Shear behavior of high-volume fly ash self-compacting concrete (HVFA-SCC) T-beams strengthened with carbon fiber reinforced polymer (CFRP)

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Abstract. Fly ash from coal combustion waste was utilized in this study as a key component in self-compacting concrete (SCC), specifically high-volume fly ash self-compacting concrete (HVFA-SCC) with 50% fly ash content, strengthened using carbon fibre reinforced polymer (CFRP) wrap-type sheets. The HVFA-SCC T-beams had dimensions of 120 mm web width × 240 mm web height, 80 mm flange thickness, and 440 mm flange width, with a total length of 3000 mm. There were three types of beams made in this study. The first type was HVFA-SCC T-beam without CFRP. The second type was strengthened by CFRP with the width of 100 mm and the spacing of 150 mm. The third type was the HVFA-SCC T-beam strengthened by CFRP with the width of 250 mm and the spacing of 300 mm. The beams were tested under monotonic two-point loading. The result showed that all beams were failure controlled by flexural failure. There was no shear failure occurred because the shear capacity of the beams exceeded the flexural capacity of the beams. These results confirm that the structural failure of the tested beams was governed by a flexural-controlled failure mechanism, rather than by shear. This is due to the actual concrete compressive strength exceeded the design compressive strength, increasing the concrete shear strength, leading to flexural failure in the beam

1 Introduction

Increasing carbon dioxide (CO_2) pollution has led many countries to strive to reduce emissions each year. In its production process, concrete mixtures consist of sand, gravel, cement, and water. The use of cement in normal concrete production is one of the triggers of global warming. Cement production or manufacturing creates significant CO_2 gas emissions. Annualy, the cement production industry contributed 7% of CO_2 gas emissions that trigger global warming. It can be calculated that for every 1 ton of cement produced by the cement production industry, it emits 1 ton of CO_2 gas [1].

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Based on this condition, the effort made is the creation of low-carbon or even zero-carbon concrete innovation without using cement as a binder. Such innovations are being widely pursued to increase production and usage. Geopolymer concrete and high-volume fly ash concrete, which utilize fly ash from coal combustion waste in coal-fired power plants, serve as alternative solutions to this problem.

Fly ash is hazardous waste categorized as B3 that endangers health. Fly ash produced from burning 1 ton of coal accounts for 15-17% of the coal mass. The high silica and alumina content in fly ash classifies it as a pozzolanic material that can react with $Ca(OH)_2$ to form a hard matrix for concrete. Fly ash offers many advantages over cement, such as better durability, workability, and late-age compressive strength compared to normal concrete. From an economic perspective, concrete with fly ash content can also reduce production costs, making it not only an environmentally friendly building material but also relatively inexpensive [2].

Self-compacting concrete (SCC) is concrete that can flow under its own weight. SCC has very high flowability and mixture homogeneity that prevents bleeding or segregation. Self-compacting concrete (SCC) provides benefits such as reduced construction time and labor costs, minimized vibration and noise pollution, higher compressive strength, and improved structural density [3].

Carbon Fiber Reinforced Polymer (CFRP) is a polymer material widely used for repairing and strengthening concrete structures. Initial studies on the failure behavior of concrete beams with added fiber reinforced polymer (FRP) found that the shear capacity of reinforced concrete beams can be increased by up to 150% compared to unstrengthened reinforced concrete beams [4].

Currently, studies on the shear behavior of T-section beams made of High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) using 50% fly ash strengthened with Carbon Fiber Reinforced Polymer (CFRP) do not exist. In practice, floor beams are generally monolithically integrated with floor slabs. Therefore, a study is needed on the shear strengthening of T-section beams made of High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) strengthened with Carbon Fiber Reinforced Polymer (CFRP), with the aim of providing references for designing the shear strength of T-beams made of High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) that are environmentally friendly and safe for use in construction practice.

