

Structural Performance of Hybrid Reinforced Concrete T- Beams Combining High Strength Concrete and Lightweight Concrete

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Abstract: This paper investigates the structural performance of reinforced concrete hybrid beams, focusing on the effects of the flexural reinforcement ratio and concrete strength on key parameters such as ultimate load, first cracking load, deflection, and crack patterns. An extensive experimental study was conducted on ten simply supported reinforced concrete beams, including nine hybrid concrete reinforced beams and one conventional beam. All beams featured a T-shaped cross-section with dimensions of 200 mm flange width, 60 mm flange depth, 190 mm web depth, and 100 mm web width. For the hybrid beams, lightweight concrete (19 MPa) was used in the web, while high-strength concrete was used in the flange. The conventional beam was constructed entirely of high-strength concrete (46 MPa). The beams were designed with varying flexural reinforcement diameters (8, 10, and 12 mm) and web concrete strengths (46, 62, and 84 MPa). The results demonstrate that increasing the reinforcement ratio (from 0.00217 to 0.00341 and 0.00493) significantly enhances load capacity. Similarly, increasing the compressive strength of the web concrete (from 46 to 62 and 84 MPa) effectively raises the failure load. However, early cracking load values remained consistent across all hybrid specimens due to the uniform use of lightweight concrete in the web. The first cracking load was found to be more influenced by the quality of the concrete within the web, than by the reinforcement ratio. The reference beam, constructed with a web concrete strength of 46 MPa, exhibited superior crack control, with a 21.7%–47% improvement in the first cracking load compared to the hybrid beams. Optimal performance was achieved by combining a higher flexural reinforcement ratio with increased flange concrete strength. The hybrid beam with 84 MPa web concrete strength and 12 mm flexural reinforcement diameter demonstrated the best structural performance, achieving lowest deflection (17.60 mm) at failure and a maximum load capacity of 176.17 kN. This beam exhibited excellent load capacity, stiffness, and crack resistance. In Addition, all beams showed negligible slip between concrete layers, further confirming the effectiveness of the hybrid design. These findings provide valuable insights into designing robust and efficient structural elements with enhanced strength and crack resistance, offering potential applications in various structural contexts.

Keywords: Hybrid reinforced concrete beams, reinforcement diameter, concrete strength, retrofitting strategies, structural

performance, failure load, crack resistance, deflection behavior, stiffness enhancement, load-strain analysis.

1. Introduction

Efficiency and reliability are two major concerns in civil engineering, and an RC beam represents the fundamental load-carrying member in many forms of constructions and structural installations ranging from buildings and bridges to many other types. Thus, design consideration and structural integrity have a vital relation to safety, serviceability, and durability. Hence, an engineer and designer need to have a notion about the parameters which influence its performance [1,2].

Increasing demand for such sustainable construction materials and methods has prompted research in hybrid-reinforced concrete beams using high-strength concrete in conjunction with lightweight concrete. This creates balancing among strength, durability, and weight reduction-characteristics increasingly sought in modern structural applications. Hybrid beams can have improved structural performance, but they can also be positive with respect to environmental concerns in terms of reducing materials and, consequently, the carbon emissions associated with those materials. Also, lighter self-weight of the structures with hybrid beams reduces the foundation loads that is economical and enhances construction speed. In seismic areas these advantages become very important since lighter structures reduce earthquake-induced forces [3-6].

The most significant synergy between HSC and LWC in hybrid beams refers to a number of key advantages: HSC enhances load-carrying capability, especially under compressive stresses, while LWC reduces the overall weight without losing structural integrity. This provides even broader perspectives for improving energy efficiency in buildings, as lighter structures require less energy to be invested in heating and cooling [2]. Hybrid beams also satisfy new emerging tendencies in progressive construction practice, including prefabrication and modular construction. The complementary properties of HSC and LWC have made it possible to satisfy diversified performance requirements for hybrid beams from residential buildings to long-span bridges.

It will finally develop substantial understanding of material property and structural effectiveness that may allow reasoned decision-making processes to be realistically applied to optimize these designs for economic and functional benefits. It identifies and discusses significant gaps within the present literature while giving opportunities for new ways to approach design that can merge sustainability with performance excellence in structural engineering.

1.1 Key Factors Influencing RC Beam Behavior

The main parameters that affect the structural performance of RC beams are concrete strength, the diameter of reinforcement, and stirrup spacing. Among them, the highest influencing variable will be that of concrete compressive strength. High-strength concrete has come into prominence in recent times since it has greater carrying and compressive resistance and less deflection for a given applied load. For example, Al-Negheimish et al. [1] noted that the deflection of HSC beams is much lower, with high shear resistance compared to conventionally concrete beams. In the application of flexural loads alone, for instance, Al-Osta et al. [2] reported that the load-carrying capacity of HSC beams improved.

Another important factor could be considered as the diameter of the reinforcing bars. Greater diameter bars, of course, increase tensile strength and rigidity, and beams can withstand greater loads before yielding to failure. Luo et al. [3] pointed out that increasing the diameter of reinforcement significantly increases the failure load-carrying capacity. Furthermore, larger bars reduce stress concentrations; thus, better distribution of load can be achieved with better

structural performance. Extensive research related to the reinforcement diameter and beam performance has yielded valuable knowledge useful in developing the reinforcement configurations [7-13].

1.2 Objective of the Current Study

The present paper deals with the structural behavior of hybrid RC beams for detailing the trend of a few major variables-namely, diameter of reinforcement, compressive strength of concrete, and stirrup spacing-on major performance parameters such as failure load, initial cracking load, nature of deflection, and crack propagation. Variations of various factors acting on stability and durability issues in hybrid RC beams are discussed hereby [14-18].

The findings of this study will help develop better designs for hybrid RC beams by improving the load-carrying capacity of the beams by reducing crack propagation, thereby adding value to the civil engineering knowledge base. Also, the findings of this study will help make provisions in design guidelines and usage applications about hybrid fiber-reinforced concrete for the construction projects by integrating experimental findings with the insights gained from the current literature to encourage improvements in the design approach of reinforced concrete.

2. Experimental Methodology

This study investigates the structural flexural performance of hybrid reinforced concrete beams (RCBs) by examining the effects of concrete strength and reinforcement diameter, on load capacity, crack resistance, and deflection behavior. The experimental procedures were conducted in the Structural Engineering Laboratory at the University of Kirkuk.

