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(Research/Review) Article

Impact of Concrete Grade and Stirrups Spacing on Performance Enhancement of Hybrid T-Beams Using Lightweight Concrete and High Compressive Strength Combinations

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Abstract: This study examines the performance of a total of ten reinforced concrete T-beams, nine of which were made as hybrid beams by casting the web with LW concrete and the flange with HS concrete; the last beam was cast as a normal beam (entirely cast with HS concrete). All beams underwent testing under two-point loads following a 28-day period. The variables of the experimental program include the concrete grade within the web (46, 62, and 82 MPa) and stirrup distribution distances (100, 200, and 300 mm). The experimental program includes load-deflection curves and failure modes for hybrid and normal beams. The results showed that all the beams failed in shear-flexural mode. Also, increasing flange compressive strength increased shear. strength. Increasing stirrup distribution distance from 100 to 200 and 300 mm reduced the ultimate load capacity; specimens with stirrup spacing of 300 mm failed directly after yielding of steel due to crushing the concrete over the support and spalling concrete cover within the shear zone. The study also determined that reducing stirrup spacing to 100 mm did not alter the failure mode, as shear failure was dictated by the compressive strength of the lower layer of the hybrid beams (19 MPa compressive strength of LW concrete).

Keywords: Hybrid Beams; Shear Strength; Lightweight Beam; Stirrup Spacing; Deflection

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1. Introduction

Efficiency and dependability are crucial factors in construction. Regarding RC beams in civil engineering, these elements serve as primary load-bearing components in many constructions, including buildings, bridges, and numerous other infrastructure projects. Design considerations and structural integrity are closely associated with safety, serviceability, and durability issues related to reinforced concrete beams. In that respect, the engineers and designers' understanding of influencing parameters regarding performance becomes vital.

The benefits of interaction between LWC and HSC in hybrid sections are numerous. To begin, LWC reduces overall weight without affecting the strength of the structure, while HSC increases load-bearing capacity, especially when compressive stresses are present, Ezzulddin and Merie [1]. This hybrid strategy offers several advantages in enhancing energy efficiency within a building, as lighter buildings necessitate reduced energy for heating and cooling.

Lightweight Concrete (LWC) is an environmentally sustainable material characterized by low density, which decreases building expenses by lowering the dead load. A variety of lightweight aggregates with diverse characteristics is presently accessible. Lightweight aggregates may originate from natural sources such as tuff, diatomite, scoria, and pumice, or from artificial sources including industrial by-products and permeable materials like slag, vermiculite, slate, and expanded clay, Salahaldin et al. [2]. Low-density aggregate makes SLW concrete, with a density range from 1440 to 1840 kg/m³ in an air-dry state. And with a minimum 28-day compressive strength of 18 MPa. Kassim, [3].

One of the main factors in the design of RCB is the strength of concrete. HS concrete is gaining much recognition in the construction of RCB because it can bear very high compressive loads. HS concrete resists deflection. resulting from loading; this improves its performance as a structural element. Al-Osta et al. [4] constructed from high-strength concrete (HSC) exhibited a considerable decrease in deflection and an enhancement in shear resistance relative to beams fabricated from conventional concrete. Al-Zu'bi et al. [5] have indicated that HSC exhibits minimal deflection at failure with larger reinforcement sizes, resulting in enhanced structural performance under load.

Shear reinforcement with the use of stirrups is of paramount importance to avoid shear failure. The ability of beams to withstand shear stresses is substantially affected by the spacing and diameter of the stirrups. This is evident from the study conducted by Makki, [6]. Closer spacings of stirrups increase the shear strength by reducing crack opening and thus strengthening the structural element Chen et al, [7]. Mofidi and Chaallal, [8] also established that different stirrup configurations can provoke critical changes in the concrete beam load-carrying capacity, hence making reinforcement design very important in shear behavior.

In recent years, retrofitting techniques have also been drawing much attention as an effective method of enhancing the performance of existing RCBs and even in prolonging the service life of these old infrastructures. Shadmand et al. [9] tried retrofitting steel fiber-reinforced composite jackets and achieved remarkable enhancement of ductility and load-bearing capability. Baghi and Barros, [10] developed hybrid composite plates to strengthen beams and reported quite considerable increments in shear resistance. These retrofitting strategies would increase the shear capacity of the RCBs and improve normal durability for safe and efficient serviceability in the longer term.

While all these studies have been performed, the interaction effect of reinforcement diameter, concrete strength, spacing of stirrups, and method of retrofitting on the shear behavior of hybrid beams remains uninvestigated to date. While many have addressed the individual factors, detailed investigation of these interactions within a hybrid beam remains unavoidable. Various authors, like Makki, [6] and AL-Farttoosi et al. [11], stated that this finally will result in appropriate structural performance, especially under high-intensity load applications.

2. Experimental Program

This study provides a comprehensive examination of the experimental configuration established to assess the performance of hybrid beams, which are composed of HS concrete and LW concrete. The influences of different concrete properties and stirrup spacings on the carrying and deflection behavior of these hybrid beams are discussed. Experimental tests in the work were carried out at the Structural Engineering Laboratory in the College of Engineering, University of Kirkuk. The sections that follow describe the materials used, concrete mix proportions, beam specimen details, preparation techniques, and procedures adopted during testing.

2.1. Study Variables

The experimental study aimed to systematically assess the key variables affecting the shear performance of hybrid RCBs. The primary variables examined include:

a. Concrete Type: Hybrid beams integrating High-Strength Concrete and Lightweight Concrete
b. Compressive strength of High-Strength Concrete: Three grades of HS concrete were used (46, 62, and 84 MPa).
c. Stirrups Distribution Spacing: The study examined three stirrup spacing distances (100, 200, and 300 mm) to understand their impact on shear strength.