2 Literature review

The use of cement in conventional concrete production is a significant contributor to global warming. Cement manufacturing generates substantial carbon dioxide (CO_2) emissions, with the cement industry accounting for approximately 4.5% of total global CO_2 emissions. Quantitatively, the production of 1 kg of cement is estimated to release about 1 kg of CO_2 [5].Based on these conditions, low-carbon strategies in infrastructure development are strongly encouraged to reduce indirect CO_2 emissions. One such approach involves the development of low-carbon or even zero-carbon concrete by eliminating cement as a binder. Innovations such as geopolymer concrete and high-volume fly ash concrete are increasingly promoted as viable alternatives to address this challenge.

Physically, fly ash exhibits particle fineness comparable to cement. Most of the coal fly ash particles were lower than 45μm. The particle retained on the 45μm sieve were from 15 to 30%, and the particle retained on 63μm sieve were from 10 to 20% [6]. Chemically, fly ash is rich in silica and alumina, with contents reaching approximately 80%. These similarities make fly ash a suitable replacement material for reducing cement content in concrete.

From the previous research's result [7] indicated that the shear capacity of square-section beams made of High Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) with 60% cement replacement by fly ash is higher than that of conventional concrete beams tested at 28 days, reaching 26.125 kN for HVFA-SCC 60% compared to 21.500 kN of normal concrete beam.

Normal concrete T-section beams strengthened with carbon fiber reinforced polymer (CFRP) using a U-wrap configuration exhibited a 45% increase in shear capacity [8]. However, this study did not involve HVFA-SCC.

CFRP wrapping is highly effective for beams with insufficient shear capacity, as it enables strain and deflection responses comparable to those of beams designed with adequate shear capacity [9].

Recent studies have investigated the flexural behavior of High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) beams strengthened with Carbon Fiber Reinforced Polymer (CFRP); however, these investigations were limited to square-section beams. Research on HVFA-SCC beams with T-sections remains unavailable, despite the fact that floor beams in practice are typically cast monolithically with slabs, and increased fly ash content tends to reduce shear strength and increase brittleness [10]. Therefore, a study on the shear strengthening of T-section HVFA-SCC beams using CFRP is required. The authors' previous work focused on square-section beams with 50% cement replacement by fly ash. The novelty of the present study lies in evaluating the shear capacity of T-section HVFA-SCC beams strengthened with CFRP, using 50% fly ash replacement, a target compressive strength of f′c = 25 MPa, and HVFA self-compacting concrete.

3 Experimental program

Experimental study was selected as the method used in this research, as direct testing can produce cause-and-effect relationships of a variable by comparing the influence of other variables. In this experimental test, the variable examined is the shear strengthening of T-beams made of high-volume fly ash self-compacting concrete with carbon fiber reinforced polymer (CFRP), conducted at the Structure and Building Materials Laboratory, Civil Engineering Study Program, Faculty of Engineering, Atma Jaya Yogyakarta University.

3.1 Material

3.1.1 High-volume fly ash self-compacting concrete (hvfa-scc)

High-volume fly ash self-compacting concrete (HVFA-SCC) is concrete with high flowability properties, capable of self-compacting without compaction equipment, and offers advantages such as greater homogeneity, impermeability, and smaller porosity.

The HVFA-SCC concrete material used in this research employs ready-mix concrete supplied by PT. Solusi Bangun Beton (SBB), a subsidiary of PT. Solusi Beton Indonesia engaged in concrete production.

It targets a compressive strength fc' = 25 MPa with 50% fly ash replacement for cement in the HVFA-SCC test specimens.

3.1.2 Carbon fiber reinforced polymer (CFRP)

The function of CFRP strengthening system is to increase strength or provide enhancement in flexural and shear capacity on columns or beams. CFRP has mechanical properties characterized by very high tensile strength.

In the research on shear enhancement of test beams, the CFRP type used was produced by PT SIKA Indonesia. The CFRP used was SIKAWrap® type 301C, which has specifications of tensile strength 4900 N/mm², modulus of elasticity 230,000 MPa, material thickness 0.167 mm, product width 500 mm, and uses SIKADUR®-330 as the adhesive to concrete. The installation method involves attaching it to the concrete surface that has been roughened and coated with epoxy, then pressing it with a roller during attachment so that the epoxy can penetrate into the fibers.