2.1 Variables and Specimen Design

The main variables tested include:

1. Concrete Type: High-strength concrete (HSC) in the flange, lightweight concrete (LWC) in the web.
2. Concrete Grades: HSC with compressive strengths of 46 MPa, 62 MPa, and 84 MPa.
3. Reinforcement Ratios: Longitudinal reinforcement ratios (0.00217, 0.00341 and 0.00493), corresponding to diameters of 8 mm, 10 mm, and 12 mm, respectively.
4. Stirrup Spacing: Constant for all specimens at 100 mm center to center.

A total of 10 beams were fabricated, consisting of 9 hybrid beams and one reference beam cast entirely with HSC. The beams were tested simply supported over a (1500mm) clear span under two-point loading as shown in Figure (1). Also, Figure (2) shows details of the tested beams. All details of the specimens are shown in Table (1).

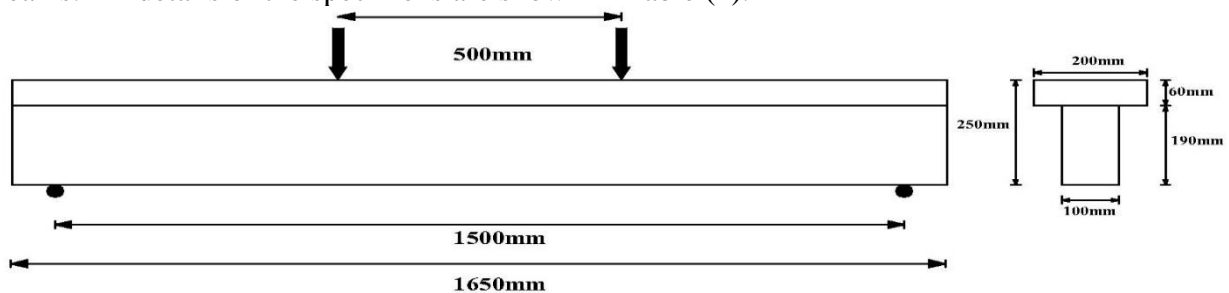


Figure (1): Setup of the tested beams.

