Basrah Journal for Engineering Sciences, Vol. 22, No. 1, (2022), 115-128

Original Article

Journal homepage: www.bjes.edu.iq
ISSN (Online): 23118385, ISSN (Print): 18146120

OPEN ACCESS

Shear Behavior of Two-Layer Beams Made of Normal and Lightweight Concrete Layers

Hayder Kadhem Adai AL-Farttoosi [1,*], Oday A. Abdulrazzaq [2], Haleem K. Hussain [3]

[1,2,3] Department of Civil Engineering, College of Engineering, University of Basrah, Basrah, Iraq

E-mail addresses: hayder.k.alfarttoosi@gmail.com , oday.abdulrazzaq@uobasrah.edu.iq , haleem.hussain@uobasrah.edu.iq

Received: 13 December 2021; Accepted: 16 January 2022; Published: 24 April 2022

Abstract

This study investigates the shear strength behavior of two-layer reinforced concrete beams consisting of two different types of concrete. One of the layers made of lightweight concrete (LWC) and the other was normal weight concrete (NWC). A total of 16 shear deficient reinforced concrete beams were fabricated and cast with NWC, LWC, and two-layer beam of both material with different configuration. All the beams were tested under four-point loading after 28 days. The variables of the experimental program include the ratio of thickness of the lightweight concrete layer to the overall depth of beam (h_{LW}/h), and concrete compressive strength. Experimental results which include load-deflection response curves along with failure modes for NWC, LWC and two-layer beams. The results showed that all beams failed in a similar mode, due to diagonal tension shear crack. Based on the experimental results it can be also concluded that the shear load is governed by compressive strength of lower layer of the concrete when the shear span to overall depth (a/h) of the beams is 2.75 or more. While for the a/h 2.375 and 2.00 the two-layer beam has a significant reduction in the shear capacity compared to the NWC beams and increasing compared to LWC beam. The ratio of experimental shear stress divided by the root square of concrete compressive strength $\left(vexp/\sqrt{f_c'}\right)$, which demonstrates the diagonally cracked concrete's ability to transfer strain and shear was maintained for all configurations greater than 0.17, which is the minimal value recommended by ACI318-19.

Keywords: Layered beams, Two-layer RC beams, LWAC beams, NWC beams.

http://dx.doi.org/10.33971/bjes.22.1.14

1. Introduction

Concrete has become one of the most widely used materials in the construction industry as a result of the rapid development of massive infrastructure throughout the world in recent decades. An estimated 31 billion tons of concrete have been used around the world which makes concrete one of the biggest consumers of natural resources [1]. Natural aggregates are primarily obtained from rock quarries and gravel pits. The extraction of coarse aggregates from a range of natural resources, on the other hand, has had a significant and perpetual environmental impact [2]. Numerous studies indicate that the United Kingdom and other developed countries consumed two hundred eight million tons of crushed aggregates extracted from the ground. As a result, natural aggregates are scarce in the majority of developed and developing countries worldwide [3]. Lightweight aggregate (LWA) was developed as a partial or complete replacement for natural normal weight aggregates in concrete mixtures as a result of a scarcity of natural aggregates [4]. LWA was developed by researchers and engineers using a variety of technologies and construction waste to address the scarcity of natural aggregates. The LWA is made from a variety of materials, including clay, shale, and palm oil, which results in concrete that is more porous and lighter in weight [5]. Because of the reduction in dead loads associated with structural design and foundations, a reduction in horizontal inertia actions associated with buildings in earthquake-prone areas is possible. Lightweight concrete (LWC) exhibits higher brittleness and lower stiffness when compared to normal weight concrete (NWC) [2], [6].

The lightweight aggregate is a popular alternative that alleviates the impacts of using typical coarse aggregates [7-10]. A popular alternative to using normal coarse aggregates is the lightweight aggregate, which is made artificially from a variety of sources. Low density, freeze-thaw resistance, thermal conductivity, smaller seismic demand, fire resistance, and a high strength-to-weight ratio make lightweight concrete (LWC) a viable alternative to conventional normal weight concrete (NWC) in the construction industry. Other advantages include lower cost, smaller cross-sections, and a higher strength-to-weight ratio. As a result, the use of LWC has increased significantly over conventional NWC due to the advantages and performance of structural members (such as beams, slabs, columns, walls, etc.). For this reason, the LWC has a wide range of properties and structural properties depending on the type of lightweight coarse aggregates that are incorporated into the concrete mix. [11-14].

LWC's mechanical properties, durability, and bond strength have been the subject of numerous studies previously. Yasar et al. [15] exploited basaltic volcanic pumice lightweight aggregate as a normal weight aggregate substitute, using 20 % fly ash as a cementitious replacement. Based on the results of the experiments, the researchers conclude that volcanic pumice aggregate can be utilized in structural applications. Korol and Sivakumaran [16] investigated the energy consumption of LWC slabs under extreme loading, the results demonstrated that LWC slabs can absorb more energy than NWC slabs during collapse. Onoue et al. [17] carried out a similar experiment using volcanic pumice aggregates and found that lightweight aggregate concrete had a 28-41 % higher shock-absorbing capacity than conventional concrete. In contrast, Zhang and Gjorv [7] found that LWC's tensile strength-to-weight ratio was lower than NWC's.

The strength of the bond between the reinforcing bars and the surrounding concrete is also affected using LWA in the concrete. Many studies have been done in the last few years on the strength of the bond between various types of LWA concrete. According to published research, the bond strength of LWA concrete varies depending on the type of LWA. The studies showed contradicting results. For instance, Bogas et al. [8] reported, for example, that light weight concrete made with expanded clay aggregates has a greater bond strength than NWC. Other researchers [9], [10] found similar results, showing that the bond strength between LWC and NWC is comparable.