2.2 Beam Specimens Details

The experimental program involved the testing of ten T-beams simply supported as shown in Figure (1). Nine of those beams were hybrid beams casted with high strength concrete in the flange and lightweight concrete in the web, while the last beams were fully cast using HS concrete as reference beams. The beam specimens were designed to have an overall length of 1650 mm, a web width of 100 mm, a height of 190 mm, a flange width of 200 mm, and a flange thickness of 60 mm.

Entire beams were reinforced with four longitudinal compression bars (4ϕ8mm) and (2ϕ12mm) flexural reinforcement of deformed steel bars. The vertical shear reinforcement (stirrups) was composed of 8 mm diameter stirrups with spacings (100, 200, and 300 mm).

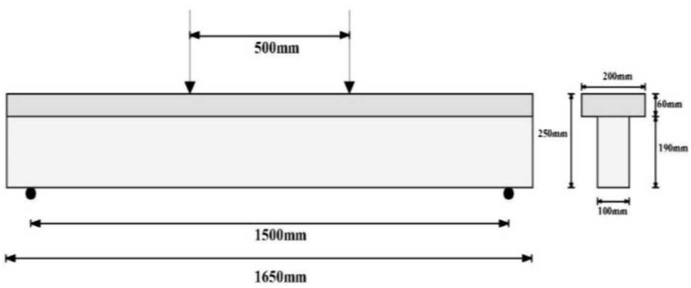


Figure 1. Cross section of the tested beams.

2.3. Experimental Groups

The experimental program divided into three groups. Each containing beams with different configurations of concrete type, stirrup spacings, and fixed flexure reinforcement (2ϕ12 mm). The groups are cleared in Figure (2) and summarized below:

a. Group 1: Three hybrid beams with three grades of HS concrete (46, 62, and 84 MPa) within the flange, LW concrete in the web, and stirrup spacing (100 mm), designated as HB-F1-D3-S100, HB-F2-D3-S100, and HB-F3-D3-S100.

b. Group 2: Three hybrid beams with three grades of HS concrete (46, 62, and 84 MPa) within the flange, LW concrete in the web, and stirrup spacing (200 mm), designated as HB-F1-D3-S200, HB-F2-D3-S200, and HB-F3-D3-S200.

c. Group 3: Three hybrid beams with different grades of HS concrete (46, 62, and 84 MPa) within the flange, LW concrete in the web, and stirrup spacing (300 mm), designated as HB-F1-D3-S300, HB-F2-D3-S300, and HB-F3-D3-S300.

d. The reference beam (NTB-F1-D3-S300) is made entirely with HS concrete (46 MPa) with flexural reinforcement of (2ϕ12 mm) and stirrup spacing of 300 mm.

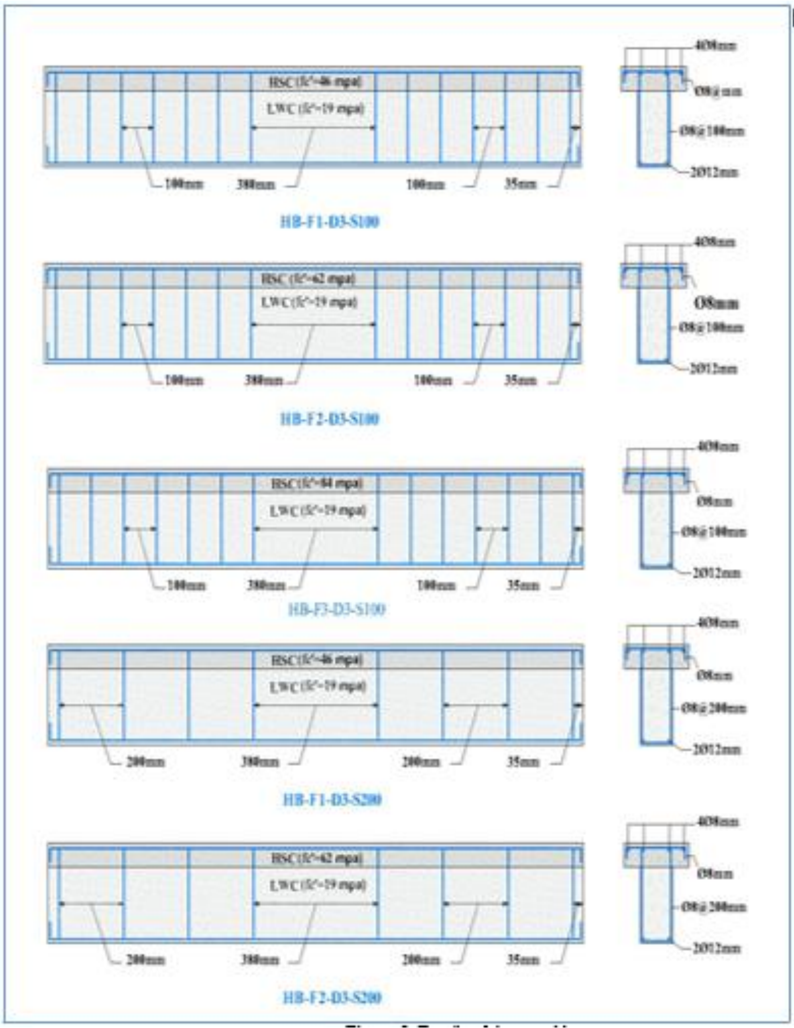


Figure 2. Details of the tested beams.