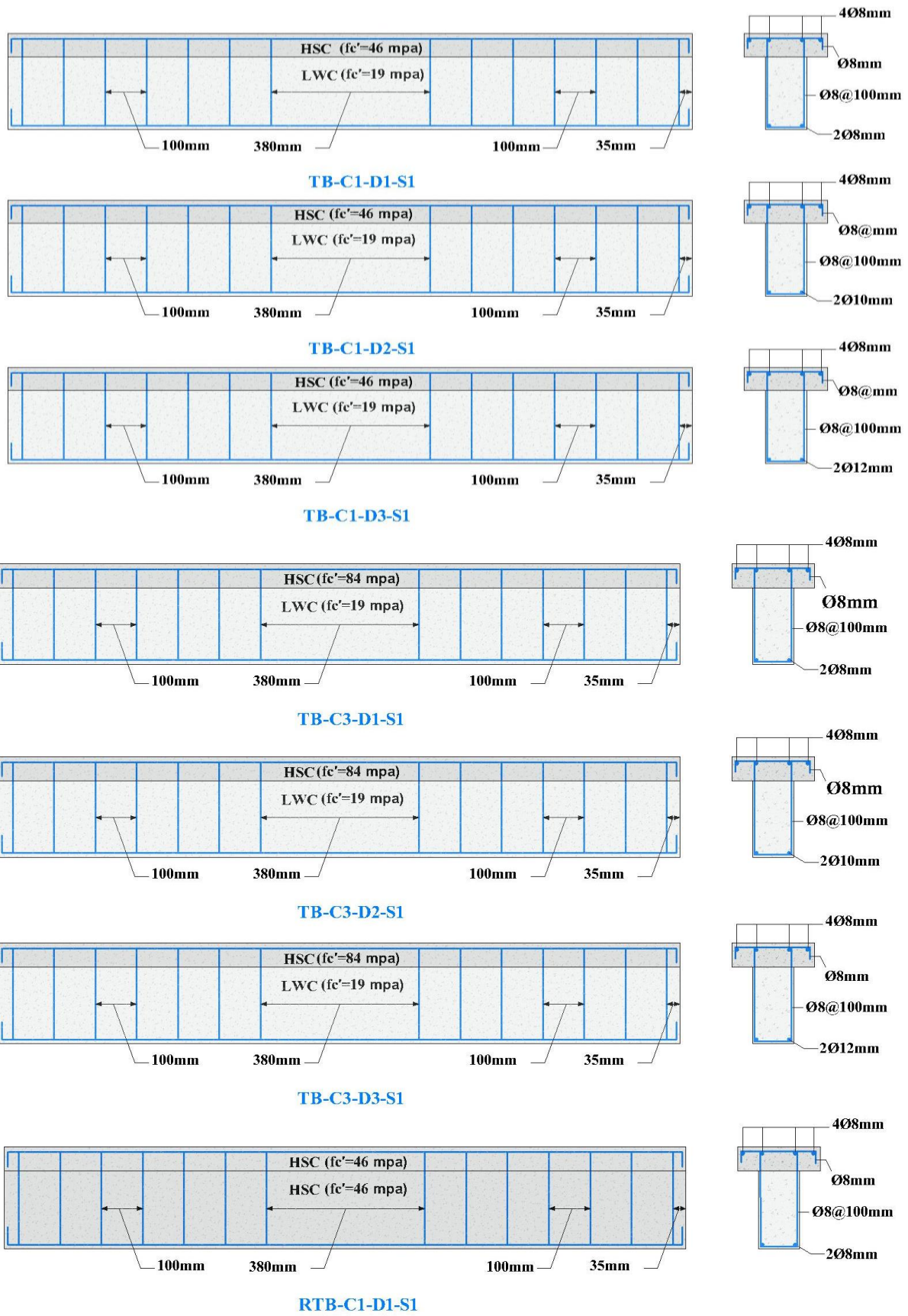


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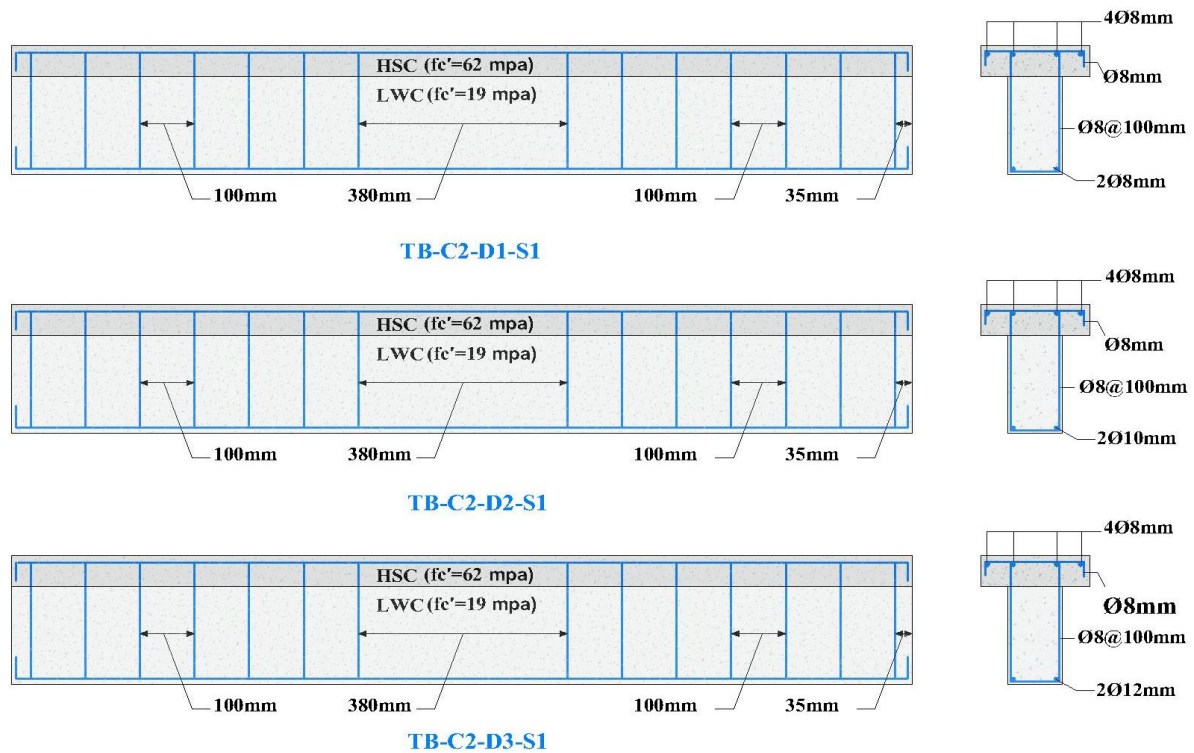


Figure (2): Details of the tested beams.

Table (1): specimens' details.

Group no.	Specimen Designation	Concrete compressive Strength (MPa), flange/web	Flexure reinforcement, (mm)	Stirrup Spacing, mm
Reference beam	RTB-C1-D1-S1	46/46	2Ø 8	100
Group 1	TB-C1-D1-S1	46/19	2Ø 8	100
	TB-C1-D2-S1	46/19	2Ø 10	100
	TB-C1-D3-S1	46/19	2Ø 12	100
Group 2	TB-C2-D1-S1	62/19	2Ø 8	100
	TB-C2-D2-S1	62/19	2Ø 10	100
	TB-C2-D3-S1	62/19	2Ø 12	100
Group 3	TB-C3-D1-S1	84/19	2Ø 8	100
	TB-C3-D2-S1	84/19	2Ø 10	100
	TB-C3-D3-S1	84/19	2Ø 12	100

2.2 Material Properties

- Cement: Ordinary Portland cement (Type I) was used, following ASTM C150.
- Aggregates: Natural river sand and crushed gravel for HSC; lightweight claystone aggregate (Bonza) for LWC.
- Admixtures: Silica fume and Viscocrete-1681 superplasticizer to enhance the workability and strength of the concrete.

2.3 Fabrication and Testing Procedures

1. Casting and Curing: The beams were cast in two stages HSC in the flange and LWC in the web, and using a needle vibrator to ensure proper compaction. The beams were cured in water for 28 days.

2. Testing Setup: The beams were tested under two-point loading to simulate uniform bending. A hydraulic jack (300 KN capacity) applied incremental loads of 5 KN. The deflection was measured with an LVDT, and strain was recorded using strain gauges attached to the steel reinforcement and concrete surfaces.

3. Measurements: Deflection, first cracking load, and ultimate failure load were recorded. Crack propagation was visually observed and confirmed via load-displacement curves, as shown in Figure (3).

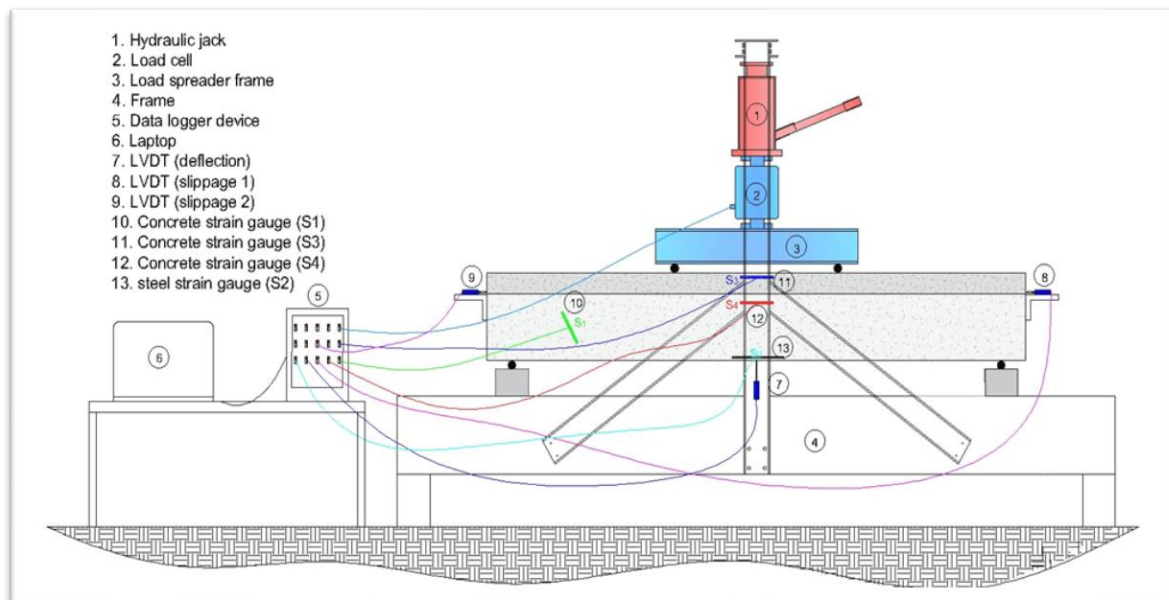
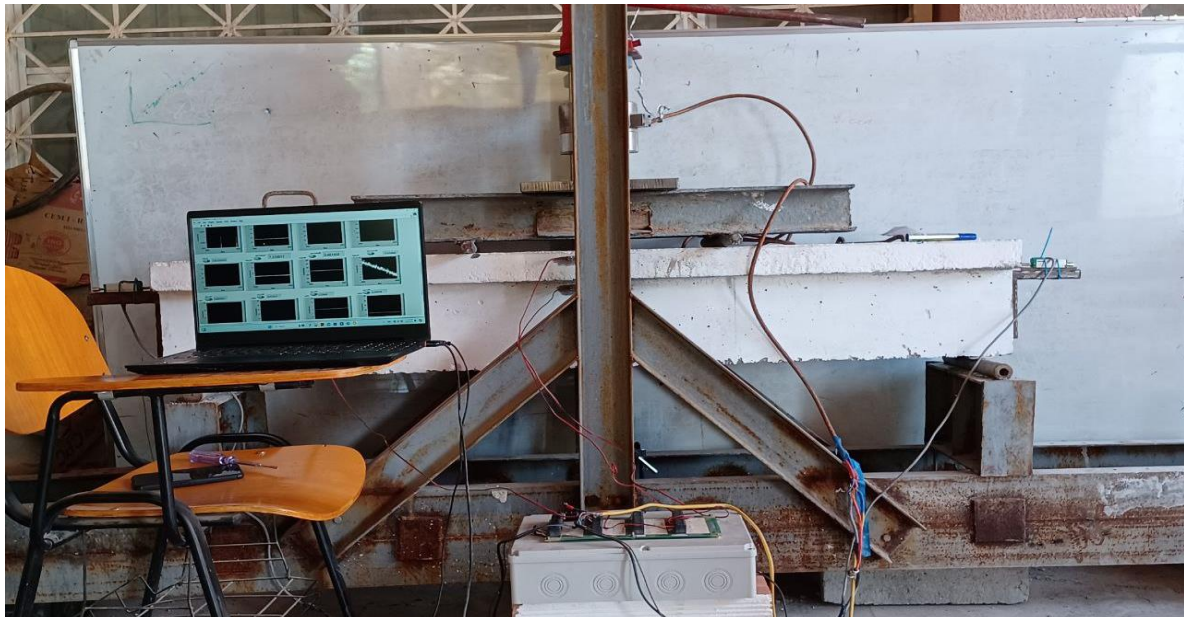