Previous research focused on LWA concrete's mechanical, flexural, and bond strength properties. [18-20]. However, little in the literature is documented about the shear behavior and strength of LWA-cast reinforced concrete beams. Weak aggregate interlocking is one of the key variables contributing to concrete shear strength. [10], [12], [13]. Many experiments on the shear behavior of LWA have revealed that the type of LWA, such as oil palm and palm kernel shell aggregate, has an impact on aggregate interlock action [21]. Before using such LWA types in casting RC beams and slabs, the concrete shear strength (Vc) and performance of shear deficient RC beams cast with LWA should be investigated. The shear strength of RC beams is determined by a number of factors, including compressive strength of concrete, shear span to effective depth ratio (a/d), shear reinforcement, maximum size of aggregate, and transition zone bond strength. Jumaat et al. [14] investigated RC beam specimens made of oil palm LWA with densities of 1650 kg/m^3 and compressive strengths of 20 MPa, respectively. The experimental results revealed that the beam's shear capacity was 10 % greater than that cast with NWC. Johnson et al. [21] conducted a similar study on the shear behavior and strength of RC beams constructed from palm kernel shell aggregates. Eight beam specimens were subjected to four-point loading tests, the shear strength of RC beams cast with LWA was found to be 24 % higher than that of RC beams cast with NWA. The realized shear strength of LWC specimens was 10-24 percent higher than that of NWC specimens in those investigations [14], [21] owing to its shorter and narrower formed cracks with rough surfaces, which improved and raised the shear strength of LWC beam specimens. When compared to normal weight concrete, LWC beams performed better in terms of crack spacing and aggregate interlock. It may also be deduced that the nature and source of LWA have a significant impact on RC beam shear behavior. Another study of the shear strength and behavior of sedimentary LWA was undertaken by Chao et al. [20], with four-point loading, twenty-four beam specimens with different compressive strengths were tested, the experimental results showed that beams made with lightweight concrete had comparable cracking and ultimate shear stress to those with normal weight concrete. For all specimens, the lightweight modification factor (l) specified by the American Concrete Institute (ACI 318-08) [22] shear design provisions were evaluated and ranged from 1.21 to 2.71.

Despite their incredible potential, the use of beams comprised of two layers with two distinct materials in constructing sustainable composite beams has been limited in recent years. A full-scale two-layer beam and a continuous two-layer beam with standard strength concrete in the tensile zone and high strength concrete with steel fiber in the compression zone were recently investigated [23], [24]. Other researchers have concentrated on using Engineered Cementitious Composite (ECC) to replace the stress zone and improve the tensile strength of the concrete around the primary steel reinforcement [25-27]. Mohsin et al. [28] presented evaluations of a new two-layer RC beam with a high-strength concrete compression zone and a normal-strength concrete tension zone. In an experimental investigation, Dybel and Wałach [29] looked at the development of bond strength between two concrete layers. Normal concrete (NC) to high-performance concrete (HPC) and HPC to HPC kinds have been established, as well as comparisons with NC-to-NC examples.

The main objective of this research is to evaluate the strength and behavior of two-layer beams consisting of normal and lightweight concrete, the parameters have been chosen to investigate the effect of combining these two materials together in the same two-layer beams. The depth of each layer and compressive strength of normal and lightweight concrete were the main parameters of this study.

2. Experimental program

2.1. Materials

Ordinary Portland cement (OPC) with a specific gravity and surface area of 3.0 and 390.7 m^2/kg, respectively, was used for all mixes. All of the tests were performed with cement from a single delivery. Sand of sizes in the range of 0.15-4.75 mm with specific gravity, fineness modulus, and loose density of 2.65, 2.64, and 1645 kg/m^3, respectively was used as fine aggregate. Pumice with normal aggregate of sizes in the range of 4.75-25 mm, and 4.75-19 mm were used as a coarse aggregate. The other properties of pumice are shown in Table 1.

Table 1. The properties of Pumice aggregate.

Property	Pumice	Unit
Loose density	826	kg/m^3
Oven dry density	802	kg/m^3
Specific gravity	1.75	-
Water absorption	10	%
Crushing Resistance	3.6	-
Cl	0.02	%
SO_3	0.5	%
Total Sulphur (TS)	0.32	%

Silica fume with density, specific area, and specific gravity of 700 kg/m^3, 15 m^2/g, and 2.40, respectively was used. Superplasticizer with a density of 1061 kg/m^3 was used as a high range water reducer that provides long workability times. Table 2 gives the mix proportions and results of both the LWC and the NWC.

Table 2. Mix proportions and results of both the LWC and the NWC.

ID	w/c	Water (kg)	Cement (kg)	Sand (kg)	coarse aggregate (kg)		SF (kg)	SP (kg)	Density kg/m^3	f'_c (MPa)	f_{ct} (MPa)	E_c (MPa)
					Normal	lightweight						
1N	0.34	150	401	682	1007	-	35	4.80	2432	49.3	4.46	36534
2N	0.44	185	420	718	1077	-	0.00	2.10	2412	33.1	3.12	31139
3N	0.50	200	400	720	1054	-	0.00	0.00	2396	25.5	2.45	29194
1L	0.60	226	300	520	-	633	23	0	1801	23.2	2.50	13952
2L	0.40	200	450	562	-	473	50	3.95	1953	28.5	2.20	14590
3L	0.40	226	510	880	-	371	55	4.46	2031	35.1	2.05	17295

SF: Silica Fume, SP: superplasticizer, f'_c cylinder compressive strength, f_{ct}: splitting tensile strength, E_c: Young's modulus

The main reinforcement for the beams be made up of deformed bars with a diameter of 16 mm, while shear and compression reinforcement consisted of deformed bars with a diameter of 10 mm and a yield strength of about 620 MPa for both. The ratio of tension reinforcement was kept at 1.72 % for all the beams. However, the variable in the investigation was the shear reinforcement. Fig. 1 shows the stress-strain curve for steel reinforcement.

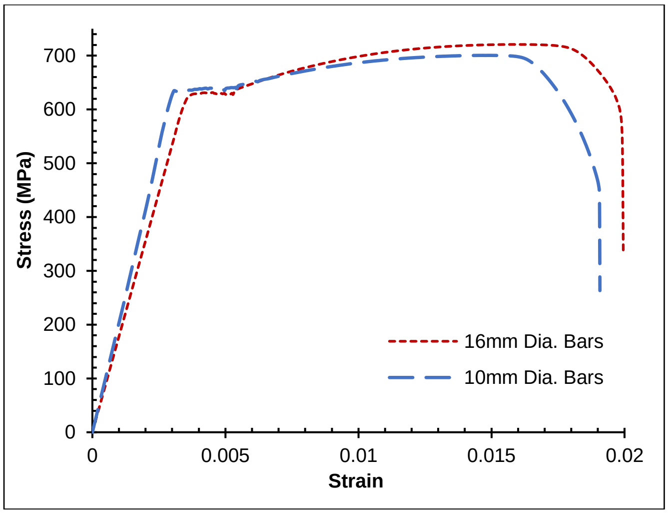


Fig. 1 Stress-strain curves for steel reinforcement bars.

