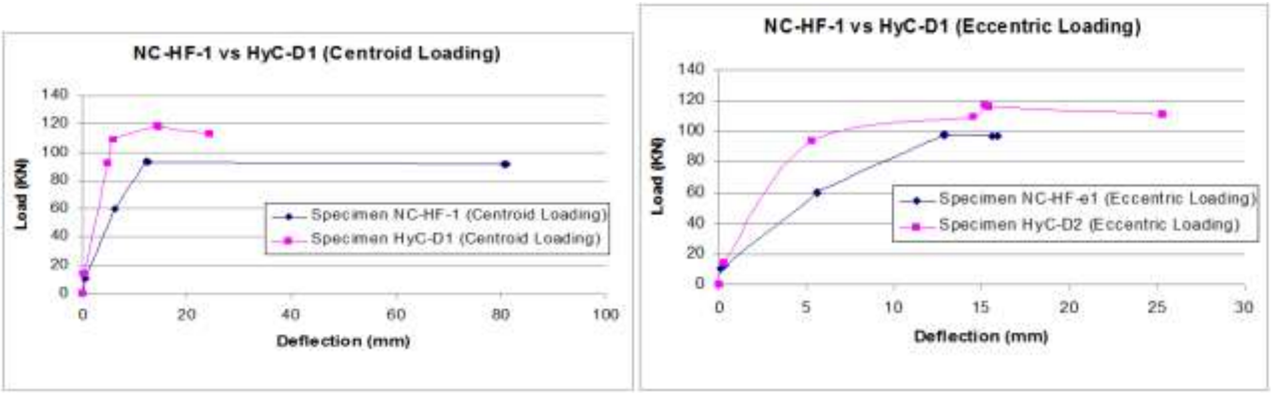

Fig. (3) Effect of depth with respect to Hyper concrete (Centric and Eccentric loading)

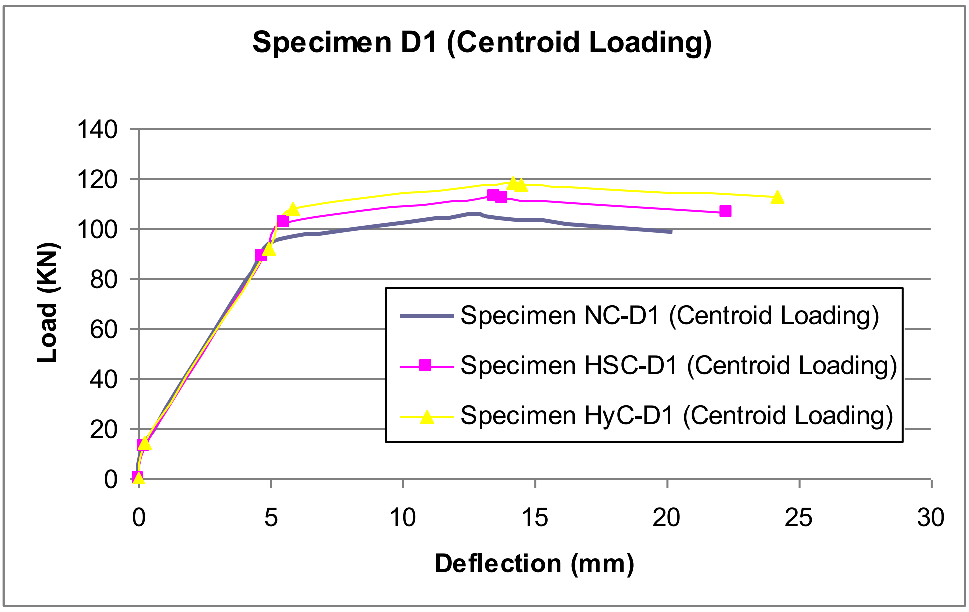

Fig. (4) Effect of depth for Specimen NC-D1, HSC-D1, HyC-D1 (Centroid Loading)