3.1.3 Strain gauge

Strain gauges were installed on the test beams to measure the strain magnitude on both concrete and reinforcing steel. Two types were used in this research: PL-06-11 type with 60 mm length for measuring concrete strain during loading, and FLA-11 type with 6 mm length for measuring reinforcing steel strain in the beams.

3.2 Test Specimens

3.2.1 T-Beams

Test beams were constructed using High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) with 50% fly ash application and target compressive strength fc' = 25 MPa, designed with T-section due to typical monolithic integration of beams and floor slabs in practice. One normal beam without CFRP strengthening served as the control, and four beams were CFRP-strengthened for shear capacity testing. T-section test beams had total width including concrete slab flange (bf) of 440 mm, web width (bw) of 120 mm, height (h) of 240 mm, slab flange thickness of 80 mm, and beam length (L) of 3000 mm; reinforcement used P12 bars for flexural reinforcement and P6 bars for shear reinforcement installed only in the flexural region (central 1/3 span), while slab reinforcement used P6-150 double layers. Test beam samples are shown in Table 1, while diagrams of the normal beam and strengthened beams are presented in Figures 1, 2, and 3

Table 1. Test beam data

Beam ID	Strengthening Type	Test Type
BR-NORMAL-3000-1	Normal beam	Control beam
BS-HVFA-SCC-100-150-1	CFRP SIKA Wrap, 1 layer, 100 mm width, 150 mm spacing	Shear beam
BS-HVFA-SCC-100-150-2	CFRP SIKA Wrap, 1 layer, 100 mm width, 150 mm spacing	Shear beam
BS-HVFA-SCC-250-300-1	CFRP SIKA Wrap, 1 layer, 250 mm width, 300 mm spacing	Shear beam
BS-HVFA-SCC-250-300-2	CFRP SIKA Wrap, 1 layer, 250 mm width, 300 mm spacing	Shear beam

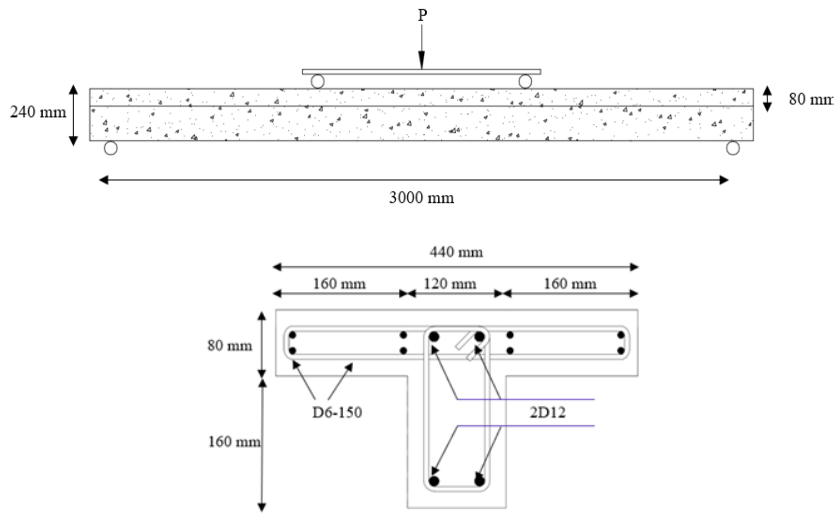

Fig. 1. BR-Normal.

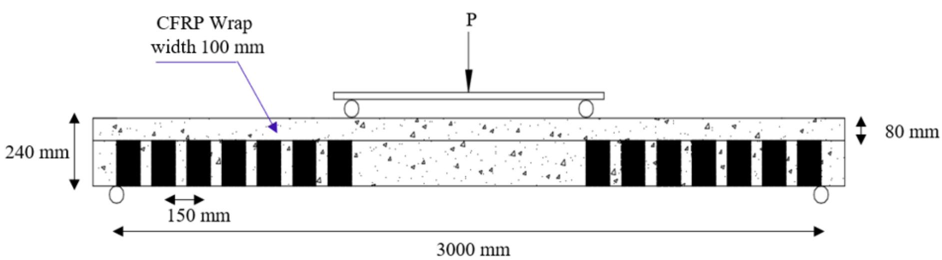

Fig. 2. BS-HVFA SCC 100-150.

