World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

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Effect of transverse reinforcement on the shear behavior of reinforced concrete deep beams

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World Journal of Advanced Research and Reviews, 2022, 16(02), 1294-1303

Publication history: Received on 14 October 2022; revised on 21 November 2022; accepted on 28 November 2022

Article DOI: https://doi.org/10.30574/wjarr.2022.16.2.1267

Abstract

Reinforced concrete deep beams are safety critical members that carry heavy loads over short spans (ACI Committee 318, 2008). Design provisions in many codes can under or overestimate their shear strength, which introduces reliability concerns in practice (Kong & Evans, 1987). This study investigates how transverse reinforcement and concrete type influence the shear behavior of deep beams. Four simply supported deep beams were tested under four point loading, two made with self-compacting concrete and two with conventionally vibrated concrete, with a shear span to depth ratio of 0.75 for all beams (EFNARC, 2002; JSCE, 2005). Web reinforcement patterns were either congested, with vertical stirrups at 50 mm, or normal, with vertical stirrups at 100 mm. Key responses recorded include load deflection, diagonal cracking load, crack patterns, and ultimate load. Results show that self-compacting concrete with normal web reinforcement produced slightly higher diagonal cracking at ultimate capacities, while both concretes reached similar capacities under congested web reinforcement (Okamura & Ouchi, 2003; Choi, Kim, & Kang, 2012; Akinpelu & Adedeji, 2018). All beams failed by sudden shear compression after diagonal crack band formation. Findings endorse self-compacting concrete for deep beams where congestion and compaction challenges exist.

Keywords: Deep beams; Shear behavior; Transverse reinforcement; Self-compacting concrete; Vibrated concrete; a/d ratio; Diagonal cracking

1. Introduction

The increasing use of deep beams in contemporary structural applications arises from their capability to transfer large loads over short spans with minimal flexural deformation. Reinforced concrete (RC) deep beams are key structural elements in high-rise buildings, transfer girders, foundation pile caps, and water tanks, where their behavior under shear stress becomes critically significant. According to ACI Committee 318 (2008), a beam is classified as "deep" if its clear span is less than or equal to four times its overall depth, or if concentrated loads are applied within twice the depth from the face of the support. Unlike slender beams, load transfer in deep beams is dominated by compression struts rather than flexural action, leading to a nonlinear strain distribution across the depth of the beam. This unique mode of load transfer introduces complexities in the analysis and design of such members, especially under shear stress conditions.

Recent studies have noted that shear capacity in deep beams is affected significantly by the degree to which the natural load path defined as the direct line from the point of loading to the support is interrupted. Openings or weak zones along this path can considerably reduce shear strength. While several models and design approaches have been proposed to predict the shear behavior of deep beams, uncertainties persist, particularly for those constructed with high-strength concrete and incorporating transverse reinforcement (Tan et al., 1997; Yang et al., 2003). These reinforcements play a

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crucial role in controlling diagonal cracking and enhancing shear resistance, yet their interaction with modern concrete types such as Self-Compacting Concrete (SCC) remains under-researched.

SCC is an innovative construction material that flows under its own weight without the need for mechanical vibration. It was introduced to address the challenges associated with placing and compacting concrete in congested reinforcement zones (Okamura & Ouchi, 2003). Compared to conventional Vibrated Concrete (VC), SCC offers superior flowability, reduced labor requirements, improved surface finishes, and better mechanical integration around reinforcement. Despite these benefits, SCC's distinct material properties such as higher powder content and lower coarse aggregate volume can significantly affect the structural behavior of RC elements, necessitating a reevaluation of design provisions that were originally developed for VC (EFNARC, 2002; Akinpelu et al., 2017). Furthermore, studies such as those by Al-Khafaji et al. (2014) and Choi et al. (2012) highlight the negative effects of poor compaction in deep beams made with conventional concrete, such as voids and weak bonds, which can be mitigated by the use of SCC. Despite these developments, a critical knowledge gap exists in understanding how the shear behavior of RC deep beams is influenced by the use of SCC, especially when transverse reinforcement is incorporated. Most existing design equations are calibrated using data from VC specimens and may not accurately capture the structural response of SCC members. The lack of comprehensive experimental data on SCC deep beams with transverse reinforcement undermines the development of reliable design models for such systems. Consequently, this study seeks to bridge this gap by investigating the shear performance of high-strength RC deep beams fabricated with both SCC and VC, with particular focus on the influence of transverse reinforcement.