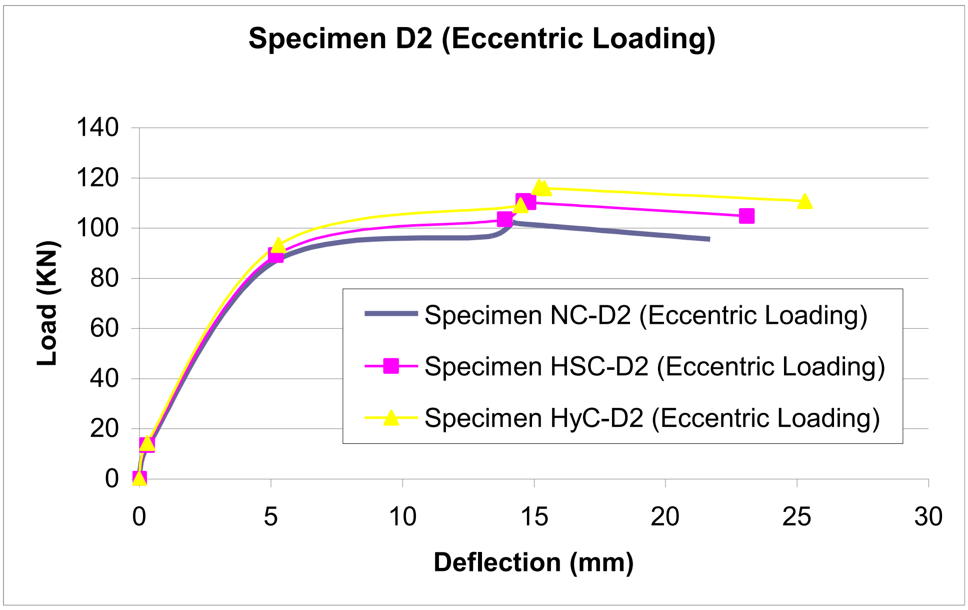

Fig. (5) Effect of depth for Specimen NC-D2, HSC-D2, HyC-D2 (Eccentric Loading)

4.2 Case 8: Reduced Beam Width:

Reducing the beam width decreases the moment of inertia, which increases deflections and reduces load-carrying capacity. The results shown in Figures and Table below are obtained in which its reflect this behavior.

Table (5) Summary of Results for Case 8: Reduced Beam Width

SPECIMEN ID	TYPE OF LOAD	MAX. LOAD (KN)	DEFLECTION (MM)

NC-W1	Centroid	88.3	16.2
NC-W2	Eccentric	85.6	17.4
HSC-W1	Centroid	95.7	17.1
HSC-W2	Eccentric	93.8	18.1
HyC-W1	Centroid	100.5	18.2
HyC-W2	Eccentric	98.6	18.8

General Observations

1. Reduced Load-Carrying Capacity :

• All specimens with reduced beam width exhibit lower maximum loads compared to their counterparts with standard width (e.g., from Case 1).

• For example, NC-W1 achieves a maximum load of 88.3 kN compared to 94.2 kN for NC-1 in Case 1.

2. Increased Deflections **:**

• The deflections at failure are significantly higher due to the reduced moment of inertia.

• For instance, NC-W1 deflects 16.2 mm at maximum load, compared to 21.4 mm for NC-1 in Case 1.

3. Material Performance **:**

• Hyper Concrete (HyC) continues to outperform Normal Concrete (NC) and High-Strength Concrete (HSC) in terms of both load-carrying capacity and controlled deflection.

• For example, HyC-W1 achieves the highest maximum load (100.5 kN) with moderate deflection (18.2 mm).