Figure (3): Test setup

3. Results and discussion

As mentioned before, the interest within this experimental campaign was focused on the structural behavior of hybrid RC T-beams made with HSC combined with LWC. Among the main results of the beam specimens, there are the following: general behavior and cracking pattern, load at crack incipient, load at ultimate limit states, mid-span load-deflection behavior, and load-slip behavior at the interface layer.

3.1 General behavior and crack pattern

Figure (4) shows the crack pattern at failure for all tested beams. The characteristic loads obtained along with the deflection values are also listed in Table (2). Overall, the behavior of the beams tested is as follows:

No major cracks were noticed in the test beams during the initial steps of loading; later, the first crack appeared at the soffit of the mid-span in the tension zone. The load at which this crack appeared is called the cracking load, P_{cr} . Successively, a number of cracks were developed in the tension zone, and with increasing loads, these cracks grew upwards and widened. With increased loading, flexural cracks became dominant and graded into flexural-

shear cracks. The ones which extend furthest in the shear span adjacent to supports became inclined upwards and propagate towards the point of loading. In the final stages, crack development and propagation became rapid with a few reaching the compression zone before the appearance of failure at the ultimate load capacity (P_u).

It is clear that the pattern and numbers of cracks approximately was the same for all hybrid beams. But, when compared to normal beam (RTB-C1-D1-S1), it was clear that the number of cracks were less and the diagonal cracks did not reach supports, that due to using HSC of 46 MPa within the web of normal beam, compared to the webs of hybrid beams which casted with lightweight concrete of 19 MPa.

Table (2): Experimental results of tested beams.

Specimen Designation	Reinforcement diameter, (mm)	Failure load, (kN)	Increasing in failure load, (%)	First cracking load, (kN)	Decreasing in first cracking load, (%)	$\frac{P_{cr}}{P_u}$ %
RTB-C1-D1-S1	2Ø8	86.18	Ref.	28	Ref.	32.5
TB-C1-D1-S1	2Ø8	78.75	-8.62	19	32.1	24.12
TB-C1-D2-S1	2Ø10	106	23	21	25	18.8
TB-C1-D3-S1	2Ø12	144	67.1	20	28.6	13.9
TB-C2-D1-S1	2Ø8	96.25	11.7	20	28.6	20.77
TB-C2-D2-S1	2Ø10	124.4	44.34	23	17.85	18.5
TB-C2-D3-S1	2Ø12	160	85.6	23	17.85	14.37
TB-C3-D1-S1	2Ø8	113	31.1	20	28.6	17.7
TB-C3-D2-S1	2Ø10	147.7	71.4	22	21.4	14.9
TB-C3-D3-S1	2Ø12	176.17	104.4	22	21.4	12.44