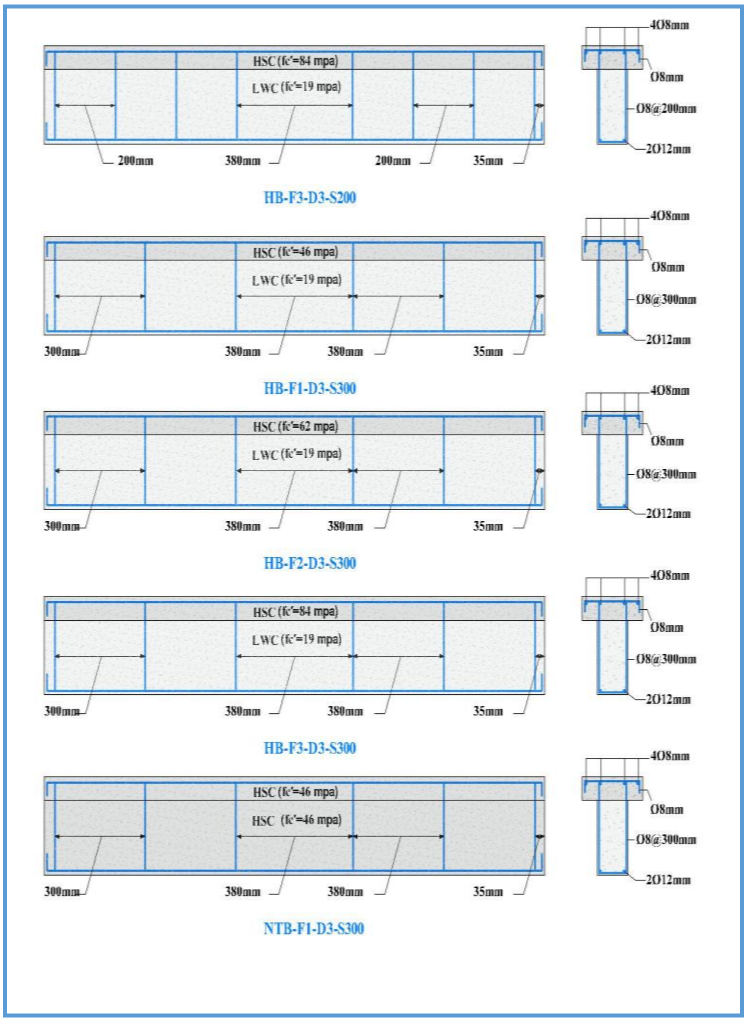


Figure 3. Continued…

2.5. Materials

- **Cement**: Type I (Ordinary Portland cement) was used for all concrete mixes, tested under **ASTM C150** standards.
- **Fine Aggregate**: Natural river sand sourced from Qara Salem, Kirkuk/Iraq, was used as fine aggregate. The sand met ASTM C33 standards.
- **Coarse Aggregate**: NW crushed aggregate with a maximum size of 12 mm and lightweight claystone coarse aggregate with maximum size 19 mm and specific gradations adhering to **ASTM C33** specifications
- **Silica Fume**: Silica fume was added to the high-strength concrete mixes to enhance mechanical properties, meeting **ASTM C1240** standards.
- **Superplasticizer**: Viscocrete-1681, a third-generation superplasticizer, was used to improve workability and reduce water content in high-strength concrete mixes.

2.6. Concrete Mix Design and Trial Mixes

The mix design for both the LW concrete and HS concrete was developed through trial mixes. The required compression strengths for the lightweight concrete and HS concrete are 19 MPa, 46 MPa, 62 MPa, and 84 MPa, respectively. An electric mixer with a capacity of 0.06 m^3 was used for batching, and trial batches were conducted to ensure proper workability and mix proportions.

2.7. Fabrication of Specimens

The beams were constructed in two phases. Initially, the web of each beam was cast using lightweight concrete, subsequently followed by the casting of the flange using high-strength concrete after a duration of 24 hours. A needle vibrator was employed during casting to provide adequate compaction and reduce voids. The beams underwent curing through immersion in a water bath for 28 days to guarantee sufficient strength development, as depicted in Figure (3).

Figure 4. beams casting and curing.

2.9 Instrumentation and Measurement

- Deflection Measurement: Vertical deflection at mid-span was measured using (LVDT), achieving an accuracy of 0.01 mm.
- Strain Gauges: The strain gauges were affixed to the concrete face to monitor strain during loading. These gauges were placed at critical locations to capture strain behavior during testing, as illustrated in Figure.

2.10 Test Setup and Loading Procedure

The experimental beams underwent static loading via a hydraulic jack with a capacity of 300 kN. The stresses were symmetrically delivered at two points on each beam, with increments of 4 kN. Load and deflection data were automatically captured via a computerized data-gathering system. Figure (4) depicts the test configuration, comprising the hydraulic jack and supplementary apparatus.