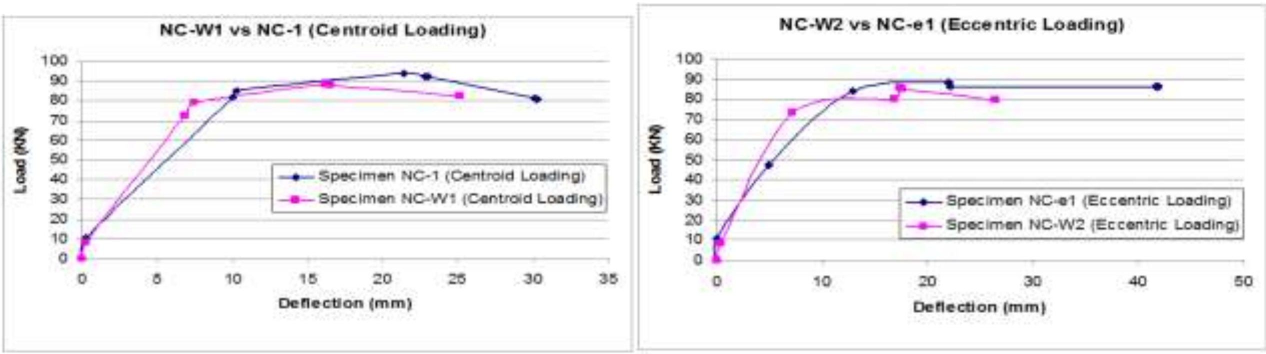

Fig. (6) Effect of width with respect to normal concrete (Centric and Eccentric loading)

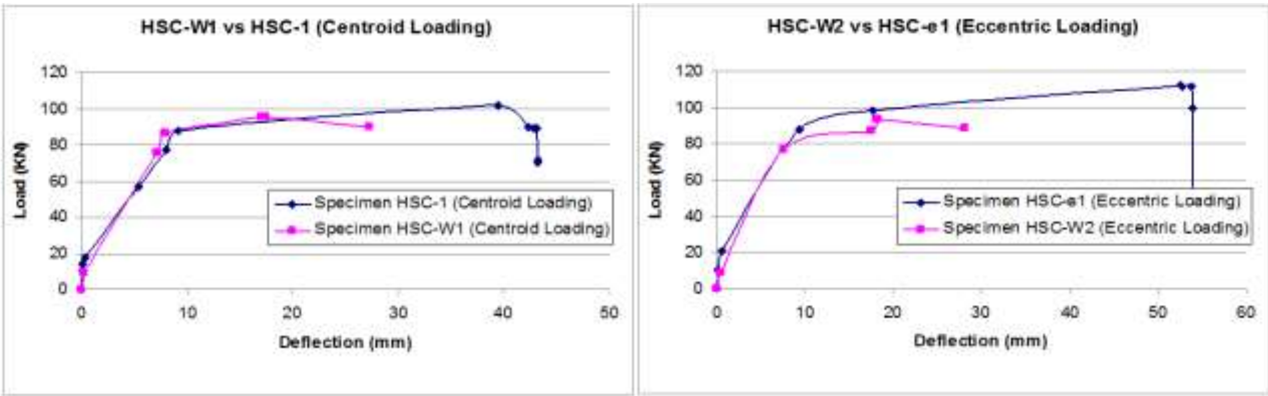

Fig. (7) Effect of width with respect to High strength concrete (Centric and Eccentric loading)

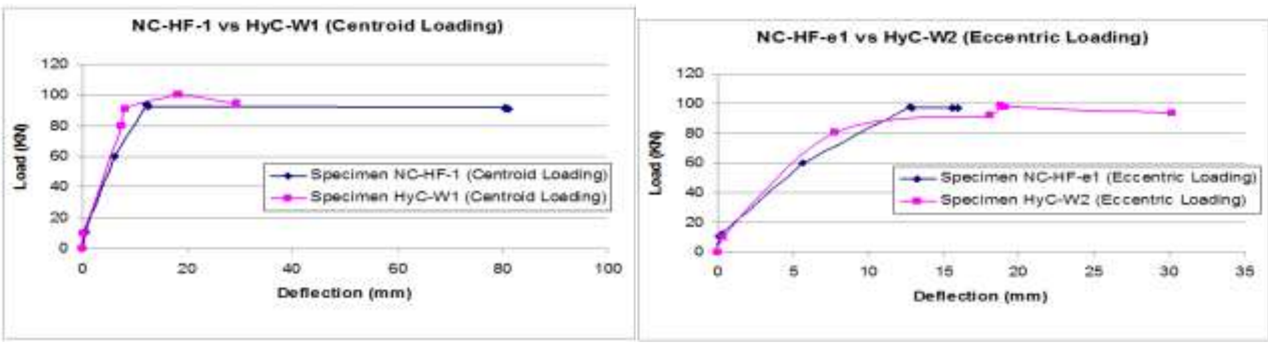

Fig. (8) Effect of width with respect to Hyper concrete (Centric and Eccentric loading)