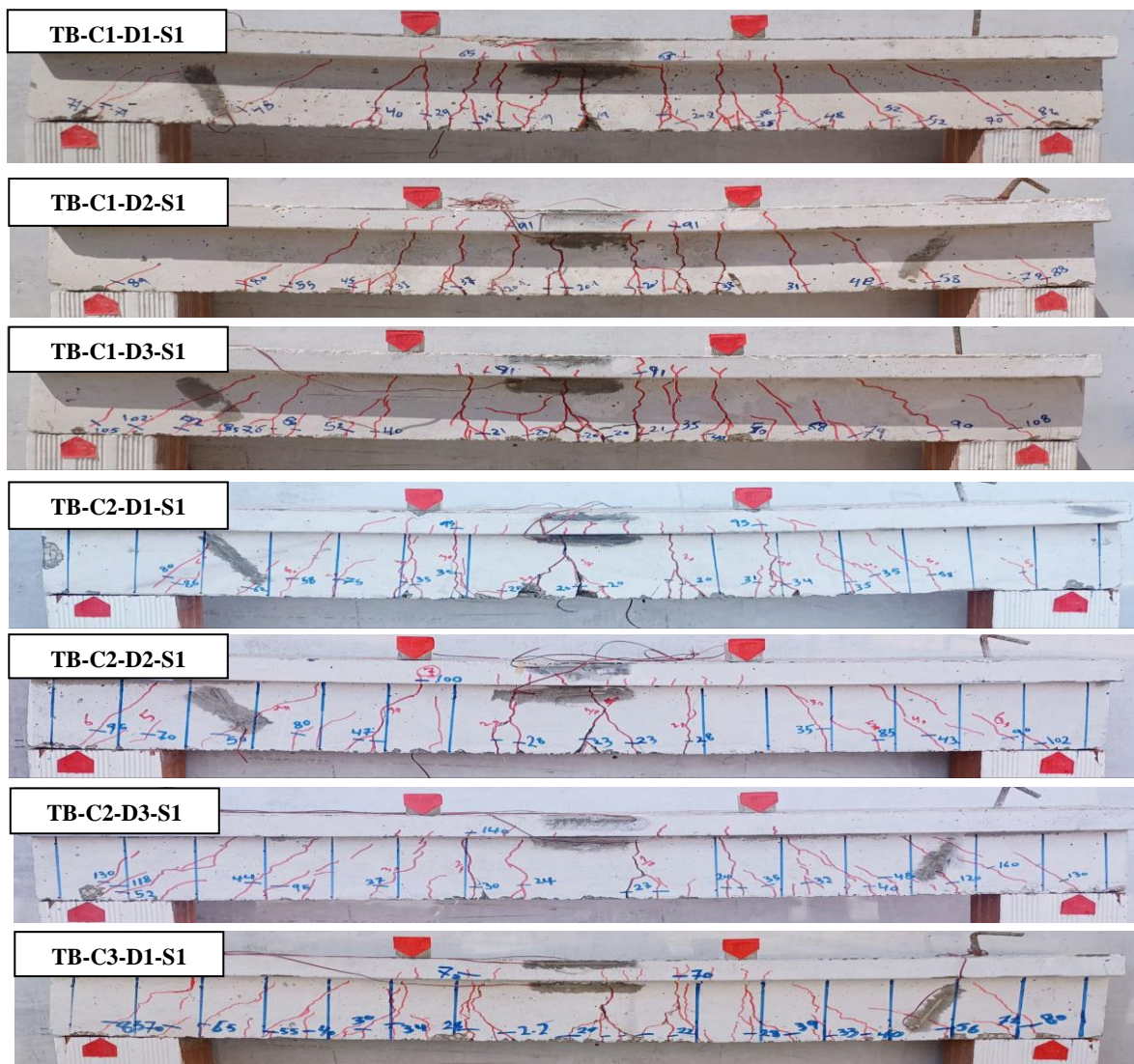


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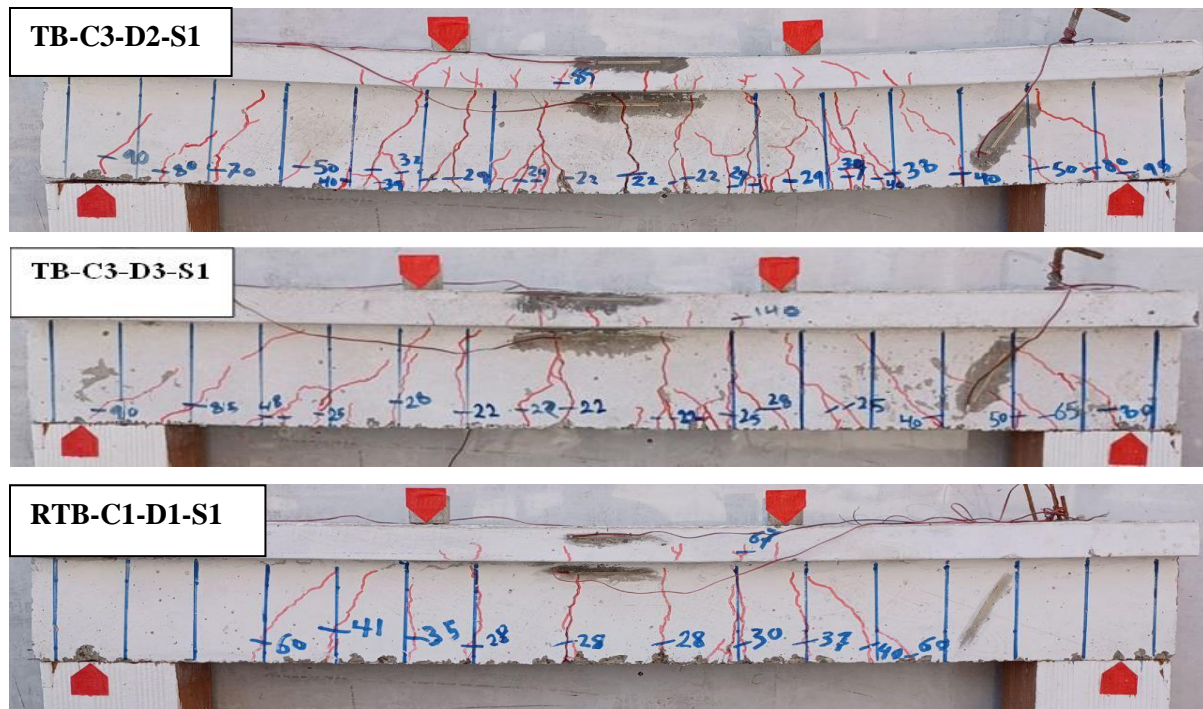


Figure (4): crack pattern for the tested beams.

3.2 Strength characteristics

First cracking load and ultimate load values were presented and discussed for all tested beams. The obtained results are detailed in Table (2). The first cracking load of the all the hybrid beams varied from (12.44% - 24.12%) of the experimental ultimate load, and the first cracks appeared in the region of constant moment.

3.2.1 First cracking load (P_{cr})

The first cracking load values presented in Table (2), (3) and Table (4), crack patterns as well as for all the beams after testing are shown in Figure (4). It is clear from the results that, increasing concrete compressive strength within the hybrid beams flange (46, 62 and 84 MPa) and increasing flexural reinforcement ratios (0.00217, 0.00341 and 0.00493), obviously did not affect the cracking load values for the hybrid beams which were in range (19-23 KN), due to using same mix (LWC 19 MPa) in the web section for all hybrid beams. The results also, showed that using HSC with 46 MPa strength, increased the cracking load for the reference RTB-C1-D1-S1 which recorded 28 kN, with such increment (21.7%-47.3%) over cracking load of hybrid beams, due to using HSC within the web of reference beam, so it had higher modulus of rupture and tensile strength to resist tensile stresses and cracking than lightweight concrete.