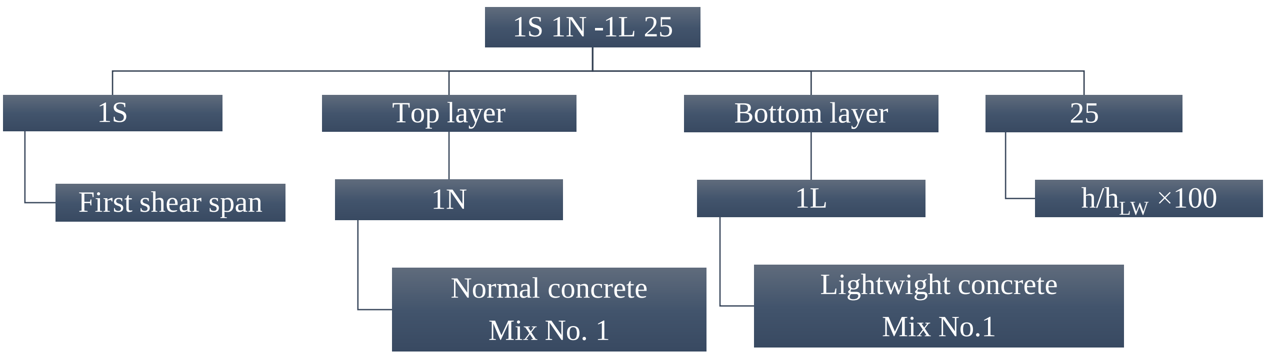
2.2. Preparation of Test Specimens

Sixteen reinforced concrete beams were fabricated and divided into four groups, based on the configurations of concrete layers. The beams have been reinforced with flexural steel bars and designed to fail in shear. All beams were tested as a simply supported with four-point loading as shown in Fig. 2. The variables in each group of specimens were the ratio of the thickness of the lightweight concrete layer to the overall depth of beam (h_{LW}/h) and concrete compressive strength which was (23.2, 28.5, and 35.1 MPa) for LWC and (25.2, 33.5, 49.3 MPa) for NWC. All the specimens were tested after 28 days. All the beams had a nominal width and height of 140 mm and 200 mm, 1700 mm long, all the beams in groups 1, 3, and 4 tested with a shear span-to-depth (a/h) ratio of 2.75. while group 2 tested with three different shear span-to-depth (a/h) ratios of 2.75, 2.33, and 2. The reinforced concrete beams in all groups were fabricated without stirrups in one shear span as shown in Fig. 3 to guarantee shear failure in that side, and the beams were subjected to four-point loading until failure.

The detailing of a typical beam in Groups 1, 2, 3, and 4 is shown in Fig. 3. Two 16 mm diameter rebars were installed at a depth of 167 mm from the top concrete surface on the beam's tension side, and two 10 mm diameter rebars were inserted on the beam's compression zone. The reinforcement ratios for all specimens were 1.72 %. The beams were reinforced in shear on one side of the beam's shear span with 10 mm diameter stirrups that were at intervals of 50 mm. The sample designation and detailing for each beam specimen are provided in Table 3.

The designation of beams included a combination of letters and numbers: For example, (1S1N-1L25) 1S stands for first (a/h) shear span which is 2.75 beams, part 1N is the first normal concrete mix ID ,1L for first lightweight aggregate concrete mix ID and 25 indicate the ratio of lightweight layer thickness to overall depth of beams.

All the beams were cast in plywood forms as shown in the Fig. 4. The control specimens, cylinders with a diameter of 150 mm and a height of 300 mm for tests of compressive strength, splitting tensile strength and Young's modulus. These specimens were cast in parallel with the beams and cured under similar conditions to those used for the beams. The parameters of the concrete utilized for the beams are summarized in Table 1.



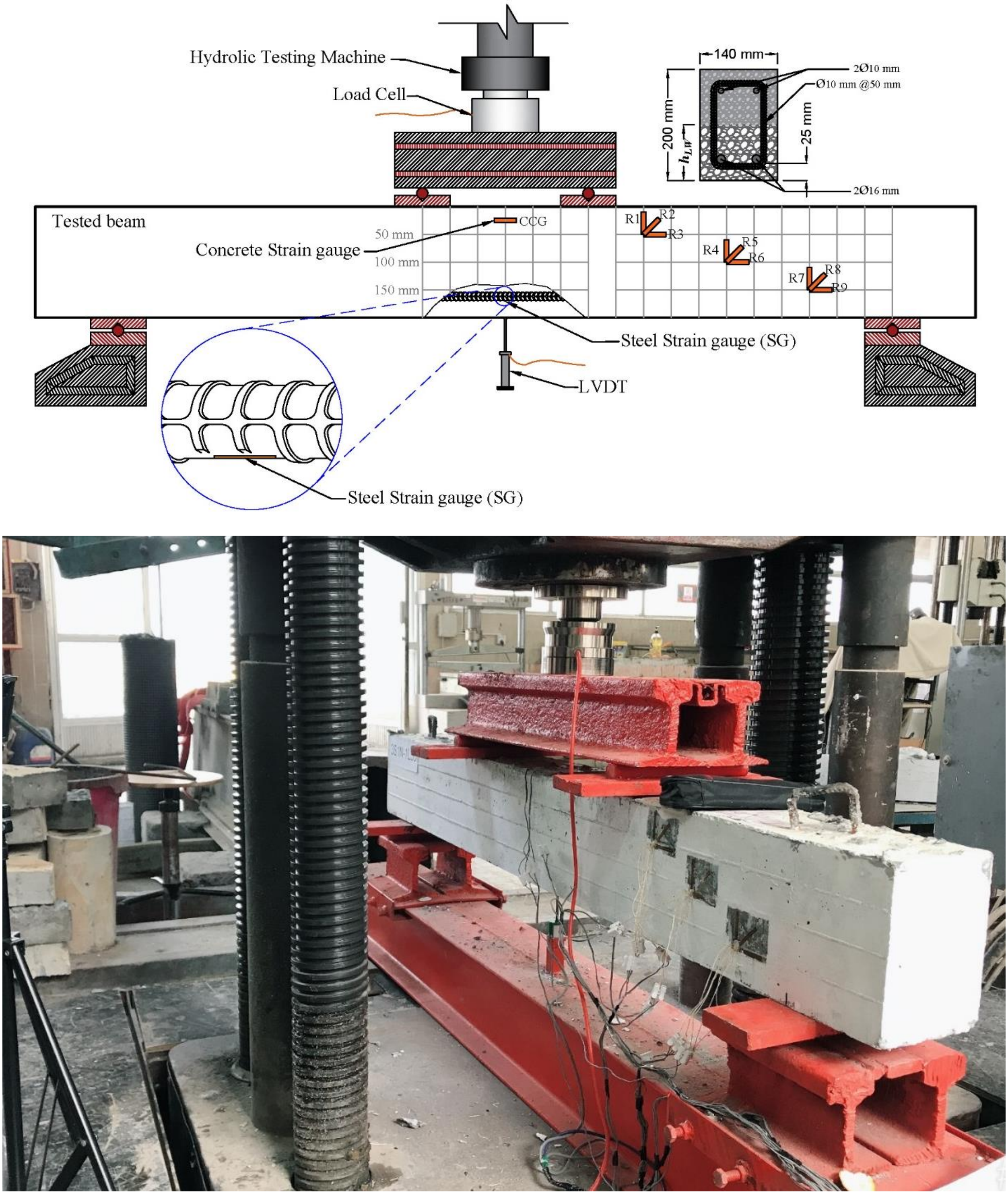


Fig. 2 The experimental set-up for the reinforced two-layer beam.