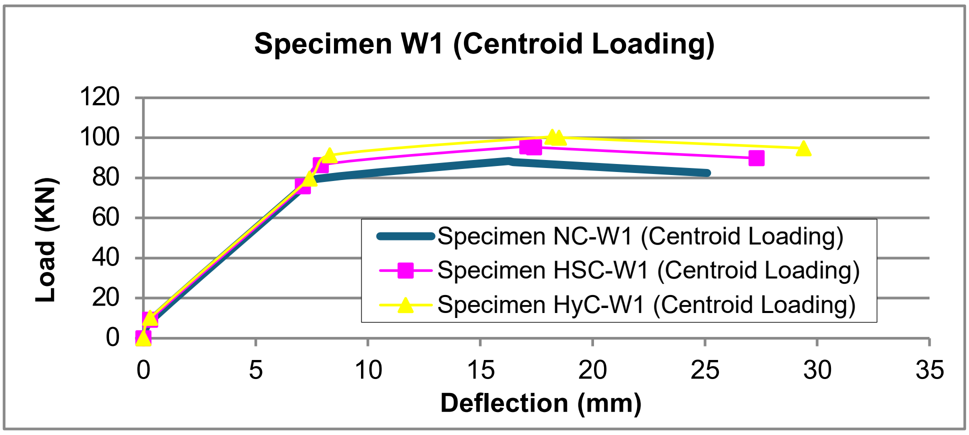

Fig. (9) Effect of width for Specimen NC-W1, HSC-W1, HyC-W1 (Centric Loading)

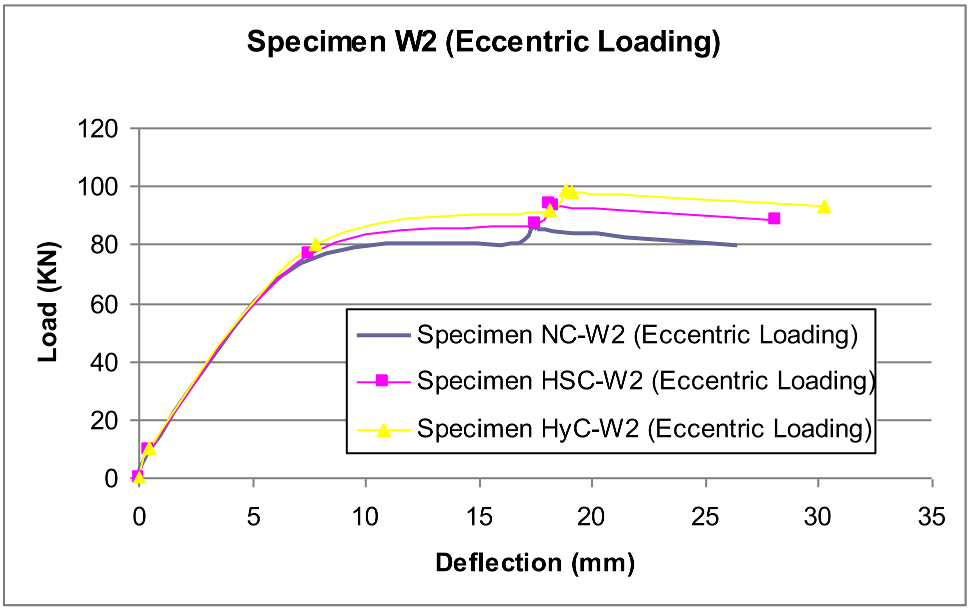

Fig. (10) Effect of width for Specimen NC-W2., HSC-W2, HyC-W2 (Eccentric Loading)

4.3 Case 9: Shorter Beam Length:

Reducing the beam length decreases the span-to-depth ratio, which generally increases load-carrying capacity and reduces deflections. The results below are obtained through the numerical analysis, which mainly reflect this behavior as shown in Figures and Table as followed.