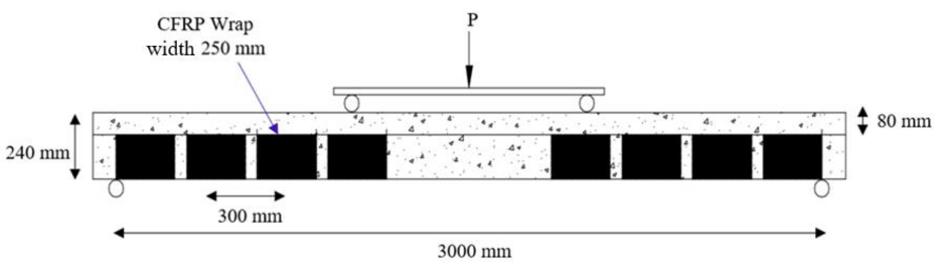

Fig. 3. BS-HVFA SCC 250-300

3.2.2 Testing Methods

Shear reinforcement was provided only in the central 1/3 span of the beams (flexural region) to ensure shear failure during testing, with one strain gauge installed on the shear reinforcement to measure shear-induced strain. Two additional strain gauges for concrete strain monitoring were placed on the side concrete surface at 45° and -45° angles. Figure 4 shows the strain gauge placement.

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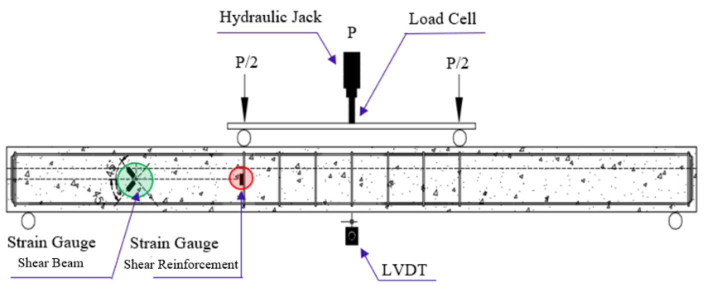


Fig. 4. Placement of strain gauge on beam

3.2.3 Test Setup

Test beams were placed on a loading frame with roller supports at both ends, tested under static loading. Loading was applied at two points 1000 mm apart to induce pure shear and flexure. Beam surfaces were coated with white paint and marked with perpendicular black ink lines every 50 mm for crack monitoring. LVDT (Linear Variable Displacement Transducer) with 150 mm capacity measured mid-span deflection. Loading stopped when beam collapsed and data logger ceased recording load increase.

4 Results and Discussion

4.1 Concrete Material

The concrete properties tested in this research were compressive strength and modulus of elasticity, tested at 28 days as shown in Table 2.

Table 2. 28-Day Concrete Compressive Strength Test Results

Compressive Strength	Strengthening Type		Experimental Modulus of Elasticity	Average
Sample	**Load (kN)**	**fc (Mpa)**	E=4700 $\sqrt{fc}$	**fc (Mpa)**
SCC 50% (9)	600	33.95	27387	35.16
SCC 50% (10)	615	34.80	27727	
SCC 50% (11)	580	32.82	26926	
SCC 50% (12)	690	39.05	29369	

The compressive strength of HVFA-SCC concrete with 50% fly ash addition averaged around 35 MPa at 28 days, exceeding the design strength of 25 MPa

4.2 Experimental Beam Testing for Shear Strengthening

Test beams subjected to loading produced results recorded by data logger, processed into graphs showing load-deflection and load-strain relationships. Beams were tested to their ultimate capacity until failure. Results for each test beam are shown in Table 3.