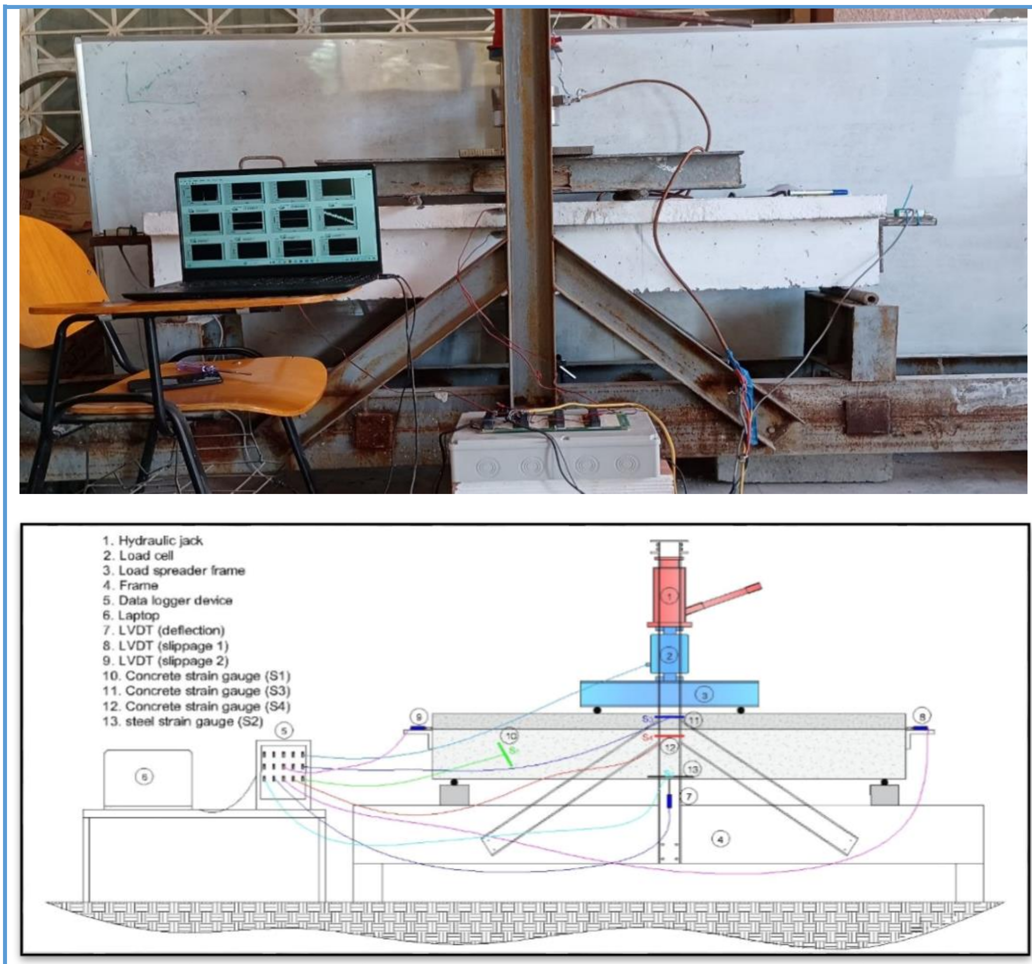


Figure 5. Test setup.

3. Results and Observations

Cracks were noticed and documented in all tested beam specimens. until their failure. All specimens failed in flexure-shear mode, with the initial crack occurring as flexural cracks. Figure (5) illustrates the cracking pattern and modes of failure. The initial cracking load for all the hybrid beams was established at a load level of approximately 12.5%–18.8% of the ultimate load values. With further increased load, flexural cracks became more pronounced, and further flexural-shear cracks emerged. With increased load, the cracks began to propagate at an angle of 42-45 degrees and extended toward the loading point. Figure (5) indicates that around the base, horizontal cracks have appeared running parallel to the longitudinal reinforcement. This makes the shear stress and dowel action between the concrete and steel reinforcement less strong. At load values nearing failure, the pre-existing vertical flexural and inclined flexure-shear cracks propagated toward the compression zone, accompanied by the emergence of new inclined cracks parallel to the initial cracks within the shear span. Furthermore, the number of cracks and their propagation within the hybrid sections observed exceeds those in the conventional beam (NTB-F1-D3-S300), attributed to the complete casting of the conventional beam with HS concrete possessing a compression strength of 46 MPa, which enhanced the beam's shear strength (Vc), see Table (1).

Table 1. Results of all the tested beams.

Specimen Designation	a/h	Pu, (KN)	Pcr, (KN)	Vu, (KN)	Pcr/Pu, (%)
NTB-F1-D3-S300	2	131.42	26.7	65.71	20.3
HB-F1-D3-S300	2	111.3	21	55.65	18.8
HB-F2-D3-S300	2	129.5	22	64.75	17
HB-F3-D3-S300	2	142	22	71	15.5
HB-F1-D3-S200	2	120.7	20	60.35	16.6
HB-F2-D3-S200	2	147.5	22	73.75	15
HB-F3-D3-S200	2	158	21	79	13.3
HB-F1-D3-S100	2	144	20	72	13.8
HB-F2-D3-S100	2	160	22	80	13.7
HB-F3-D3-S100	2	176.17	22	88.08	12.5

Pu: ultimate load capacity, Pcr: cracking load, Vu: ultimate shear strength

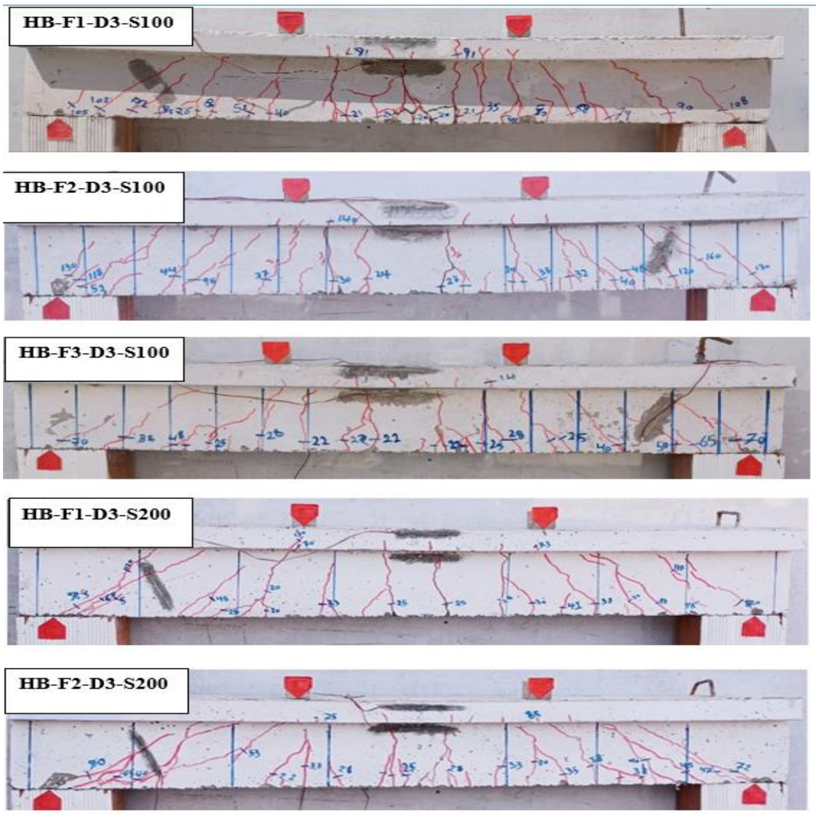


Figure 6. Beams after testing.