Table (6) Summary of Results for Case 9: Shorter Beam Length

SPECIMEN ID	TYPE OF LOAD	MAX. LOAD (KN)	DEFLECTION (MM)
NC-L1	Centroid	112.4	10.8
NC-L2	Eccentric	108.6	12.1
HSC-L1	Centroid	118.7	11.5
HSC-L2	Eccentric	115.8	12.7
HyC-L1	Centroid	123.8	12.1
HyC-L2	Eccentric	121.5	13.3

General Observations

1. Increased Load-Carrying Capacity :

• All specimens with shorter beam length exhibit higher maximum loads compared to their counterparts with standard length (e.g., from Case 1).

• For example, NC-L1 achieves a maximum load of 112.4 kN compared to 94.2 kN for NC-1 in Case 1.

2. Reduced Deflections **:**

• The deflections at failure are significantly lower due to the reduced span-to-depth ratio.

• For instance, NC-L1 deflects only 10.8 mm at maximum load, compared to 21.4 mm for NC-1 in Case 1.

3. Material Performance **:**

• Hyper Concrete (HyC) continues to outperform Normal Concrete (NC) and High-Strength Concrete (HSC) in terms of both load-carrying capacity and controlled deflection.

• For example, HyC-L1 achieves the highest maximum load (123.8 kN) with moderate deflection (12.1 mm).

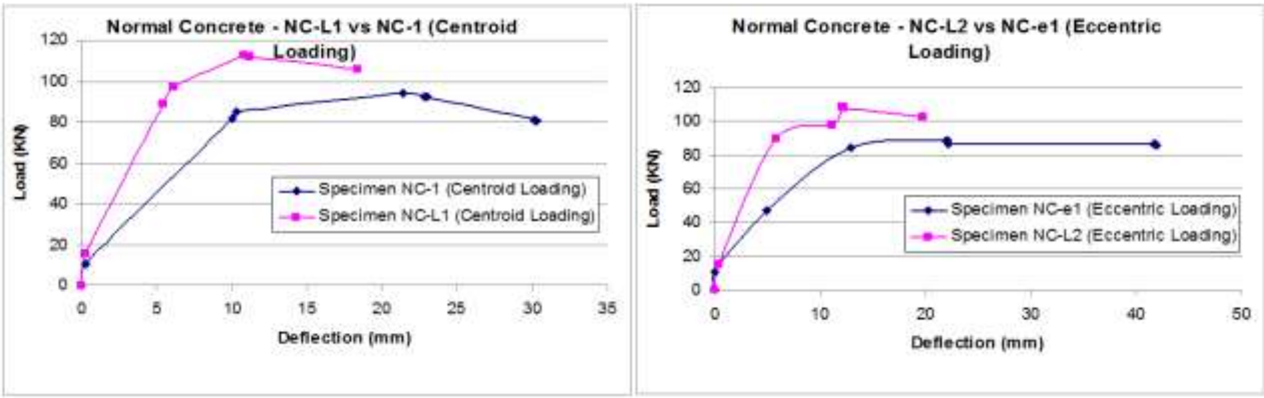

Fig. (11) Effect of Span with respect to normal concrete (Centric and Eccentric loading)