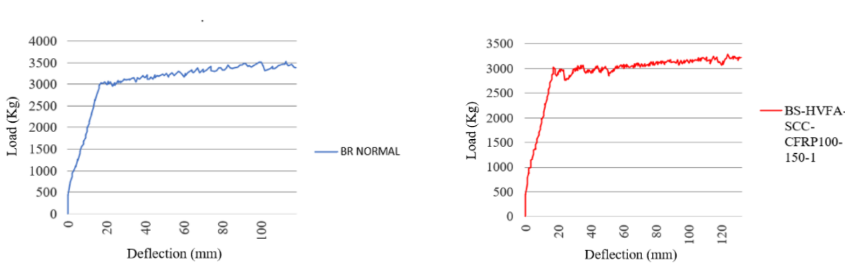
Table 3. Test Beam Capacity Results

Test beam	Ultimate Load (kg)	Deflection (mm)	Rebar Strain (με)	Concrete Strain (45°) (με)	Concrete Strain (-45°) (με)
BR-NORMAL-3000-1	3387.5	118.5	559.59	45.28	199.06
BS-HVFA SCC 100-150-1	3222.5	132.85	527.86	50.94	46.23
BS-HVFA SCC 100-150-2	3370	132.8	6198.79	1195.16	40.57
BS-HVFA SCC 250-300-1	3312.5	140.85	28.85	0.94	13.21
BS-HVFA SCC 250-300-1	3382.5	130.9	92.30	118.86	19.81

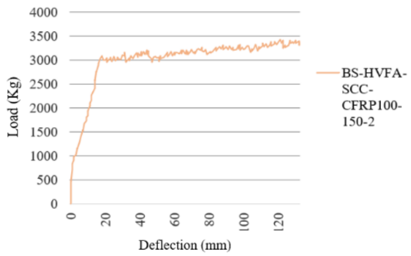
Table 3 results show the normal beam (BR-NORMAL) withstood maximum load of 3387.5 kg with deflection of 118.5 mm and rebar strain 559.59 με, while concrete strains were 45.28 με and 199.06 με for 45° and -45° strain gauges. Modified HVFA-SCC-CFRP beams showed slightly lower load capacity than normal beams but different deflection and strain combinations, indicating changes in stiffness and cracking behavior due to alternative materials and CFRP strengthening.

4.3 Load-Deflection Relationship

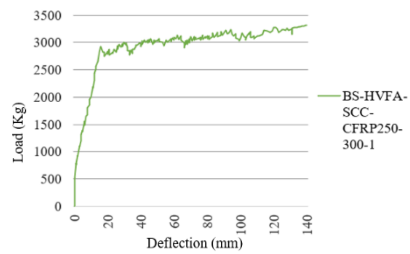
Dial load readings were processed into graphs depicting load-deflection relationships from reinforced concrete beam specimen testing, shown in Figure 5.



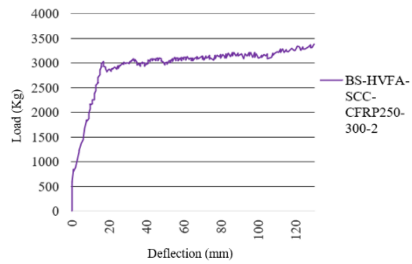
(a) (b)



(c)



(d)



(e)

Fig. 5. (a) Load-Deflection Relationship Graph – BR-NORMAL-3000-1; (b) Load-Deflection Relationship Graph – BS-HVFA SCC 100-150-1; (c) Load-Deflection Relationship Graph – BS-HVFA SCC 100-150-2; (d) Load-Deflection Relationship Graph – BS-HVFA SCC 250-300-1; (e) Load-Deflection Relationship Graph – BS-HVFA SCC 250-300-2

In general, variations of HVFA in SCC concrete tend to increase the ductility of beams (greater deformation capacity before collapse), and the graphs above show that the HVFA-SCC beam with 50% fly ash addition for the normal beam (BR-NORMAL-3000-1) tested at 28 days age has smaller deflection values at maximum load compared to HVFA-SCC beams reinforced with CFRP wrapping in the shear region. The load-deflection graphs for normal HVFA-SCC beams as well as those with CFRP reinforcement show that the deflection values increase with the applied load increments; the increase in deflection values is always proportional to each load increment, such that at the initial loading stage, the load-deflection relationship exhibits a linear pattern until the end when the beam collapses. The changes in deflection increments that occur, both in normal HVFA-SCC beams and those with CFRP reinforcement, are caused by the appearance of crack openings immediately before collapse, which results in significantly increased deflection values while the load tends not to increase further.