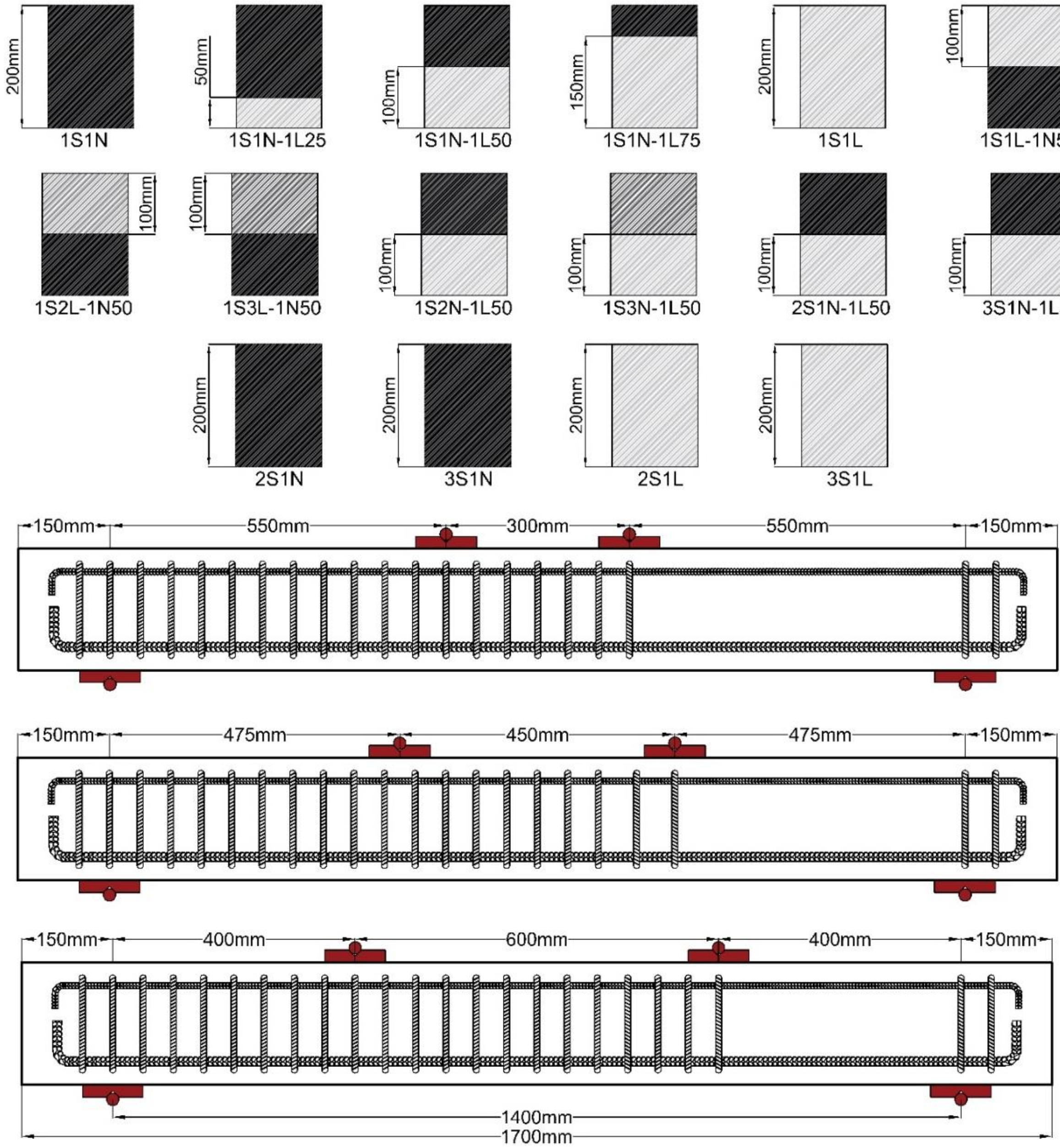


Fig. 3 Beams' layout and reinforcement detailing.

Fig. 4 Plywood forms, steel placing and concrete casting.

Table 3. Test beam details and properties.

Beam ID	Layer thickness of		a/h	h_{LW}/h Ratio	Type of concrete	
	NWC (mm)	LWC (mm)			Top layer	Bottom layer
1S1N	200	-	2.750	0%	NWC	-
1S1N-1L25	150	50	2.750	25%	NWC	LWC
1S1N-1L50	100	100	2.750	50%	NWC	LWC
1S1N-1L75	50	150	2.750	75%	NWC	LWC
1S1L	-	200	2.750	100%	-	LWC
1S1L-1N50	100	100	2.750	50%	LWC	NWC
1S2L-1N50	100	100	2.750	50%	LWC	NWC
1S3L-1N50	100	100	2.750	50%	LWC	NWC
1S2N-1L50	100	100	2.750	50%	NWC	LWC
1S3N-1L50	100	100	2.750	50%	NWC	LWC
2S1N-1L50	100	100	2.375	50%	NWC	LWC
3S1N-1L50	100	100	2.000	50%	NWC	LWC
2S1N	200	-	2.375	0%	NWC	-
3S1N	200	-	2.000	0%	NWC	-
2S1L	-	200	2.375	100%	-	LWC
3S1L	-	200	2.000	100%	-	LWC

2.3. *Testing Setup*

The beams were tested under four-point loadings with a constant effective span. For all beams the shear span to overall depth (*a/h*) ratio was maintained in Table 3. The test setup is shown in Fig. 2.

A universal testing machine with a portable load cell capacity of 740 kN was used to test the beams. Electrical resistance strain gauges were used to measure the strains in the main reinforcements, which were then recorded using a data logger. The compressive strains at the concrete surface in the mid-span were also measured using the electrical resistance strain gauges. The strains on the surfaces of the concrete through diagonal line from load to support have been measured using electrical resistance strain gauges in rosette configurations as shown in the Fig. 2. To measure the deflections, linear voltage differential transducer (LVDT) was placed under the beam mid-span.