The primary aim of this research is to evaluate the shear behavior of high-strength concrete deep beams constructed with self-compacting and vibrated concrete, with special emphasis on the role of transverse reinforcement. To achieve this aim, the study investigates the effect of concrete type on failure loads and deflection response, determines the diagonal cracking and ultimate failure loads of deep beams, and examines how vertical web reinforcement distribution influences failure patterns and load-deflection behavior in deep beams with low shear span-to-depth (a/d) ratios.

The significance of this study lies in its potential to inform structural design practices and improve safety and performance standards for deep beams in modern construction. The findings will assist engineers and researchers in validating and possibly revising existing analytical models to better reflect the behavior of RC deep beams using innovative concrete technologies like SCC. Furthermore, it contributes to the broader goal of optimizing the structural efficiency and durability of critical load-bearing elements in civil infrastructure.

2. Background and Related Work

Shear design for deep beams is commonly treated with strut and tie models, where stirrups act as tension ties and crack control reinforcement while the concrete between load and support is represented as a compression strut (Ritter, 1899; ACI Committee 318, 2008). Aggregate interlock, dowel action, and crack bridging contribute to shear transfer after diagonal cracking, and adequate transverse reinforcement helps preserve strut efficiency (Kong & Evans, 1987; Kong et al., 1970).

Self-compacting concrete is proportioned to flow under its own weight without vibration, with slump flow targets verified by EFNARC and JSCE procedures (EFNARC, 2002; JSCE, 2005). Studies have reported improved bond and reduced defects near bars, which can be beneficial in regions of bar congestion and complex formwork (Okamura & Ouchi, 2003; Choi et al., 2008).

3. Materials and Methods

3.1. Specimens and Variables

A total of four deep beams (two made with SCC and two with VC) are manufactured, both concrete types will be designed to a target strength of 60 N/mm^2, where the size of the beams is 100mm (width) 250mm (height) 1000mm (length). Shear span to effective depth ratio (a/d) is 0.75 for all deep beams so that shear compression or tension failure can be induced. Two deformed steel rebars with 12-mm diameter (T12) are placed at the top of deep beams, while two deformed steel rebars with 12-mm diameter (T12) are situated at the bottom of the deep beams as longitudinal reinforcements. Web reinforcements, consisting of vertical closed stirrups with 4-mm diameter (T4), are incorporated in the deep beams as detailed in the experimental set-up on Table 1. The VC specimens are cast as reference beams. B9 and B11 specimens having stirrups spaced at 50 mm are manufactured as deep beams with congested reinforcement in shear, as shown in Fig. 1, while B10 and B12 specimens having stirrups spaced at 100 mm are casted as deep beams with a normal shear reinforcement condition, as shown in Fig. 2 consistent with prior deep beam studies on web reinforcement effects (Kong et al., 1970; Yang et al., 2007).

The formworks are detached after 24hrs of casting. The specimens are put in a tank and water was supplied to the specimens during the curing period for 28 days to prevent drying shrinkage cracks.