4.4 Crack Patterns in Test Beam Specimens

The crack patterns in beam specimens BR-NORMAL-3000-1 (see Figure 6 (a); (b); and (c)), BS-HVFA-SCC-CFRP100-150-1 (see Figure 7 (a); (b); and (c)), BS-HVFA-SCC-CFRP100-150-2 (see Figure 8 (a); (b); and (c)), BS-HVFA-SCC-CFRP250-300-1 (see Figure 9 (a); (b); and (c)), and BS-HVFA-SCC-CFRP250-300-2 (see Figure 10 (a); (b); and (c)), which reveals that no shear failure crack patterns are present in the test beam specimens, either in normal HVFA beams or HVFA beams with added reinforcement. This indicates that the shear capacity of HVFA concrete is higher than the maximum shear force occurring in the beams during testing, where no shear cracking failure occurs in the shear region of the beams.

(a) (b) (c)

Fig. 6. (a) Detailed crack pattern at midspan – BR-NORMAL-3000-1; (b) detailed crack pattern at one-third span on the right edge – BR-NORMAL-3000-1; (c) detailed crack pattern at one-third span on the left edge – BR-NORMAL-3000-1.

The control beam specimen exhibited flexural cracking as the initial failure mode, with the first crack occurring at a load of 1275 kg and a corresponding deflection of 5.5 mm. Loading progressed until the peak load was reached, after which no further increase in load was observed while deflection continued to increase, indicating post-peak ductile behavior. The maximum load attained was 3387.5 kg with a deflection of 118.5 mm, accompanied by reinforcement strain of 559.59 με and concrete strains of 45.28 με and 199.06 με at the monitored locations

(a) (b) (c)

Fig. 7. (a) Detailed crack pattern at midspan – BS-HVFA SCC 100-150-1; (b) detailed crack pattern at one-third span on the right edge – BS-HVFA SCC 100-150-1; (c) detailed crack pattern at one-third span on the left edge – BS-HVFA SCC 100-150-1.

The initial flexural cracking of specimen BS-HVFA-SCC-CFRP100-150-1 occurred at a load of 1357.5 kg with a corresponding deflection of 6.3 mm**.** The maximum load reached 3222.5 kg**,** after which deflection continued to increase up to 132.85 mm without any further load increment. At peak load, the steel reinforcement strain was 527.86 με**,** while the measured concrete strains were 50.94 με and 46.23 με**,** respectively.

(a) (b) (c)

Fig. 8. (a) Detailed crack pattern at midspan – BS-HVFA SCC 100-150-2; (b) detailed crack pattern at one-third span on the right edge – BS-HVFA SCC 100-150-2; (c) detailed crack pattern at one-third span on the left edge – BS-HVFA SCC 100-150-2.

The BS-HVFA-SCC-CFRP100-150-2 beam specimen exhibited initial flexural cracking as the first crack at a load of 1552.5 kg with a corresponding deflection of 7.7 mm. Loading continued until the peak load of 3370 kg, beyond which no further load increase occurred while deflection continued to grow, reaching 132.8 mm**.** At the peak condition, the steel reinforcement strain was 6198.79 με**,** whereas the measured concrete strains were 1195.16 με and 40.57 με**,** respectively.

(a) (b) (c)

Fig. 9. (a) Detailed crack pattern at midspan – BS-HVFA SCC 250-300-1; (b) detailed crack pattern at one-third span on the right edge – BS-HVFA SCC 250-300-1; (c) detailed crack pattern at one-third span on the left edge – BS-HVFA SCC 250-300-1.

The control beam specimen exhibited initial flexural cracking as the first crack at a load of 757.5 kg with a corresponding deflection of 1.65 mm**.** Loading progressed to the peak load of 3312.5 kg**,** after which the load remained constant while deflection continued to increase, reaching 140.85 mm**.** At the peak condition, the steel reinforcement strain was 28.85 με**,** while the recorded concrete strains were 0.94 με and 13.21 με, respectively.

(a) (b) (c)

Fig. 10. (a) Detailed crack pattern at midspan – BS-HVFA SCC 250-300-2; (b) detailed crack pattern at one-third span on the right edge – BS-HVFA SCC 250-300-2; (c) detailed crack pattern at one-third span on the left edge – BS-HVFA SCC 250-300-2.