3. Experimental results

3.1. Observation of Cracking and Failure Modes

The formation of cracks in all of the tested beams was monitored and recorded until failure. As shown in Fig. 5, all of the beams failed in shear as expected, due to the development of a typical diagonal significant crack between the loading point and the right-side of support (side without stirrups). Flexural cracks were initiated and found at the mid-span of beams, where the bending moment was the maximum, during the early stages of the loading. Fig. 5 shows the cracking pattern and failure modes of the selected NWC, two-layer and LWC beams. These cracks developed at a load level of about 11-15 % of the ultimate load. However, in the case of LWC and two-layers beam, flexural cracks appeared early in the loading process, which could be related to the lightweight concrete's lower modulus of rupture.

Table 4. Experimental results of tested beams.

Beam	a/h	P_u	P_{cr}	V_u	P_{cr}/P_u	$\dfrac{V_u}{bd\sqrt{f'_{c\,eq.}}}$
1S1N	2.750	85.32	12.50	42.66	14.7 %	0.22
1S1N-1L25	2.750	75.70	10.50	37.85	13.9 %	0.21
1S1N-1L50	2.750	68.15	9.00	34.08	13.2 %	0.20
1S1N-1L75	2.750	68.78	8.50	34.39	12.4 %	0.23
1S1L	2.750	68.52	8.00	34.26	11.7 %	0.25
1S1L-1N50	2.750	79.88	10.10	39.94	12.6 %	0.24
1S2L-1N50	2.750	81.06	10.50	40.53	13.0 %	0.23
1S3L-1N50	2.750	83.62	10.80	41.81	12.9 %	0.23
1S2N-1L50	2.750	67.95	9.50	33.98	14.0 %	0.23
1S3N-1L50	2.750	67.34	10.30	33.67	15.3 %	0.24
2S1N-1L50	2.375	118.12	15.52	59.06	13.1 %	0.40
3S1N-1L50	2.000	144.93	21.89	72.46	15.1 %	0.52
2S1N	2.375	143.42	17.04	71.71	11.9 %	0.36
3S1N	2.000	179.96	22.05	89.98	12.3 %	0.46
2S1L	2.375	74.67	11.28	37.33	15.1 %	0.28
3S1L	2.000	95.86	16.22	47.93	16.9 %	0.36

Flexural cracks were more visible as the load increased, and as the cracks migrated into the shear span, they became flexural shear cracks. These cracks suddenly progressed toward the loading point and were inclined at an angle of 34.8°-45.8°. Some horizontal cracks developed near the bottom longitudinal reinforcement, which reduced the shear stress and the dowel action between the concrete and steel reinforcement, as shown in Fig. 5. Therefore, it can be concluded that smaller crack width with larger number of cracks occurred in LWC layer. For all beams with (a/h = 2.0), flexural cracks did not develop but shear cracks suddenly appeared and run through the compression zone and produced collapse as shown in Fig. 5, while for the rest of the beams (2.75 > a/h > 2.0), the initial bending cracks were occurred and became inclined early in the loading stage and at collapse, horizontal cracks were formed and running along the line of the tensile reinforcement. These horizontal cracks reduced the shear resistance of the section by destroying the dowel force and reducing the bond stresses between the steel and bottom layer in two-layer beams as shown in Fig. 5. For all reinforced concrete beams, the longitudinal steel in the tension zone did not reach the yielding strength. It is worthy of notice that the mode of shear cracking of the reinforced normal, and lightweight beams is similar, while horizontal cracks occur near the support in two-layer beams.

3.2. Load-Deflection Behavior

The load-mid-span deflection curves for all the 15 test beams of normal, lightweight concrete, and two-layer beams with different shear span-overall depth ratios (a/h) and different compressive strength are shown in Fig. 6. The effect of layer thickness of lightweight concrete on load versus mid-span deflection for reinforced concrete beams is shown in Fig. 6(a). From these figures, it can be seen that for reinforced concrete beam, as the layer thickness ratio (h_{LW}/h) increases from 0 % to 25 %, 50 %, 75 % and 100 % the ultimate load capacity decreases from 85.32 to 75.70, 68.15, 68.78, and 68.52 kN respectively, the results showed that for beams with (h_{LW}/h) ranging from 50 % to 100 %, the ultimate load capacity was not affected by the thickness of the lightweight layer. The ultimate load capacity of these beams where 20 % less than that of the normal concrete beam. Furthermore, when the (h_{LW}/h) were changed from 0 % to 25 % the load carrying capacity decreased by 11 %. There is no significant changing in ultimate load capacity by increasing the compressive strength of LWC in compressive zone from 23.2 MPa to 28.5 MPa and 35.1 MPa, where the ultimate load capacity increased from 79.88 kN to 81.06 kN and 83.62 kN as shown in the Fig. 6(b), as well as unsignificant influence occurred by decreasing the compressive strength of NWC in the compressive zone from 49.3 MPa to 33.1 MPa and 25.5 MPa, the ultimate load capacity decreased from 68.15 kN to 67.95 kN and 67.34 kN respectively as shown in Fig. 6(c).

Decreasing the shear span to depth ratio (a/h) from 2.75 to 2.375 and 2.0 increased the ultimate load capacity from 85.32 kN to 143.42 kN and 179.96 kN respectively in the fully normal weight concrete beams and from 68.52 kN to 74.67 kN and 95.86 kN respectively in fully lightweight concrete beams, while it increased from 68.15 kN to 118.12 kN and 144.93 kN respectively in two-layer beams with 50 % of h_{LW}/h. Also, by comparing the beams with same (a/h), if a/h equal to 2.75 the ultimate load capacity of two-layer beam is similar to fully lightweight concrete beams as shown in the Fig. 6(d). While the beams with 2.375 a/h the ultimate load capacity decreased from 143.42 kN for the fully normal concrete beam to 118.12 kN and 74.67 kN for two-layer and fully lightweight concrete respectively as shown in the Fig. 6(e). for the a/h to 2 as well, the ultimate load capacity decreases from 179.96 kN for fully normal concrete beams to 144.93 kN and 95.86 kN for the two-layer and fully lightweight concrete beams respectively as shown in the Fig. 6(f). The presence of LWC in the tension zone significantly decreases the ultimate load capacity of the two-layer beams with shear failure, conversely for the flexural there was slight effect for LWC in the tension zone [5].

As clearly shows in Fig. 7 changing a/h from 2.75 to 2.375 and 2 the ultimate capacity increased by 68 % and 111 % respectively for fully NWC beams, and it increased by 73 % and 113 % for two-layer beams, while these percentages change significantly lower for fully LWC beams, the ultimate load capacity increased by 9 % and 40 % by decreasing a/h from 2.75 to 2.375 and 2 respectively. The ratio remains for all configurations greater than 0.17, the minimum value recommended by the American Standard ACI-318-2014 as shown in the Fig. 8.