Table 1 Details of the experimental set-up

Group	Beam Code	Concrete Type	a/d	Lc	Vertical Web
A	B9	SCC	0.75	2T12	T4@50C/C
	B11	VC	0.75	2T12	T4@50C/C
B	B10	SCC	0.75	2T12	T4@100C/C
	B12	VC	0.75	2T12	T4@100C/C

3.2. Materials and Mix Characterization

Ordinary Portland cement, natural sand, and 12 mm nominal maximum size crushed gravel were used. The self-compacting concrete included super plasticizer which is known commercially as "CONPLAST". It is compatible with all Portland cements that meet recognized international standards. Super plasticized concrete exhibits a large increase in slump without segregation. However, this provides enough period after mixing for casting and to achieve the required flowability of SCC. Workability was verified by slump for vibrated concrete using ASTM C143 and by slump flow for self-compacting concrete per EFNARC and JSCE criteria (ASTM C143/C143M, 2003; EFNARC, 2002; JSCE, 2005).

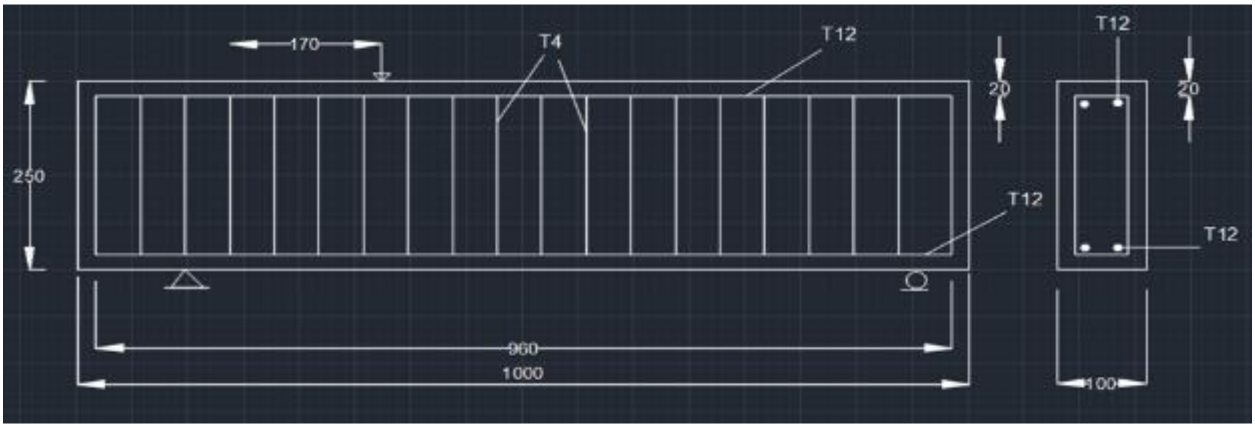


Figure 1 VC-50, B11 and SCC-50 B9 Specimen

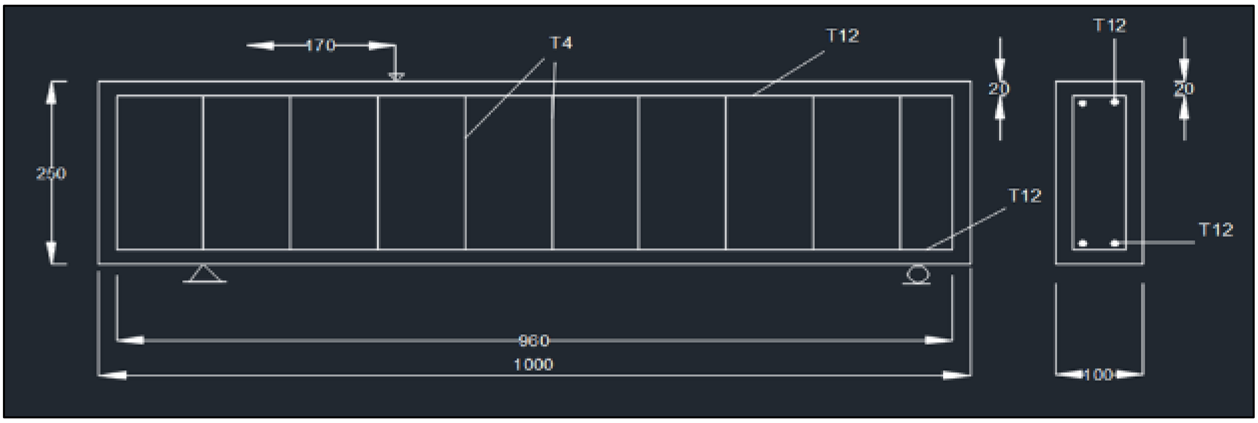


Figure 2 VC -100, B12 and SCC-100, B10 Specimen

3.2.1. Mix Design

As there is currently no standardized mix design procedure for SCC, the guideline given by EFNARC (2002) was adopted for the study. Both concrete types were designed to achieve high strength concrete of 60 N/mm^2 at 28 days. The fresh properties of VC will be evaluated based on slump cone