The control beam specimen exhibited initial flexural cracking as the first crack at a load of 1070 kg with a corresponding deflection of 3.35 mm. Loading continued until the peak load of 3382.5 kg, beyond which no further load increase occurred while deflection increased to 130.9 mm. At peak loading, the steel reinforcement strain reached 92.30 με, while the recorded concrete strains were 118.86 με and 19.81 με, respectively.

Based on crack pattern observations, all beam specimens exhibited structural failure initiated by the development of flexural cracks due to the inability of the beams to sustain loads exceeding their capacity. Crack propagation intensified within the flexural zone up to the peak load, beyond which no further load increase occurred while beam deflection continued to increase, particularly in regions with significant crack widths. This behavior was consistently observed across all specimens. The maximum shear forces recorded were relatively uniform for all beams, with values of 16.94 kN for the unstrengthened HVFA beam, 16.48 kN on average for beams strengthened with 100 mm CFRP at 150 mm spacing, and 16.73 kN for beams strengthened with 250 mm CFRP at 300 mm spacing. The actual concrete compressive strength exceeded the design compressive strength, thereby increasing the concrete's shear strength. The beam failed in flexure, so the CFRP's contribution to increasing shear strength was not apparent.

In contrast, shear capacity calculations based on SNI 8971:2021 [11], using the experimentally obtained concrete and steel strengths, indicate a significant increase in shear capacity due to CFRP strengthening. The unstrengthened HVFA beam relied solely on the concrete shear contribution (Vc), resulting in a capacity of 25.103 kN. With CFRP strengthening, the shear capacity increased to 35.86 kN for the 100 mm width–150 mm spacing configuration and further to 39.49 kN for the 250 mm width–300 mm spacing configuration, demonstrating the substantial theoretical contribution of CFRP to the beam's shear capacity.

5 Conclusion

Based on the experimental program and the discussion above, several conclusions can be drawn as follows:

1. All beam specimens failed at their maximum applied load, exhibiting relatively uniform ultimate load capacities. The unstrengthened HVFA-SCC beam reached a maximum load of 3387.5 kg, while beams strengthened with CFRP strips of 100 mm width and 150 mm spacing achieved ultimate loads of 3222.5–3370 kg, and those with 250 mm width and 300 mm spacing reached 3312.5–3382.5 kg.
2. The test results indicate that the maximum shear forces of all beam specimens were relatively uniform, ranging from 16.11 to 16.94 kN, for both unstrengthened HVFA beams and CFRP-strengthened beams, suggesting that the experimental shear demand did not reach the ultimate shear capacity of the sections. In contrast, theoretical calculations based on SNI 8971:2021 using actual material properties show a significant increase in shear capacity due to CFRP strengthening, from 25.10 kN for the unstrengthened beam to 35.86 kN and 39.49 kN for the 100 mm–150 mm and 250 mm–300 mm CFRP configurations, respectively, confirming the effective theoretical contribution of CFRP to shear capacity enhancement.
3. All specimens exhibited flexural crack–dominated failure, characterized by crack propagation from the tensile zone toward the compression zone up to the peak load, followed by continued deflection without further load increase, confirming that the structural failure mechanism was governed by flexural failure.

4. The theoretical analysis shows good agreement between the predicted and experimental flexural loads, with values of 32.60 kN and 33.88 kN, respectively, while the theoretical shear-governed concentrated load is significantly higher at 50.21 kN. These results confirm that the structural failure of the tested beams was governed by a flexural-controlled failure mechanism, rather than by shear. This is due to the actual concrete compressive strength exceeded the design compressive strength, thereby increasing the concrete shear strength and leading to flexural failure in the beam.
5. No shear failure was observed in any of the tested specimens, indicating that the shear capacity of HVFA-SCC beams exceeded the shear demands imposed during testing. Both experimental observations and theoretical analysis confirm that CFRP strengthening significantly enhances the shear capacity, thereby increasing the safety margin against shear failure, although the overall structural response remains governed by flexural-controlled behavior.

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