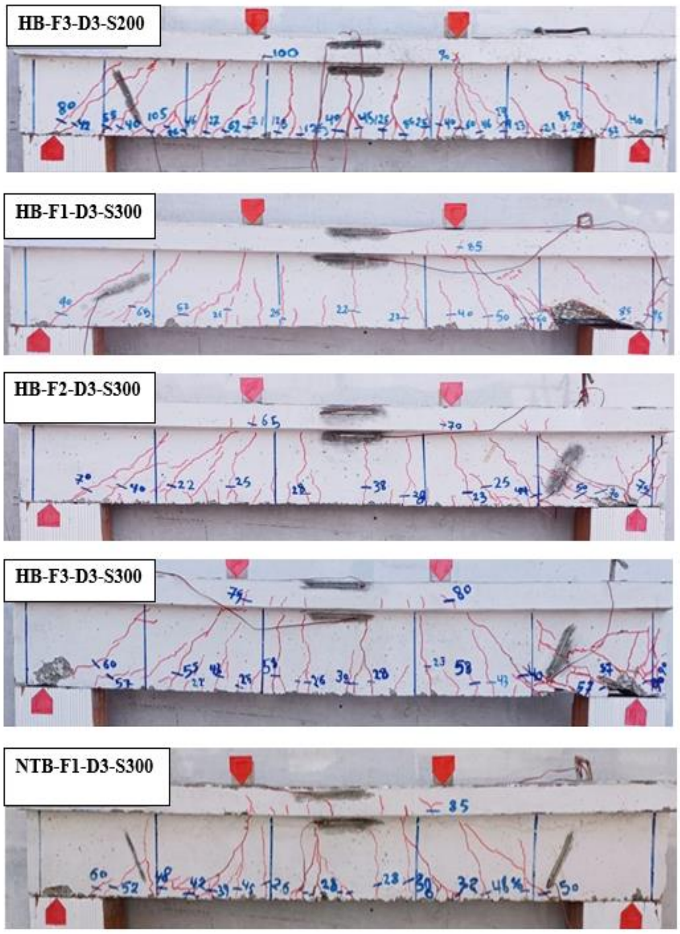


Figure 7. continued…

3.1 Cracking and Failure Load Capacity of The Tested Beams

Tables (2) demonstrate that an increase in the grade of HS concrete within the flange of hybrid beams (46, 62, and 84 MPa) results in a corresponding increase in the failure load. Depending on the studied parameters, this increase ranges from 18.8% to 56%. This indicates that an improved concrete grade allows the specimens to enhance their resistance to compressive stresses and increase their load-bearing capacity.

The results in Table (3) for the series hybrid beam with constant flange concrete strength (46 MPa) and different stirrup spacing showed that the HB-F1-D3-S100 beam had the highest failure load, at 144 kN, compared to the HB-F1-D3-S200 and HB-F1-D3-S300 beams, which had the lowest failure load, at 111.3 kN. Increasing the stirrup spacing in HB-F1-D3-S300 led to less efficient shear reinforcement, causing an earlier failure compared to HB-F1-D3-S100. For a series of beams that combined concrete strength (62 MPa) and various stirrups spacing, specimen (HB-F2-D3-S100) showed the uppermost failure load (158 kN), emphasizing the importance of maintaining a balance between stirrup spacing and concrete compressive strength. HB-F2-D3-S200 had a slightly lower failure load (147.50 kN), while HB-F2-D3-S300, with a failure load of 129.5 kN, demonstrated that altering the vertical reinforcement layout significantly reduces the beam's ability to resist shear forces. Accordingly, HB-F3-D3-S100 was the strongest of all tested groups for failure load at 176.17 kN, being the highest value among the beams that were tested. This gives clear advantages of hybrid beams when high compressive strength concrete is employed and There is an adequate, well-structured reinforcement layout. This beam realized much higher shear capability as compared to HB-F3-D3-S200, failed at 158 kN, and HB-F3-D3-S300 at 142 kN.

The comparison between hybrid beams and normal beams (HB-F1-D3-S300) and the normal beam (NTB-F1-D3-S300) were similar in reinforcement ratios, highlights the significant importance of concrete grade within the web to increase shear strength of the beam. The capacity of the normal beam (NTB-F1-D3-S300) recorded an increase about (17.7%, 1.2%, 8.6%) over HB-F1-D3-S300, HB-F2-D3-S300, and HB-F1-D3-S200 respectively.

Table 2. Influence of concrete grade on beams strength.

Beam	Pu, (kN)	Increasing in Pu, (%)	Pcr, (kN)	decreasing in Pcr, (%)
HB-F1-D3-S100	113	Rf.	20	Rf.
HB-F2-D3-S100	147.7	30.7	22	10
HB-F3-D3-S100	176.17	56	22	10
HB-F1-D3-S200	120.7	Rf.	20	Rf.
HB-F2-D3-S200	147.6	22.3	22	10
HB-F3-D3-S200	158	31	21	5
HB-F1-D3-S300	111.3	Rf.	21	Rf.
HB-F2-D3-S300	132.2	18.8	22	4.7
HB-F3-D3-S300	142	27.6	22	4.7

Table 3. Influence of stirrups spacing on beams strength.

Beam	Pu, (kN)	Increasing in Pu , (%)	Pcr, (kN)	Decreasing in Pcr, (%)
HB-F1-D3-S100	111.3	Rf.	21	Rf.
HB-F1-D3-S200	120.7	8.44	20	4.7
HB-F1-D3-S300	144	29.4	20	4.7
HB-F2-D3-S100	129.5	Rf.	22	Rf.
HB-F2-D3-S200	147.5	13.8	22	0
HB-F2-D3-S300	160	23.5	22	0
HB-F3-D3-S100	142	Rf.	22	Rf.
HB-F3-D3-S200	158	11.2	21	4.5
HB-F3-D3-S300	176.17	24.1	22	0

3.2 Load-deflection Response

It is clear from Table (4) and Figure (6), Deflection decreases with higher compressive strength. Increasing concrete strength from (46 to 62 and 84 MPa) within the flange, decreases the mid-span deflection at service and failure load stage approximately (16.1%-33%) and (5.1%-10%) respectively. This confirms that an increase in compressive strength enhances the stiffness and reduces deformation. Increasing compressive strength for Specimens HB-

F2-D3-S300 and HB-F3-D3-S300 increased the deflection value at failure. load about (12.7% - 20.3%) respectively as compared with HB-F1-D3-S300, this behavior can be explained by the fact that load-carrying capacity for beams with strengths of 62 MPa and 84 MPa exceeded the capacity of beam HB-F1-D3-S300.