3.2.2 Ultimate load (P_u)

The ultimate load values for all tested beams, are presented in Table (2). the comparison among the specimens similar in the hybrid section (19 MPa LWC strength in the web), with different grade of HSC within the flange (C1, C2 and C3) corresponding to strengths (46, 62, and 84 MPa) respectively, and different reinforcement diameters (D1, D2 and D3) corresponding to ratios (0.00217, 0.00341 and 0.00493) respectively, revealed that with increasing reinforcement ratio, and keeping concrete grade constant within the flange leads to enhances the tensile strength, resulting in improved load-carrying capacity, see Table (3). Therefore, the increase in the ultimate load values were about (29.2% - 82.8%) depending on the studied parameters. Table (4), reveals that as compressive strength of HSC increases with fixing reinforcement diameters, so the failure load does. Indicating that higher compressive strength enables the beams to better resist compressive stresses and increases their load-carrying capacity. Such, increasing compressive strength from 46 to 62 and 84 MPa and keeping reinforcement diameter constant, the increase in the ultimate load capacity was approximately

(11.11% - 43.5%). The beam TB-C3-D3-S1, with the highest compressive strength and largest reinforcement diameter, performs the best in terms of load-carrying capacity with an increment (105.2% and 124.4%) compared to RTB-C1-D1-S1 and TB-C1-D1-S1 respectively. Highlighting to the importance of the combination of these two factors to attain optimal balance between tensile and compressive performance. It is worth to mention that, increasing the reinforcement ratio had more effective factor in increasing ultimate load value than increased compressive strength.

Table (3): Influence of reinforcement ratio on failure and first cracking load.

Specimen Designation	Reinforcement diameter, (mm)	Failure load, (kN)	Increasing in failure load, (%)	First cracking load, (kN)	Change in first cracking load, (%)
TB-C1-D1-S1	2Ø8	78.75	Ref.	19	Ref.
TB-C1-D2-S1	2Ø10	106	34.6	21	10.5
TB-C1-D3-S1	2Ø12	144	82.8	20	5.2
TB-C2-D1-S1	2Ø8	96.25	Ref.	20	Ref.
TB-C2-D2-S1	2Ø10	124.4	29.2	23	13
TB-C2-D3-S1	2Ø12	160	66.2	23	13
TB-C3-D1-S1	2Ø8	113	Ref.	20	Ref.
TB-C3-D2-S1	2Ø10	147.7	30.7	22	8.7
TB-C3-D3-S1	2Ø12	176.17	56.5	22	8.7

Table (4): Influence of concrete strength on failure and first cracking load.

Specimen Designation	Reinforcement diameter, (mm)	Failure load, (kN)	Increasing in failure load, (%)	First cracking load, (kN)	Change in first cracking load, (%)
TB-C1-D1-S1	2Ø8	78.75	Ref.	19	Ref.
TB-C2-D1-S1	2Ø8	96.25	22.22	20	5.26
TB-C3-D1-S1	2Ø8	113	43.5	20	5.26
TB-C1-D2-S1	2Ø10	106	Ref.	21	Ref.
TB-C2-D2-S1	2Ø10	124.4	17.35	23	9.5
TB-C3-D2-S1	2Ø10	147.7	18.7	22	4.7
TB-C1-D3-S1	2Ø12	144	Ref.	20	Ref.
TB-C2-D3-S1	2Ø12	160	11.11	23	15
TB-C3-D3-S1	2Ø12	176.17	22.34	22	10

3.3 Load-deflection relationship

The load-deflection curves for the mid-span deflection against the applied load are drawn. These curves present the deflection of the beams subjected to two-point loading conditions. The peak values of deflection for all the beams tested are given in Tables (5) and (6) and Figures (5) and (6). All the beams that were tested exhibited similar behavior of the load-deflection. In the first instance, the curves were linear and had a straight course up to the occurrence of the cracks. After the occurrence of fracture, the gradient of the curve reduced and remained up to the yielding of reinforcement, while in the last stage the curves almost became flat. From the early observations of all the tested beams curves, one may note that all the curves started at converging values but, when the development of cracking took place, those curves started diverging, representing the variation in beams due to the concrete grade of the flange and the ratios of flexural reinforcement. In all the tested samples, it was observed that the deflection of the beam decreases as the reinforcement ratio increases, which can be credited to the additional stiffness acquired by the beam. Decrease in the deflection at service and failure load stage for beams were in range (19.8% - 38.70%) and (8% - 22%) respectively, depending on the studied parameters. Also, increasing compressive strength of the concrete within the beam's flange, and keeping steel ratio constant leads to decrease deflection value at service and failure load about, (11.45% - 45.4%) and (5.1% - 18.70%) respectively, due to increased flexural stiffness of the beams. At the failure stage, the comparison with TB-C1-D1-S1 showed decrease in deflection value for beams TB-C2-D2-S1 and TB-C3-D3-S1 approximately, (18.4% - 31.36%) respectively. Highlights to the significant improvements achieved through the use of higher compressive strength and larger reinforcement.