test, while those of SCC will be evaluated based on the slump flow in accordance with the EFNARC (2002) specification. The hardened properties of the concrete will be evaluated based on cylindrical compressive strength and splitting tensile strength in line with ASTM-C39/C39M (2014) and ASTM C496/C496M (2004) respectively using Universal Testing Machine (UTM). Data on stress strain properties of the materials will also be obtained from the UTM.

3.3. Instrumentation and Test Method

Beams were tested under four point loading as shown in Fig 4. in a 300 kN universal testing machine with load applied in 10 kN increments. Mid span deflection was recorded, and crack formation and propagation were mapped at each increment as shown in Fig 3. until failure. The configuration produced a constant moment region between the loading points with zero shear, and maximum shear in the shear spans, which is standard for deep beam evaluation (ACI Committee 318, 2008; Tan et al., 2003).

Figure 3 Typical set-up of universal testing machine

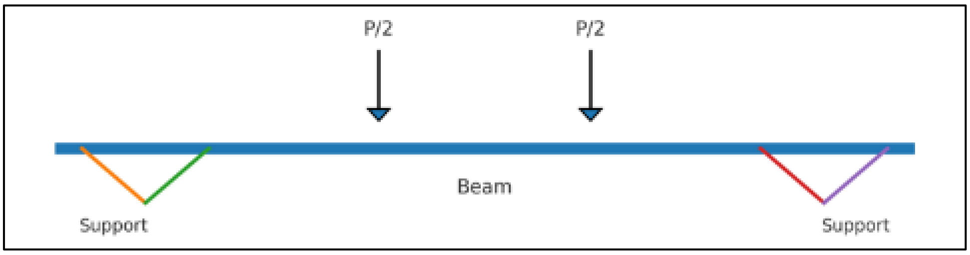


Figure 4 Four point bending test setup schematic

Figure 5 Universal Testing Machine

3.4. Mechanical Properties and Specimen Summary

Table 2 contains geometry, concrete type, measured compressive strength, cracking loads, and ultimate loads.

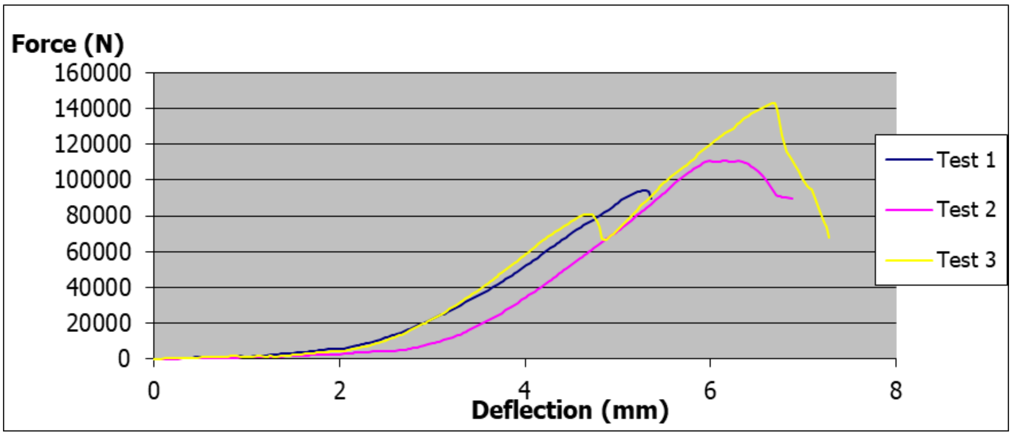
Table 2 Details and Properties of Tested Beams