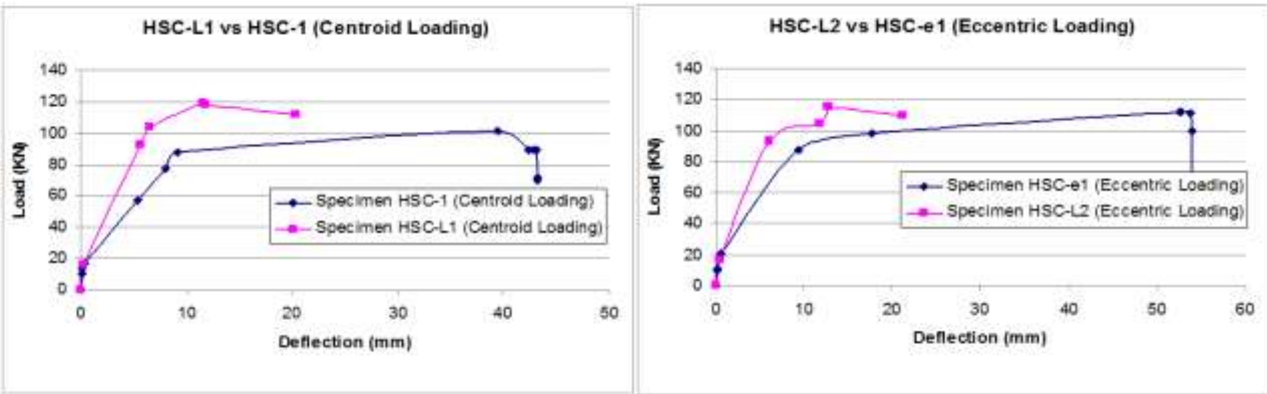

Fig. (12) Effect of Span with respect to High strength concrete (Centric and Eccentric loading)

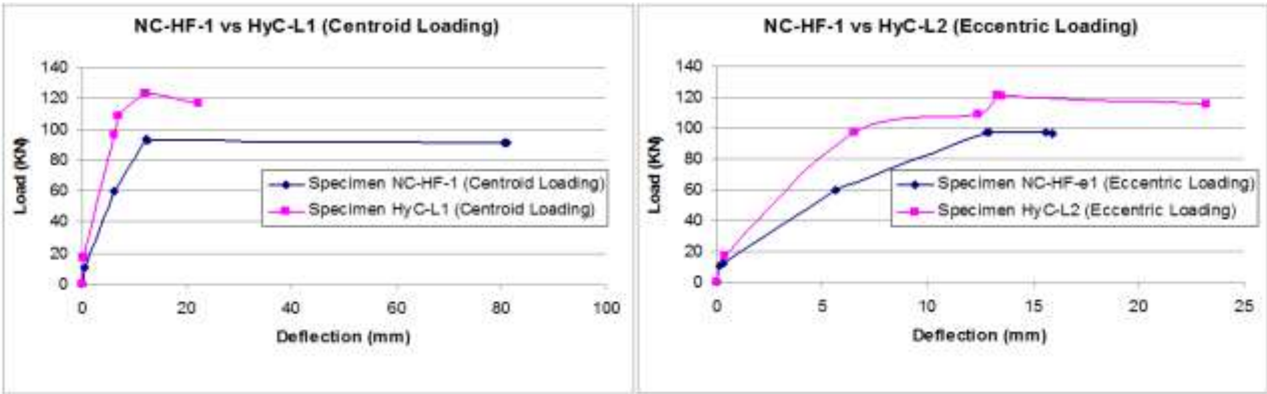

Fig. (13) Effect of Span with respect to Hyper concrete (Centric and Eccentric loading)