Tables (5) and Figure (7) indicate that an augmentation in stirrup spacing results in a reduction in shear. capacities, thereby reducing midspan deflection. Increasing Stirrup spacing from 100 to 200 and 300 mm decreases deflection at service loads in rate (9.2% - 35.2%) depending on the studied parameters. Increasing deflection value at failure load stage as stirrups distance decreased. This is because beams with less stirrup spacing can carry more weight. For example, beams with 200 mm of stirrup spacing saw an increase in rate (7.74% to 44%), while beams with 100 mm of stirrup spacing saw an increase in rate. The increase was approximately (24% - 65.28%) as compared to specimens with 300 mm stirrup spacing. The stiffness of normal beam NTB-F1-D3-S300 was higher than that of beams HB-F1-D3-S300, HB-F2-D3-S300, HB-F1-D3-S200, and HB-F1-D3-S100, with rise rates of 31.3%, 10.4%, 15.65%, and 7.8% over time. This indicates the crucial role of concrete strength within the web in enhancing shear strength and reducing deformation.

Table 4. Influence of concrete grade on load-deflection response.

Beam	Pu, (kN)	Ps of reference beam , (kN)	δs, (mm)	Decreasing in δs, (%)	δu, (mm)	Decreasing in δu,(%)
HB-F1-D3-S100	113	86.4	6.57	Rf.	19.5	Rf.
HB-F2-D3-S100	147.7	86.4	5.25	20	18.5	5.1
HB-F3-D3-S100	176.2	86.4	4.4	33	17.6	9.7
HB-F1-D3-S200	120.7	72.42	6.18	Rf.	17	Rf.
HB-F2-D3-S200	147.6	72.42	4.86	21.36	15.88	6.6
HB-F3-D3-S200	158	72.42	4.42	28.47	15.3	10
HB-F1-D3-S300	11.3	66.78	7.52	Rf.	11.8	Rf.
HB-F2-D3-S300	132.2	66.78	6.31	16.1	13.3	+ 12.7
HB-F3-D3-S300	142	66.78	5.8	22.8	14.2	+ 20.3

Ps: service load (60% of ultimate load), **δs:** deflection at service load level,

δu: deflection at ultimate load

Table 5. Influence of stirrups spacing on load-deflection response.

Beam	Pu, (kN)	Ps of reference beam , (kN)	δs, (mm)	Decreasing in δs, (%)	δu, (mm)	Increasing in δu,(%)
HB-F1-D3-S300	111.3	66.78	6.38	Rf.	11.8	Rf.
HB-F1-D3-S200	120.7	66.78	5.77	9.2	17	44
HB-F1-D3-S100	144	66.78	5.2	17.8	19.5	65.25
HB-F2-D3-S300	132.2	79.32	6.16	Rf.	13.3	Rf.
HB-F2-D3-S200	147.6	79.32	5.17	16.1	15.88	21
HB-F2-D3-S100	160	79.32	4.7	23.7	18.5	40.8
HB-F3-D3-S300	142	85.2	6.5	Rf.	14.2	Rf.
HB-F3-D3-S200	158	85.2	5.18	20.3	15.3	7.74
HB-F3-D3-S100	176.2	85.2	4.21	35.2	17.6	24