Beam Code	L(mm)	Cross Section (mm)	Type	fc (N/mm²)	a/d	Flexural Failure (kN)	Diagonal Failure (kN)	Ultimate Failure (KN)	Vertical web	Horizontal web	Failure mode
B9	1000	250 x 100	SCC	22.111	0.75	102	115	194	T4@50 C/C	2T12	shear compression
B10	1000	250 x 100	SCC	22.111	0.75	74	83	171	T4@100 C/C	2T12	flexural failure
B11	1000	250 x 100	VC	23.325	0.75	99	108	192	T4@50 C/C	2T12	flexural failure
B12	1000	250 x 100	VC	23.325	0.75	119	84	191	T4@100 C/C	2T12	shear compression

4. Results

4.1. Load Deflection Response

The applied load versus mid-span deflection curves for all 4 beams are shown in Fig 6 according to their target compressive strength. As expected, the initial stiffness and overall response of the specimens differ depending on the shear span to depth ratio (Yang et al., 2007). No significant stiffness reduction was observed after the formation of diagonal cracks for beams with shear span to depth ratio less than 1.0. As expected, the specimens which have the same shear span to depth ratio show a higher drop in stiffness after the formation of the first diagonal crack. An additional predictable change in stiffness is observed after yielding of the main flexural reinforcement (Kong & Evans, 1987; Tan et al., 2003).


Force (N)
160000
140000
120000
100000
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0
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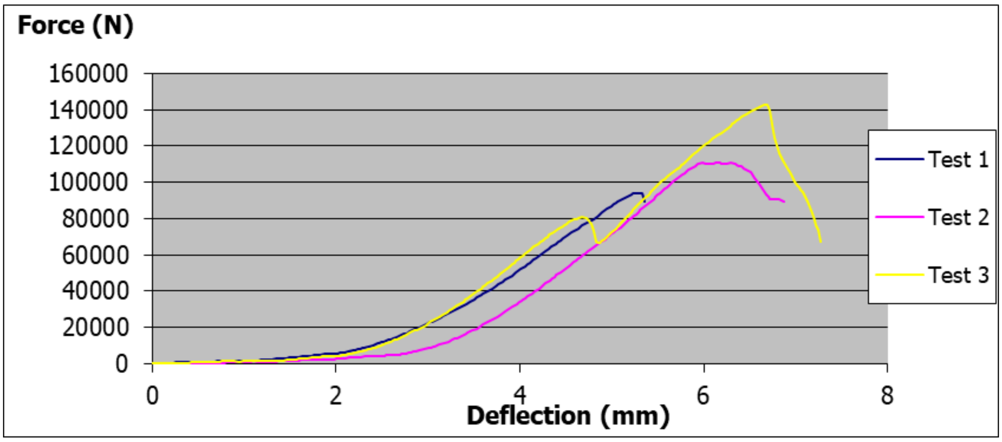
2
4
6
8
Deflection (mm)
Test 1
Test 2
Test 3