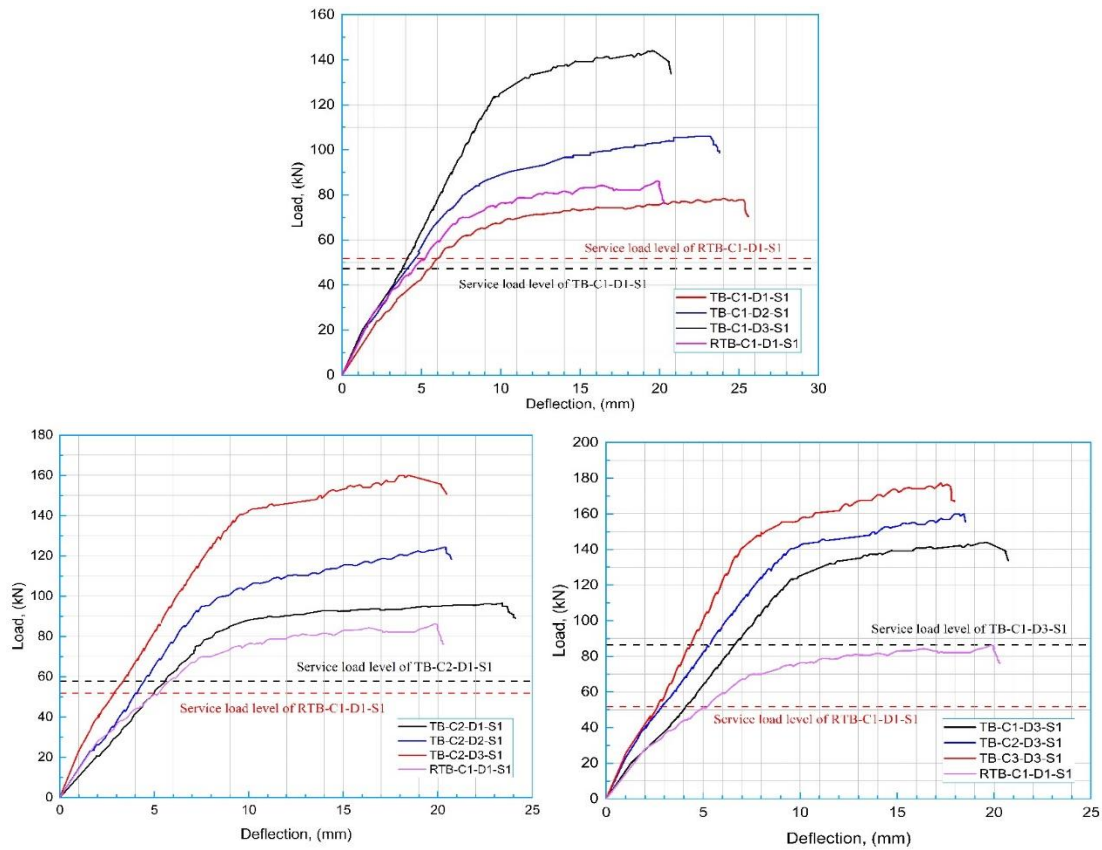


Figure (5): Influence of reinforcement ratio on load-deflection curves for tested beams.

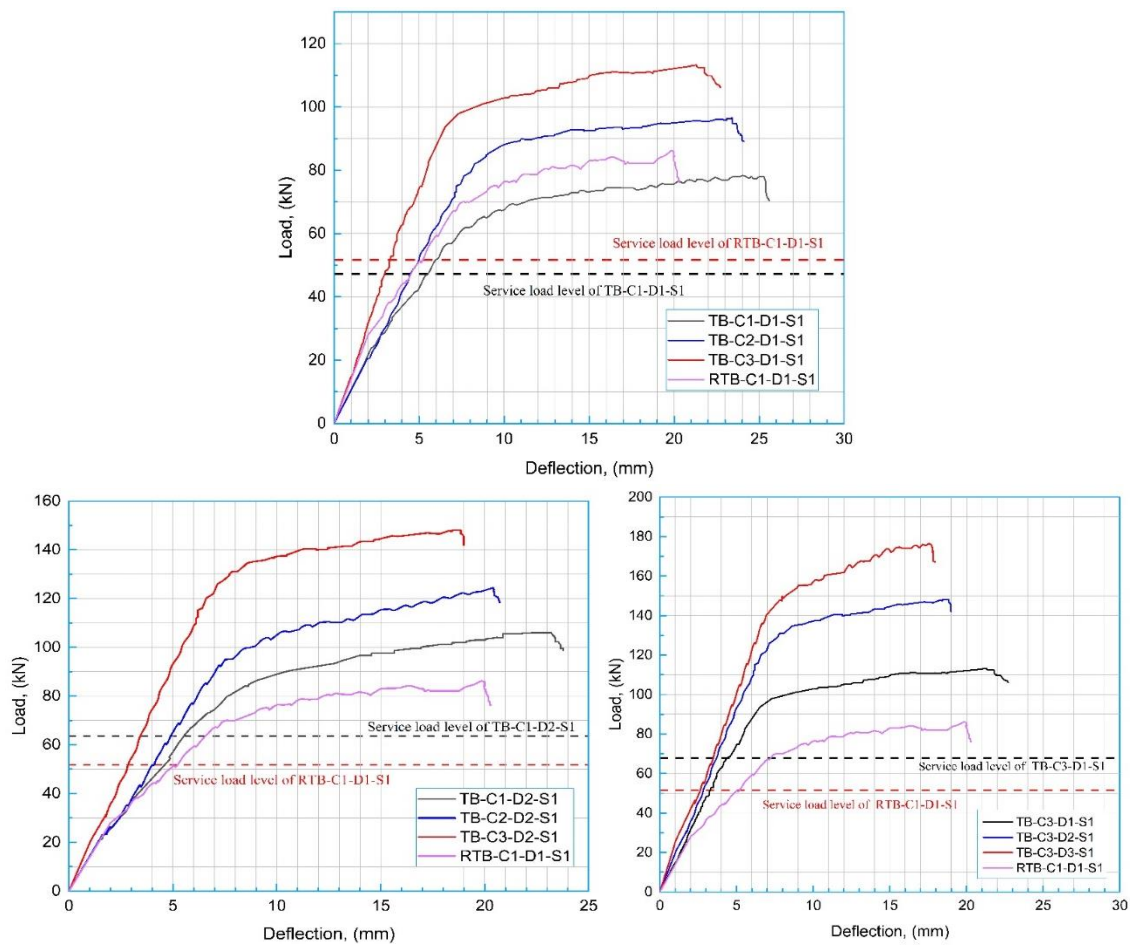


Figure (6): Influence of concrete strength on deflection.

Table (5): Influence of reinforcement ratio on deflection.

Specimen Designation	Reinforcement diameter, (mm)	Failure load, (kN)	Service load of reference beam, (kN)	Deflection at service load level, (mm)	Decreasing of deflection at service load level (%)	Deflection at failure load, (mm)	Increasing of deflection at failure load (%)
TB-C1-D1-S1	2Ø8	78.75	47.25	5.50	Ref.	25	Ref.
TB-C1-D2-S1	2Ø10	106	47.25	4.10	25.50	23	8
TB-C1-D3-S1	2Ø12	144	47.25	3.80	30.10	19.50	22
TB-C2-D1-S1	2Ø8	96.25	57.75	5.55	Ref.	23.40	Ref.
TB-C2-D2-S1	2Ø10	124.4	57.75	4.45	19.80	20.40	12.80
TB-C2-D3-S1	2Ø12	160	57.75	3.40	38.70	18.50	21
TB-C3-D1-S1	2Ø8	113	67.8	4.80	Ref.	21.20	Ref.
TB-C3-D2-S1	2Ø10	147.7	67.8	3.70	23	18.75	11.50
TB-C3-D3-S1	2Ø12	176.17	67.8	3.46	28	17.60	17

Table (6): Influence of concrete strength on deflection.