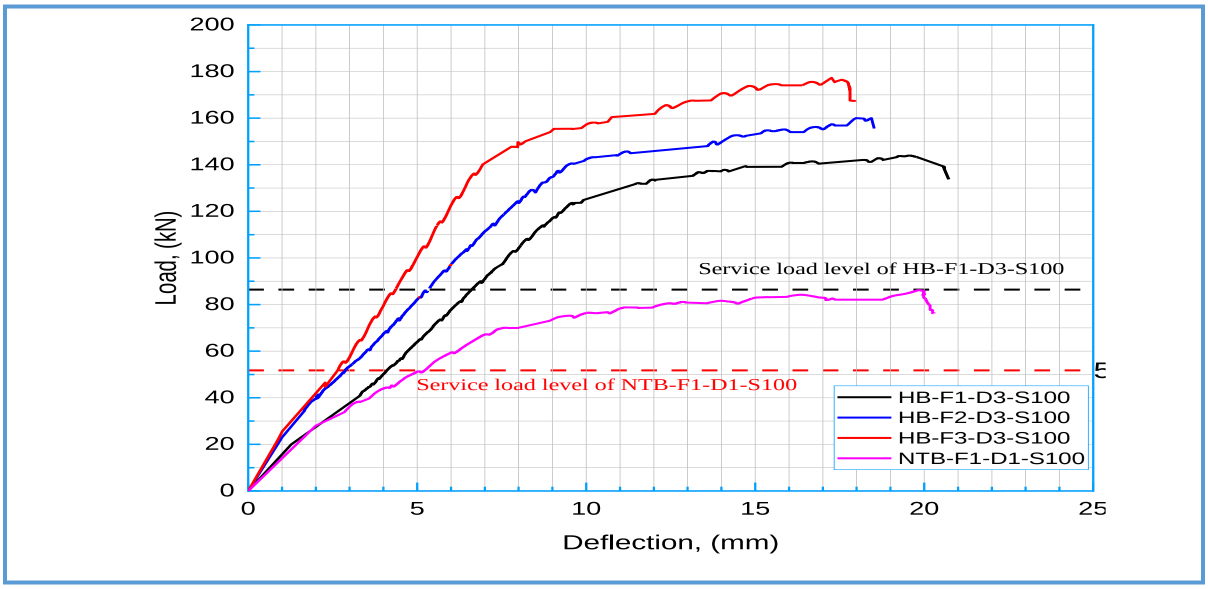
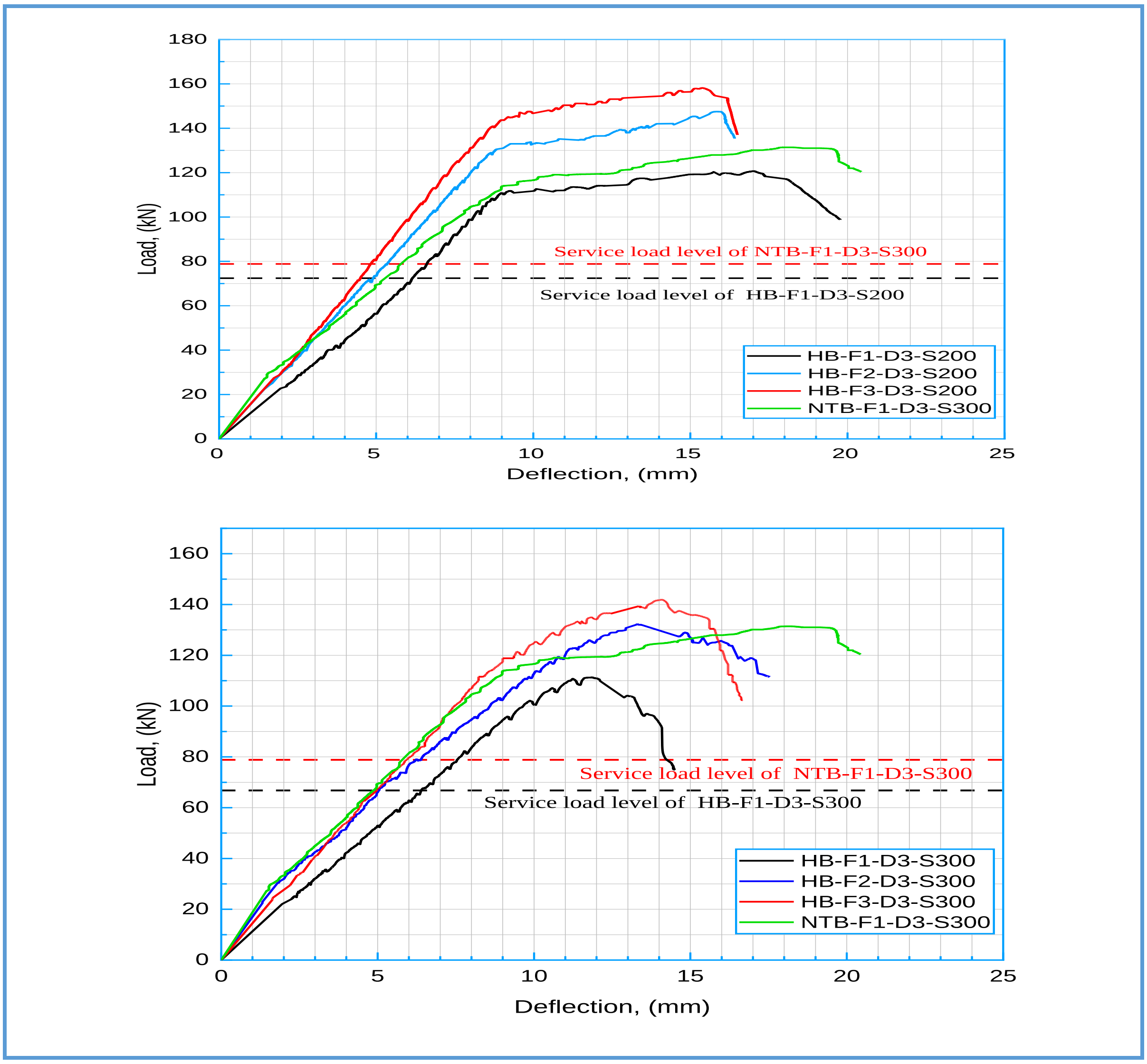


Figure 8. Effect of concrete grade on load-deflection response.