Force (N)
160000
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Deflection (mm)
Test 1
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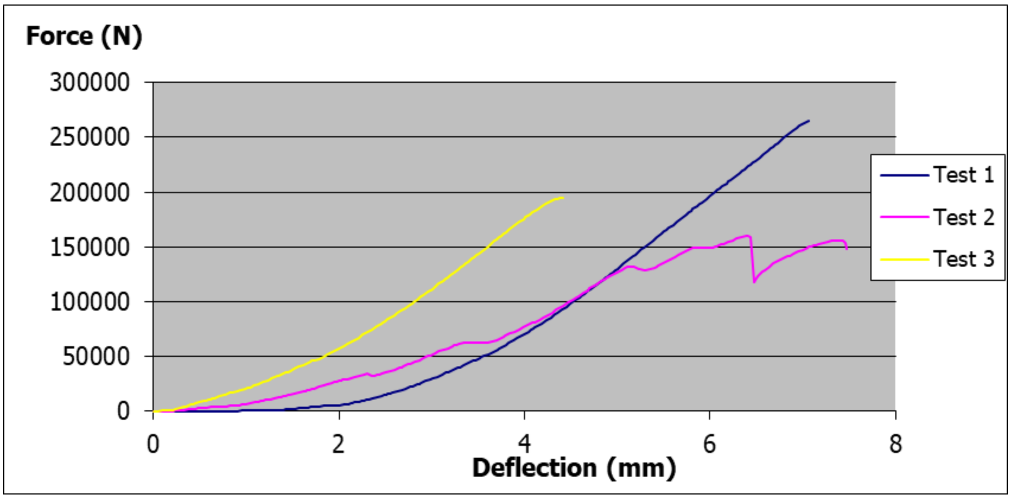
Test 3


Force (N)
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250000
200000
150000
100000
50000
0
0
2
4
6
8
Deflection (mm)
Test 1
Test 2
Test 3