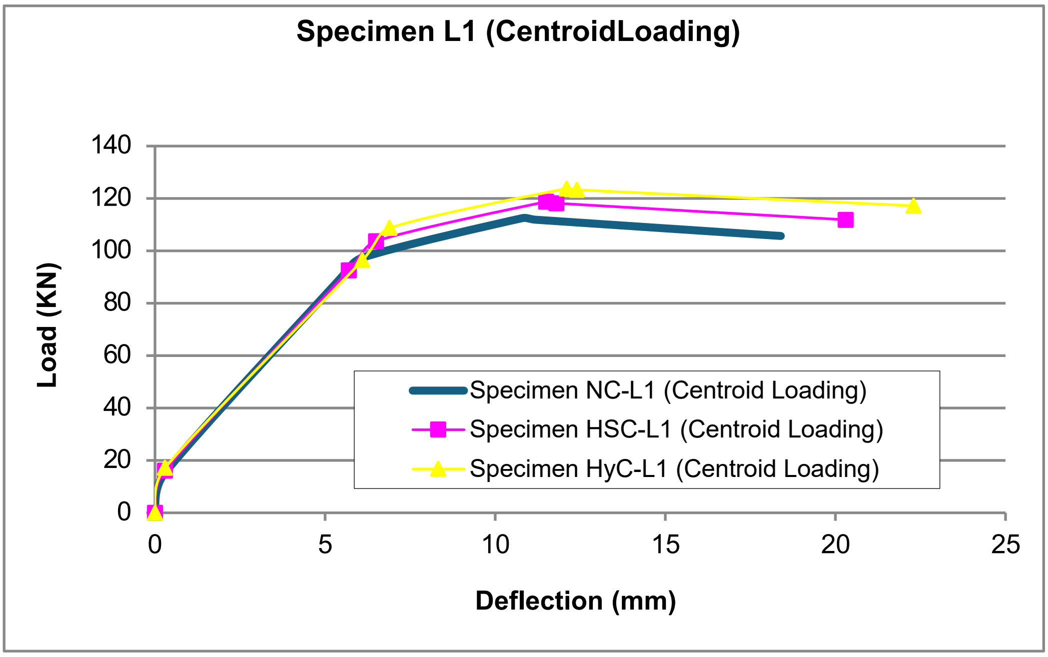

Fig. (14) Effect of Span for Specimen NC-L1, HSC-L1, HyC-L1 (Centroid Loading)

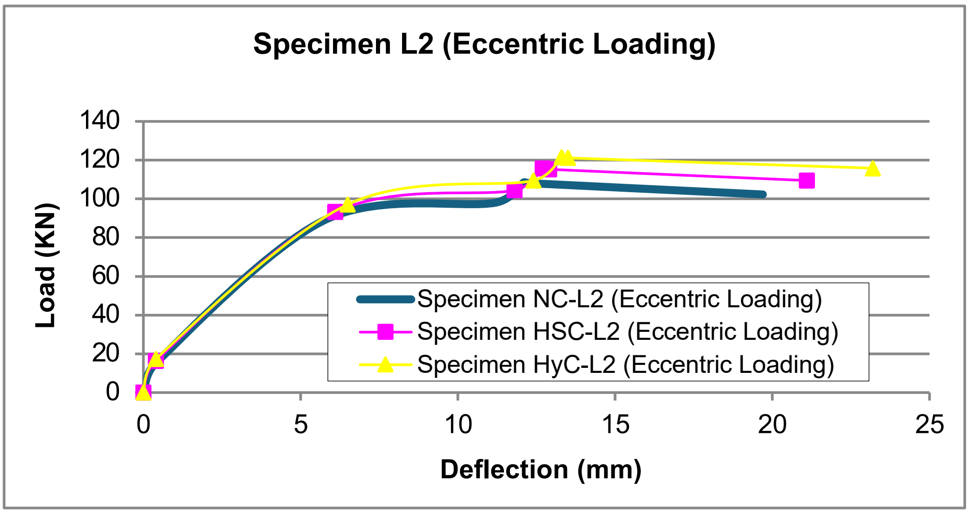

Fig. (15) Effect of Span for Specimen NC-L2, HSC-L2, HyC-L2 (Eccentric Loading)

5. CONCLUSION

This study successfully demonstrated the impact of geometric variations on the flexural behavior of reinforced concrete beams constructed with Normal Concrete (NC), High-Strength Concrete (HSC), and Hyper Concrete (HyC) under eccentric loading. Through detailed finite element modeling using Abaqus and a comparative parametric analysis, it was found that increasing beam depth and reducing span length significantly enhanced load-carrying capacity and reduced deflection. Conversely, decreasing beam width negatively affected structural performance. Among all material types, Hyper Concrete consistently outperformed NC and HSC, offering superior strength, ductility, and deflection control. These findings underscore the importance of optimized geometry and advanced materials in improving structural efficiency, and they provide valuable guidance for future design and construction of high-performance concrete structures.

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