Specimen Designation	Reinforcement diameter, (mm)	Failure load, (kN)	Service load of reference beam, (kN)	Deflection at service load level, (mm)	Decreasing in deflection at service load level (%)	Deflection at failure load, (mm)	Decreasing of deflection at failure load (%)
TB-C1-D1-S1	2Ø8	78.75	47.25	5.50	Ref.	25	Ref.
TB-C2-D1-S1	2Ø8	106	47.25	4.53	17.63	23.40	6.40
TB-C3-D1-S1	2Ø8	144	47.25	3	45.40	21.20	15.20
TB-C1-D2-S1	2Ø10	96.25	63.6	5.50	Ref.	23	Ref.
TB-C2-D2-S1	2Ø10	124.4	63.6	4.87	11.45	20.40	11.30
TB-C3-D2-S1	2Ø10	160	63.6	3.45	37.30	18.70	18.70
TB-C1-D3-S1	2Ø12	113	86.4	6.57	Ref.	19.50	Ref.
TB-C2-D3-S1	2Ø12	147.7	86.4	5.25	20	18.50	5.10
TB-C3-D3-S1	2Ø12	176.17	86.4	4.40	33	17.60	9.70

3.4 Load-slip at the interface layer

Due to the utilization of two distinct types of concrete in both hybrid and conventional beams, it is essential to assess the horizontal movement at the interface layer. Two LVDTs were placed at each end of the specimens to track any potential slippage between the layers, as illustrated in Figure (3). Throughout the experiment, the LVDTs captured minor slippage values between the layers, as shown in Figure (7). Consequently, the adhesion between the layers was sufficient to either prevent or reduce slips. This strong bond was attributed to various factors, such as the friction at the interface where the layers made contact, as well as the effect of stirrups, which act as shear connectors since they penetrate both the compression and tension zones, bonding the layers at multiple points based on the stirrup spacing.

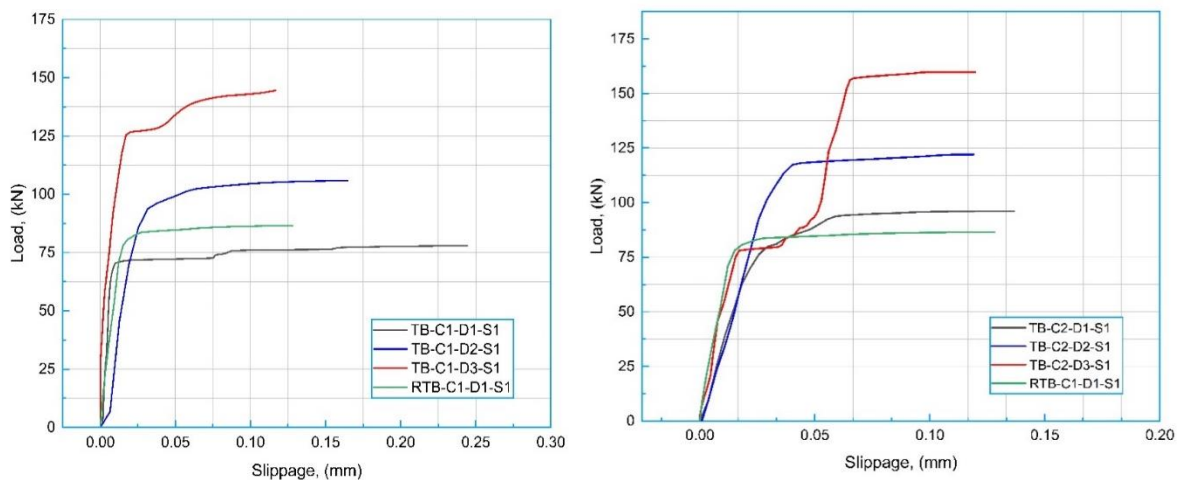


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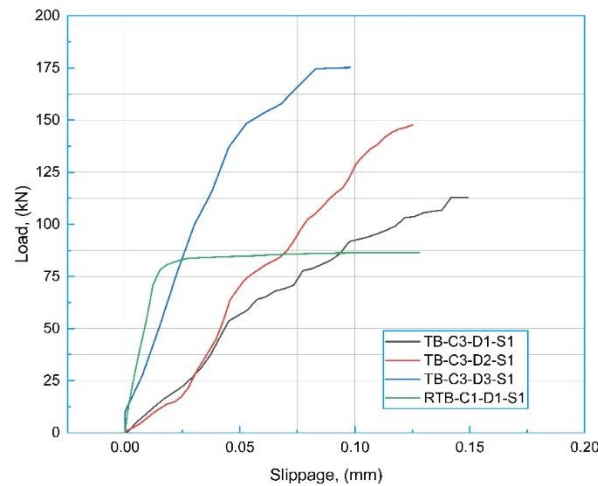


Figure (7): Load-slip at interface layer.

4. Conclusion

This paper presents an in-depth review of hybrid RCBs about the structural performance analysis of some of the critical factors: strength of concrete, diameter of reinforcement, and their influence on certain critical parameters like failure load, first cracking load, and deflection behavior. The results obtained from the present research work provide the essential understanding of the behavior of these variables on the structural behavior of the RCBs, whereas some main conclusions are included in the following:

- All the tested beams failed in flexural-shear mode.
- The behavior of the both normal and hybrid beams were similar except for number of cracks and cracks propagation, were more for hybrid beams in comparison to the cracks of control beam
- Increasing the compression strength of the HSC within the web leads to an increase in the ultimate strength load value for the beams.
- Increasing the flexural reinforcement ratio was a more effective factor in increasing the stiffness value of the beams which reduced the deflection. The beam with the optimal combination of high-strength concrete (84 MPa) and the largest reinforcement diameter ($\phi 12$ mm), TB-C3-D3-S1, exhibited the highest failure load (176.17 kN) and the lowest deflection (17.60 mm). This configuration offers the best balance between stiffness, strength, and deformation control.
- The located LVDT on both ends of the beams to record the slip between the web and flange with the development of applied load, almost did not record very small values, this indicated that the bond between layers was enough to prevent slips.
- The study highlights the novelty of combining lightweight concrete in the web and high-strength concrete in the flange of hybrid beams, which reduces dead load without compromising structural integrity. The results also emphasize the significance of optimizing both compressive strength and reinforcement diameter to achieve superior performance.

In summary, this research confirms that the optimal design for reinforced concrete beams involves a combination of high-strength concrete and larger reinforcement diameters. The interaction between these factors leads to improved load-carrying capacity, reduced deflection, and enhanced durability. Future studies should explore the application of these findings in real-world structures to validate their performance under different loading and environmental conditions.

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Declaration

The authors declare that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest. The study adhered to all ethical standards and guidelines as set forth by the institution.

Conflict of Interest

The authors declare that there is no conflict of interest with the submission of this manuscript. Furthermore, all authors confirm that financial and personal relationships, which might bias their work, have been divulged.

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