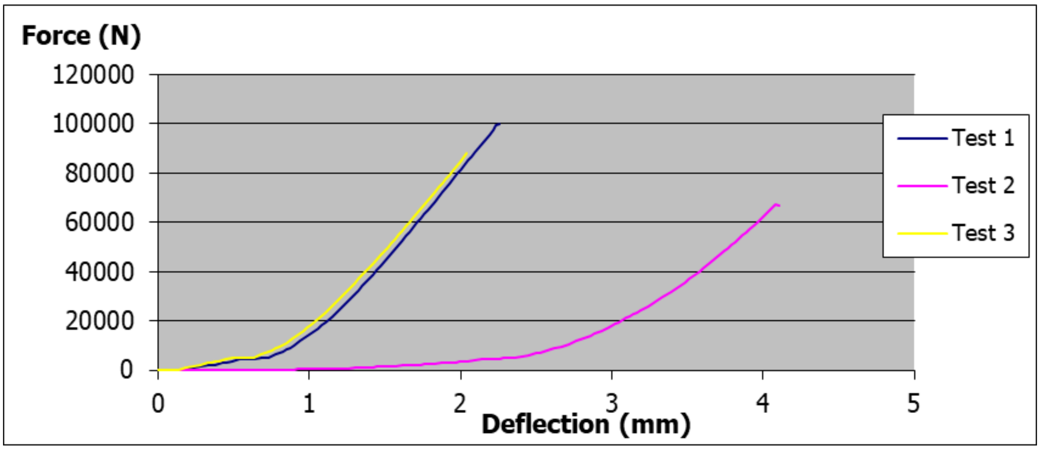

Figure 6 Load-Deflection of Deep Beams

4.2. Crack Patterns and Failure Modes

A consistent cracking sequence and sudden shear compression failure across all four deep beams, initial flexural cracks formed at the soffit at relatively low loads, then diagonal shear cracks developed in bands parallel to the compression strut and propagated toward supports and loading points until brittle failure, behavior that aligns with arch action and strut and tie mechanics for deep beams at low a/d, ACI Committee 318 provisions and classic experiments, ACI Committee 318, 2008, Kong, Robins, and Cole, 1970, Tan, Tong, and Tang, 2003, Yang, Chung, and Ashour, 2007. In Fig. 7, VC B11 with congested web reinforcement cracked in flexure at 99 kN, developed diagonal cracks at 108 kN, then failed through the inclined strut at 192 kN. In Fig. 8, VC B12 with normal web reinforcement showed flexural cracking at 119 kN that arrested short of the compression zone, diagonal cracks formed in layered bands at 84 kN, and failure occurred at 191 kN. In Fig. 9, SCC B9 with congested web reinforcement cracked in flexure at 102 kN, formed diagonal cracks at 115 kN, then failed suddenly at 194 kN. In Fig. 10, SCC B10 with normal web reinforcement cracked in flexure at 74 kN, formed diagonal cracks at 83 kN, and failed at 171 kN. For all specimens, flexural cracking initiated at about 13 to 17 percent of ultimate and did not penetrate the top compression zone due to early arch action, while diagonal cracking initiated at about 33 to 41 percent and extended simultaneously upward to the load points and downward to the supports, trends that agree with prior observations on deep beam behavior under four point loading, (Omeman et al., 2008, ACI Committee 318, 2008, Kong et al., 1970, Tan et al., 2003, Yang et al., 2007).

Figure 7 VC-50 B11

Figure 8 VC-100 B12

Figure 9 SCC-50 B9

Figure 10 SCC-100 B10

5. Discussion

5.1. Influence of Transverse Reinforcement

Reducing the stirrup spacing from 100 mm to 50 mm increased diagonal cracking loads and produced similar or slightly higher ultimate capacities, consistent with classic observations that web reinforcement improves post cracking behavior by preserving the compression strut (Kong et al., 1970; Yang et al., 2007).

5.2. Influence of Concrete Type

Self-compacting concrete with normal stirrup spacing reached higher diagonal cracking and ultimate loads than the vibrated concrete counterpart with normal spacing. Under congested stirrups, both concretes achieved similar ultimate capacities. These trends align with reports that self-compacting concrete improves consolidation near bars and can enhance shear performance where consolidation is difficult (Okamura & Ouchi, 2003; Choi et al., 2012; Akinpelu & Adedeji, 2018).

5.3. Failure Mechanics at Low Shear Span to Depth Ratio

For a shear span to depth ratio equal to 0.75, arching dominated the response, so flexural cracks did not penetrate the compression block. Failure was governed by compression strut crushing after diagonal cracking. The rate of stiffness loss and crack opening after diagonal cracking were controlled by the transverse reinforcement pattern (Kong & Evans, 1987; Tan et al., 2003).

5.4. Practical Implications

Where reinforcement congestion is unavoidable, self-compacting concrete can improve constructability and reduce casting time, while maintaining or slightly improving shear performance. Designers should still provide adequate transverse reinforcement beyond the critical section, since diagonal crack bands can extend into the compression zone before crushing (ACI Committee 318, 2008; Yang et al., 2007).

6. Conclusions

All beams failed by sudden shear compression following diagonal crack band formation. Reducing stirrup spacing from 100 mm to 50 mm increased diagonal cracking load and helped preserve stiffness after cracking. With normal stirrup spacing, self-compacting concrete showed slightly higher diagonal cracking and ultimate loads than vibrated concrete, while under congested stirrups both concretes reached similar strengths. This findings apply to beams with shear span to depth ratio equal to 0.75 and measured compressive strengths near 22 to 23 MPa. Additional tests across wider ranges of shear span to depth ratio and reinforcement ratios are recommended (Tan et al., 2003; ACI Committee 318, 2008).

6.1. Recommendations

Based on work conducted as part of this research the following recommendations for future work are reported:

- More experimental work is required to investigate the effect of different parameters such as main flexural reinforcement ratio and type and distribution of loading on the behavior and capacity of RC deep beams.
- More experimental work is needed to be done to investigate the effect of shear reinforcement on the size effect of RC deep beams.
- The finite element model needs to be further validated against experimental results

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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