From the experimental data, the cracking load P_{cr}, and ultimate load P_u, of all tests are summarized in Figs. 9(a-f), and Table 3. As shown in Table 3, the ratios of first cracking to ultimate load for fully normal beams is ranged from 11.9 % to 14.7 % with an average value of 12.9 % and standard deviation of 1.5 %, and for fully lightweight concrete beams ranged from 11.6 % to 16.9 % with an average value of 14.6 % and standard deviation of 2.7 %, while for all other two-layer beams are ranged from 12.4 % to 15.3 % with an average value of 13.5 % and standard deviation of 1 %. The shear stress was calculated using the following equation: $v_{exp} = V_u/(bd)$. The experimental shear stress, v_{exp}, has been divided by the root of the compressive strength, f_c`, as ($v_{exp}/\sqrt{f_c`_{eq}}$), where the $f_c`_{eq}$ is the equivalent compressive strength equal to (1 - (h_{LW}/h) $f'_{c\ NWC}$ + (h_{LW}/h) $f'_{c\ LWC}$), the v_{exp} indicates the ability of diagonally cracked concrete to transmit tension and shear.

3.3. Strain Results

Figure 10 displays the collected compressive concrete strain (CCG) corresponding to the load at two points as shown in Fig. 1. the steel gauge (SG) placed at the bottom of tension steel reinforcement, while the concrete gauges (CCG) placed at 25 mm measured from the top. At failure stage, the strain readings of concrete shows that the failure strain is less than the ultimate strain of the concrete since the failure occurs due to the shear failure between the loading point and the supporting point. The measured concrete strain variants among beams were due to the differences in the concrete type and concrete compressive strength.

Regarding the deformation on the longitudinal steels, Fig. 10 shows the relationship between the applied load and the strain measured by the strain gauges on the longitudinal steels. In general, the longitudinal steel bars work under the elastic stress. The behavior of the longitudinal steel is divided into two stages during loading: before and after bending concrete cracking until the failure stage.

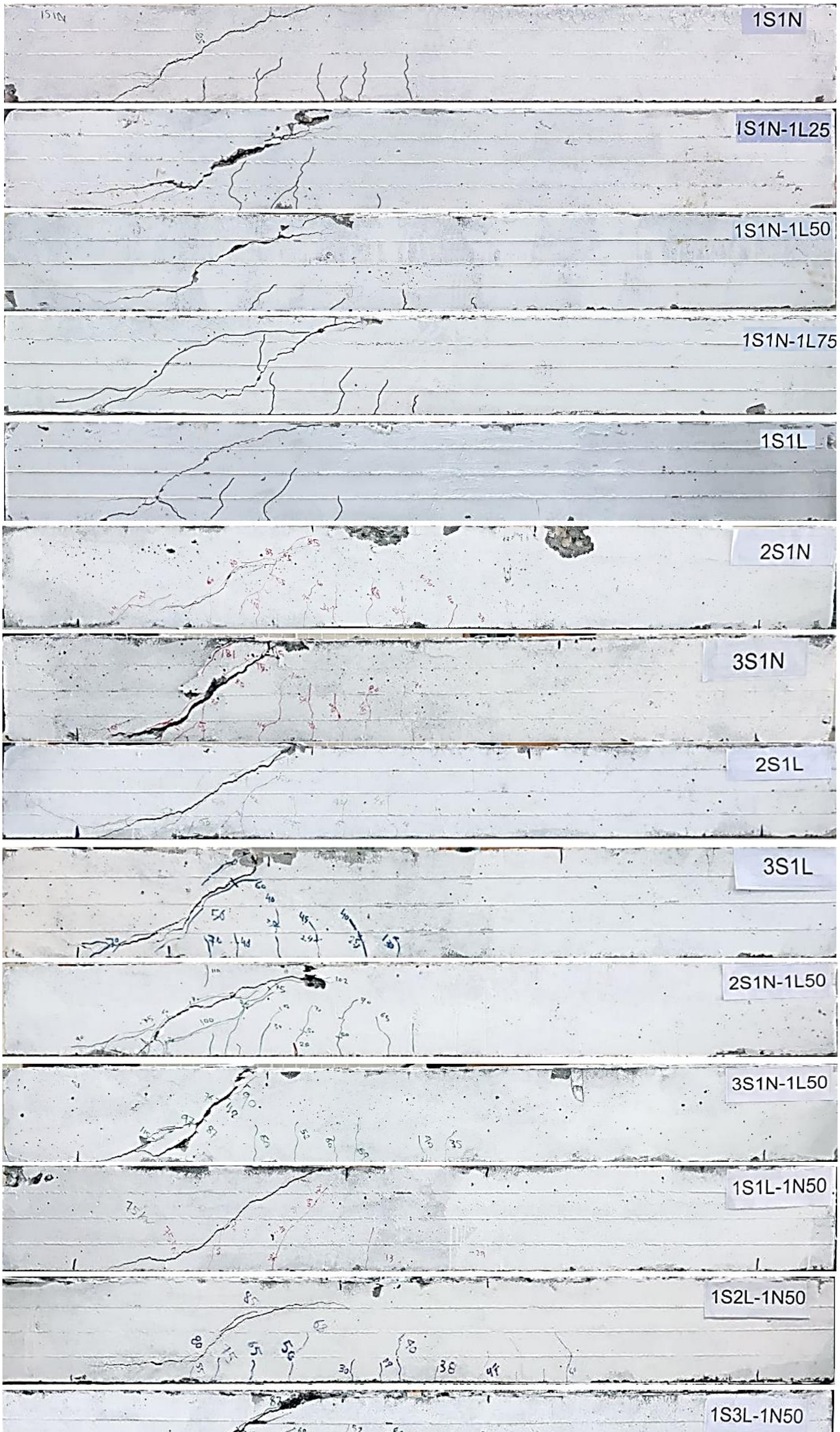


Fig. 5 Crack pattern of tested beams.