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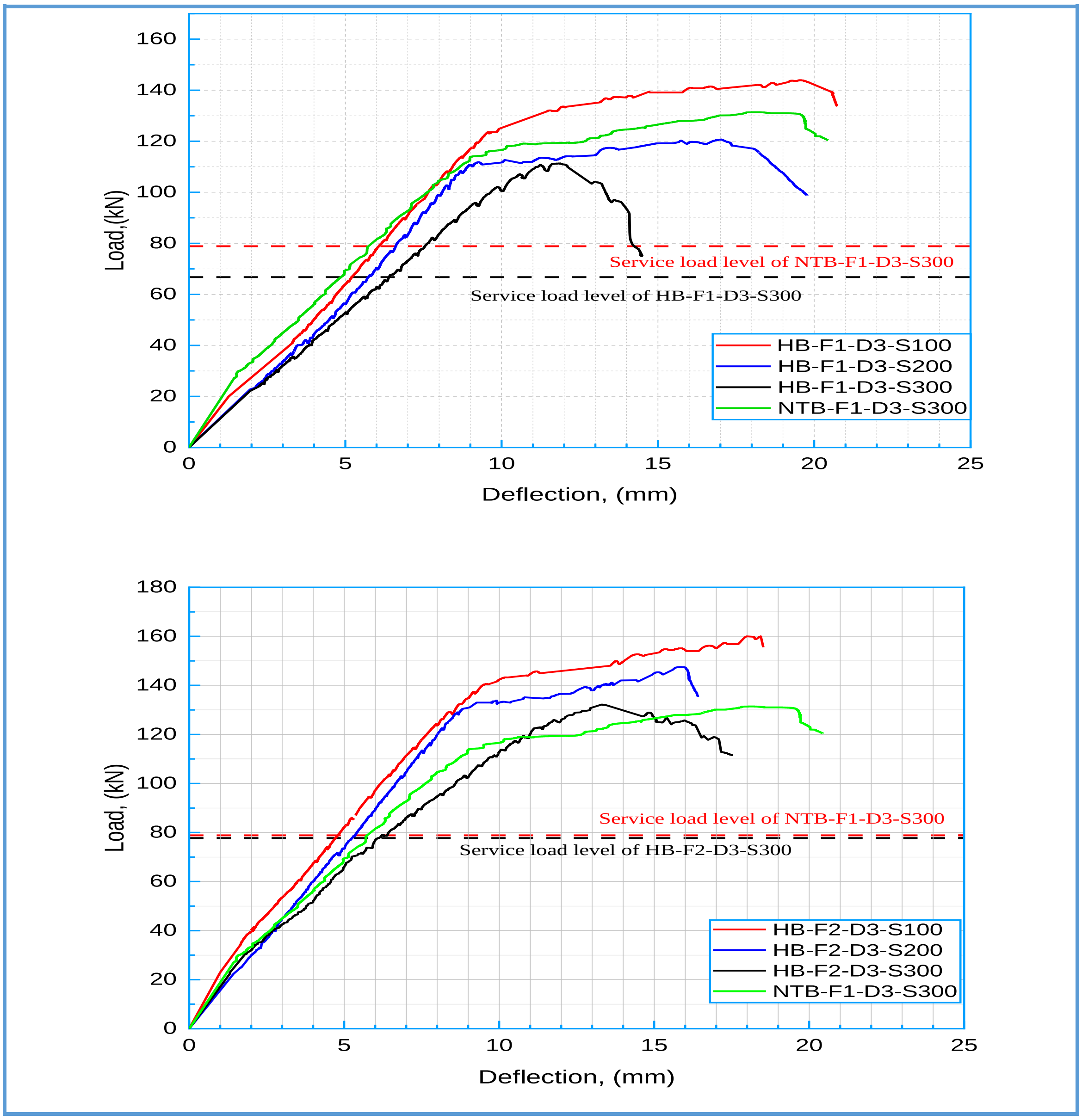

Figure 10. effect of Stirrups spacing on load-deflection behavior.

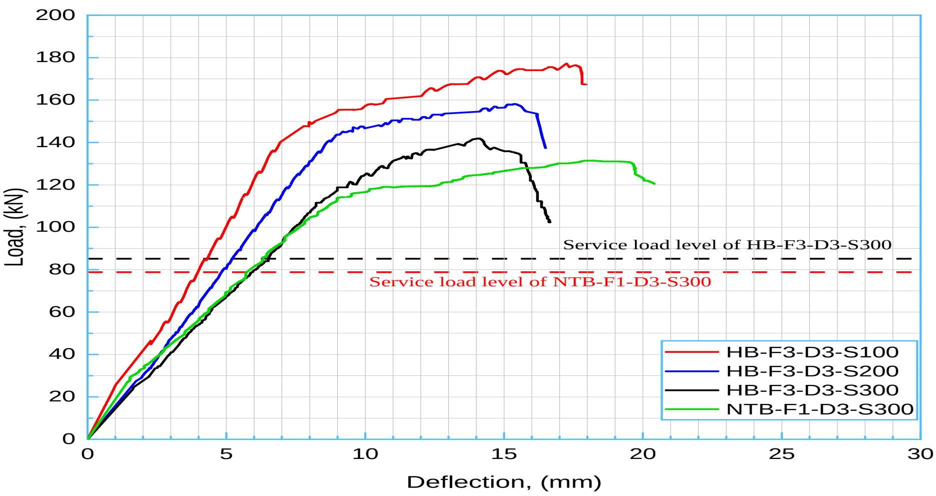

Figure 11. Continued…

4. Conclusions

From the findings of the experimental studies, the subsequent conclusion can be derived. It was emphasized that these conclusions were confined to the studies of the variable.

a. All tested Beams exhibited failure in a comparable manner, attributed to flexural shear mode.

b. Adopting varying stirrup distribution distances for hybrid beams (100, 200, and 300 mm) had a minimal impact on the crack patterns of the specimens, even those in group 1 with a stirrup distance of 100 mm. due to using the same mix of LW concrete (with 19 MPa compressive strength), within the web of all hybrid beams, therefore reduced shear strength provided by concrete (Vc)

c. The load-deflection response curves for hybrid beams exhibit behavior and trends comparable to those of regular beams, with the exception of specimens in group 3, which have a stirrup distribution distance of 300mm (HB-F1-D3-S300, HB-F2-D3-S300, and HB-F3-D3-S300) and failed immediately after reaching the yielding of steel.

d. The implementation of varying compressive strengths for HS concrete within the flange and differing stirrup spacings did not significantly influence the initial cracking loads of all hybrid beams, which ranged from 20 to 22 kN, lower than the reference beam's load of 26.7 kN, due to the continual application of LW concrete in the webs of all hybrid beams.

e. Increasing stirrups distribution distance decreased the ultimate load capacity, noticing that for specimens with stirrup distances of 300 mm c/c accompanied with concrete crush over the supports and spalling concrete cover within the shear zone near the supports.

f. From the tests conducted, it is evident that a tradeoff between shear strength and Stiffness needs to be struck by having adequate spacing of stirrups, sufficient detailing of reinforcement and HS concrete. Only then will the optimum carrying capacity be achieved along with deflection control under service situations.

The large-scale infrastructural applications requiring developing high levels of shear resistance will necessarily have to employ hybrid-reinforced concrete beams with optimized concrete mixture and reinforcement configurations. Thereafter, Hybrid beams guarantee the safety, durability, and cost-effectiveness of the structure. Also of concern to industries is the application of hybrid beams to structural systems such as bridges, highway overpasses, and high-rise buildings, among others, requiring high shear capacity with low deflection.

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