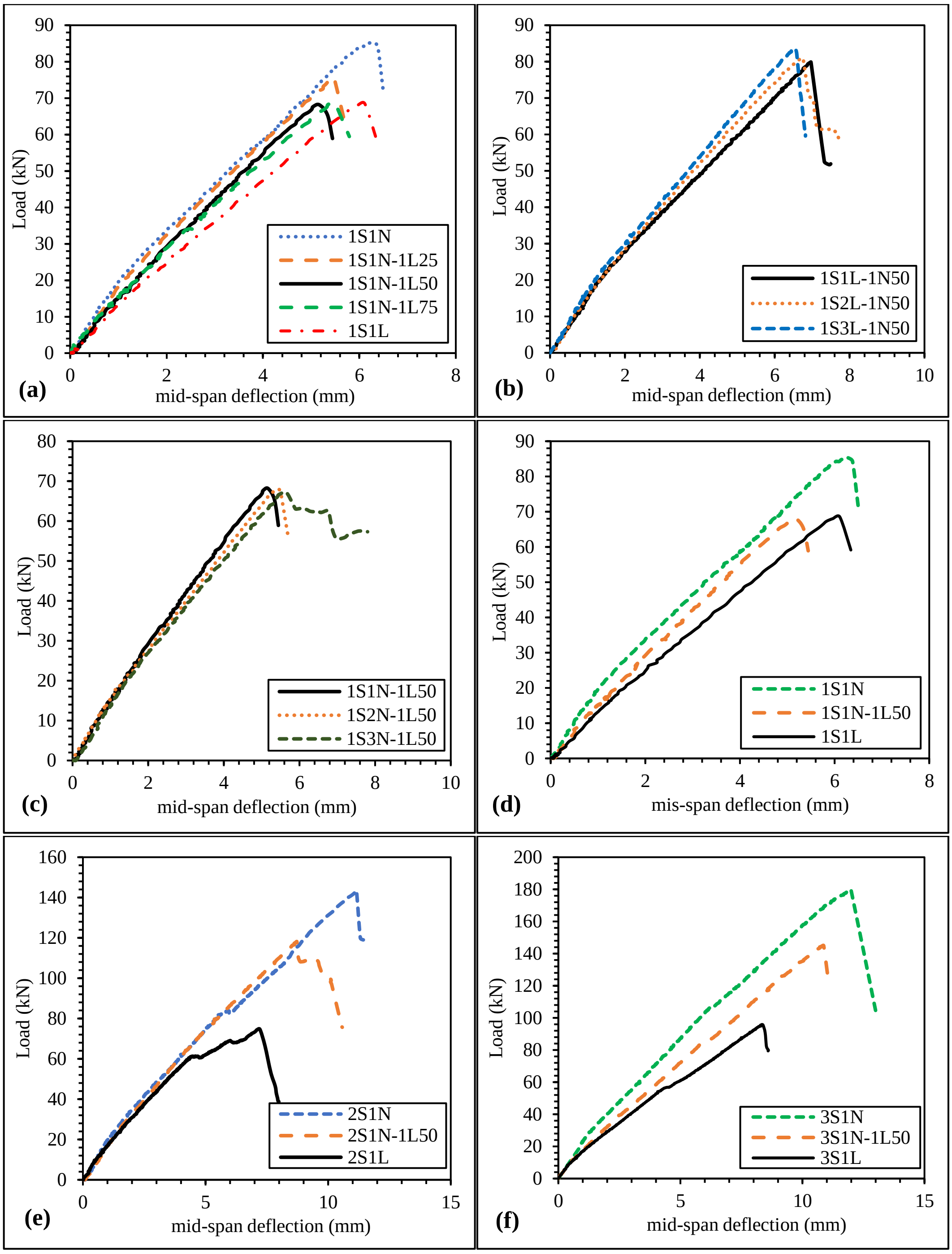


Fig. 6 load mid-span deflections.

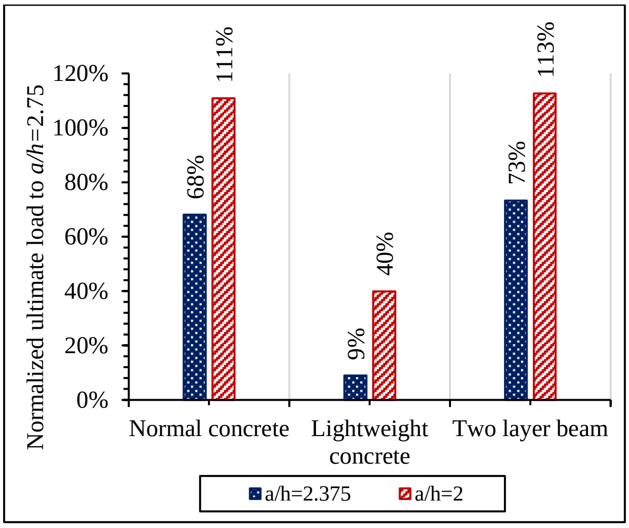


Fig. 7 effect of shear span on maximum load capacity for normal concrete beam, light weight beam, and two-layer beam.

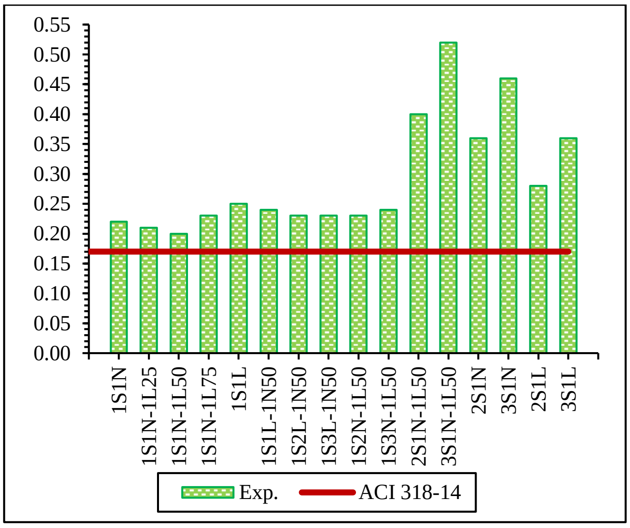


Fig. 8 Comparison between experimental and the minimum value recommended by the American Standard ACI-318-2014.

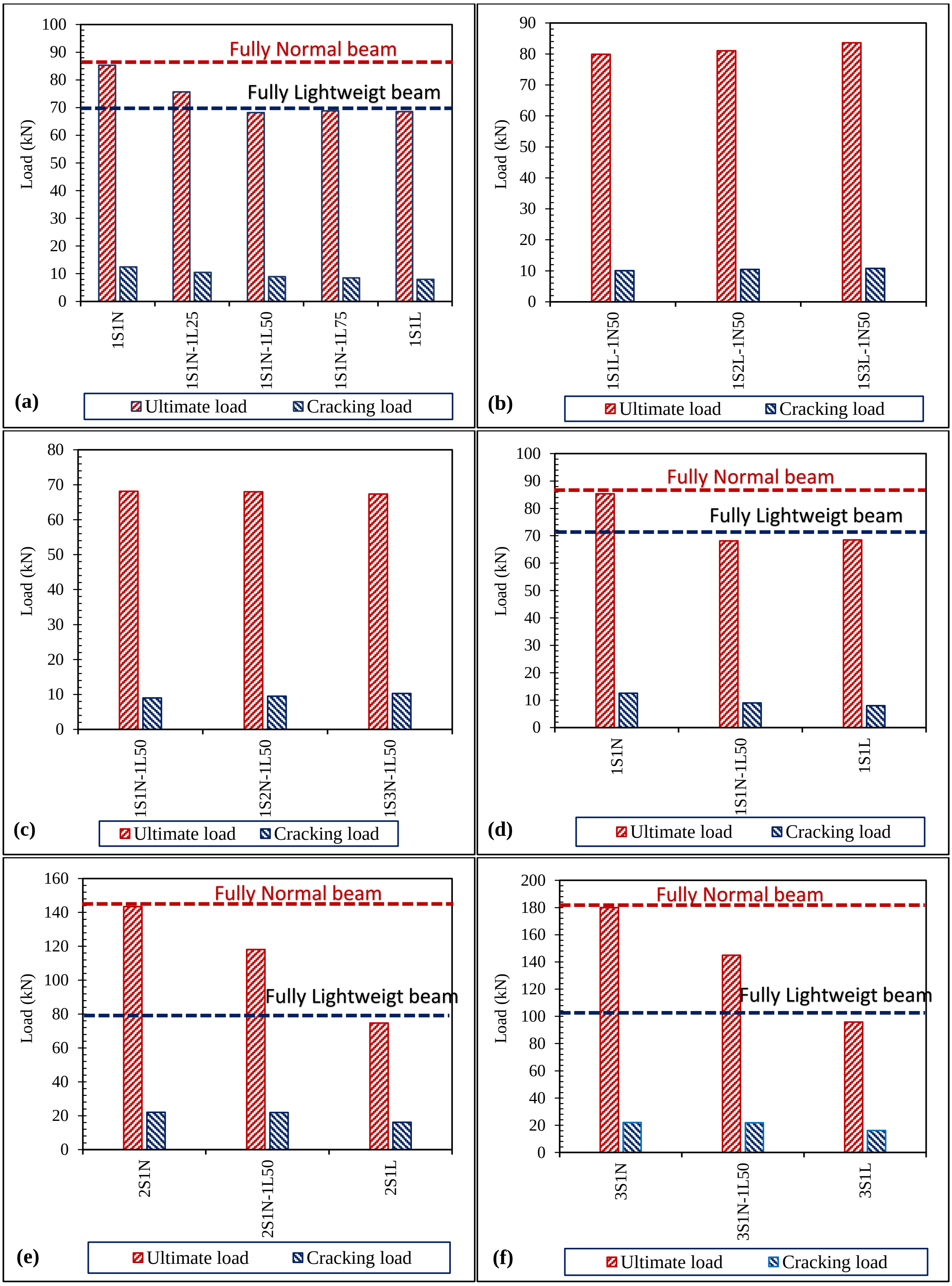


Fig. 9 experimental load of the tested beams.

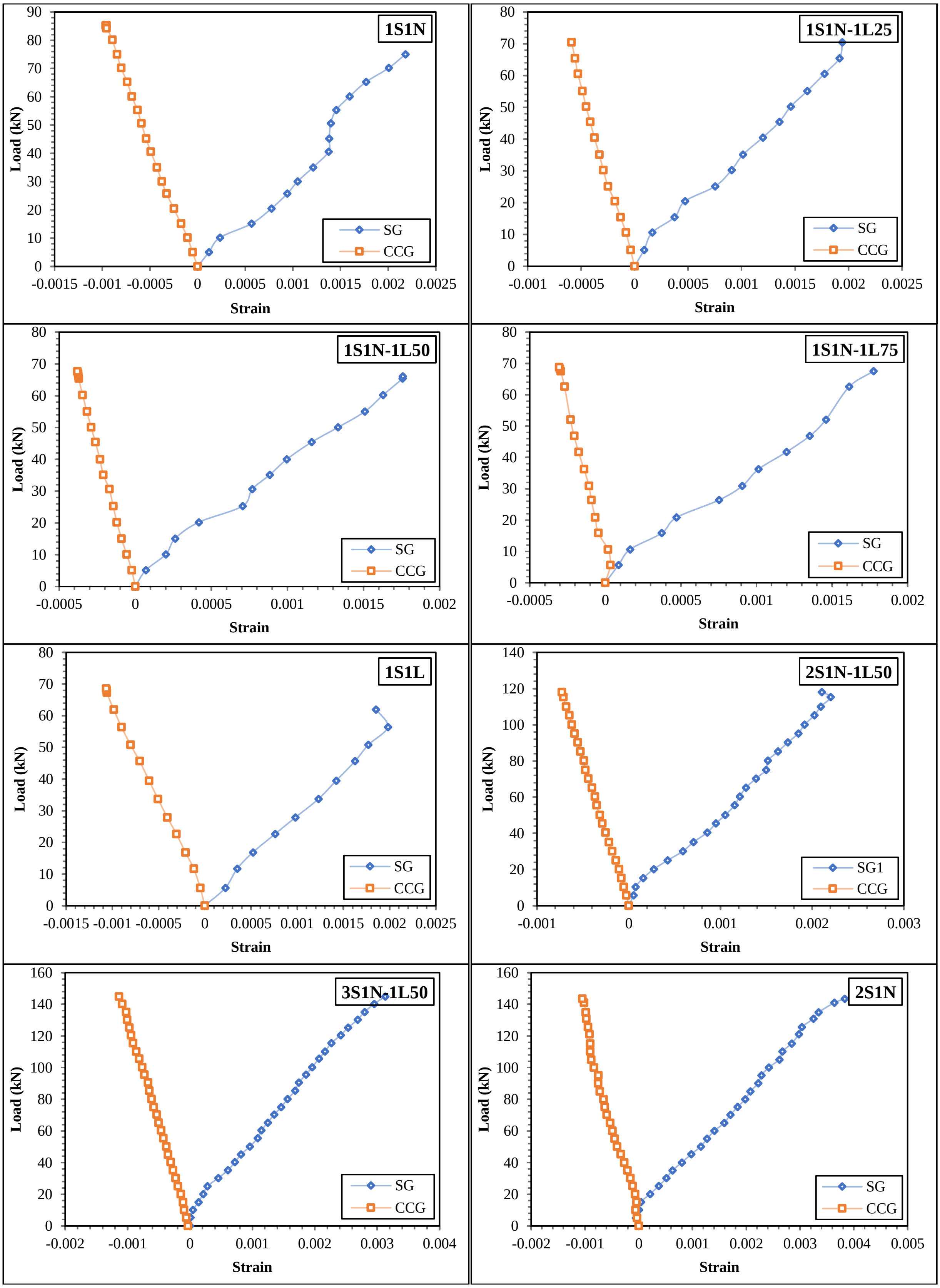


Fig. 10 Load-strain curves.

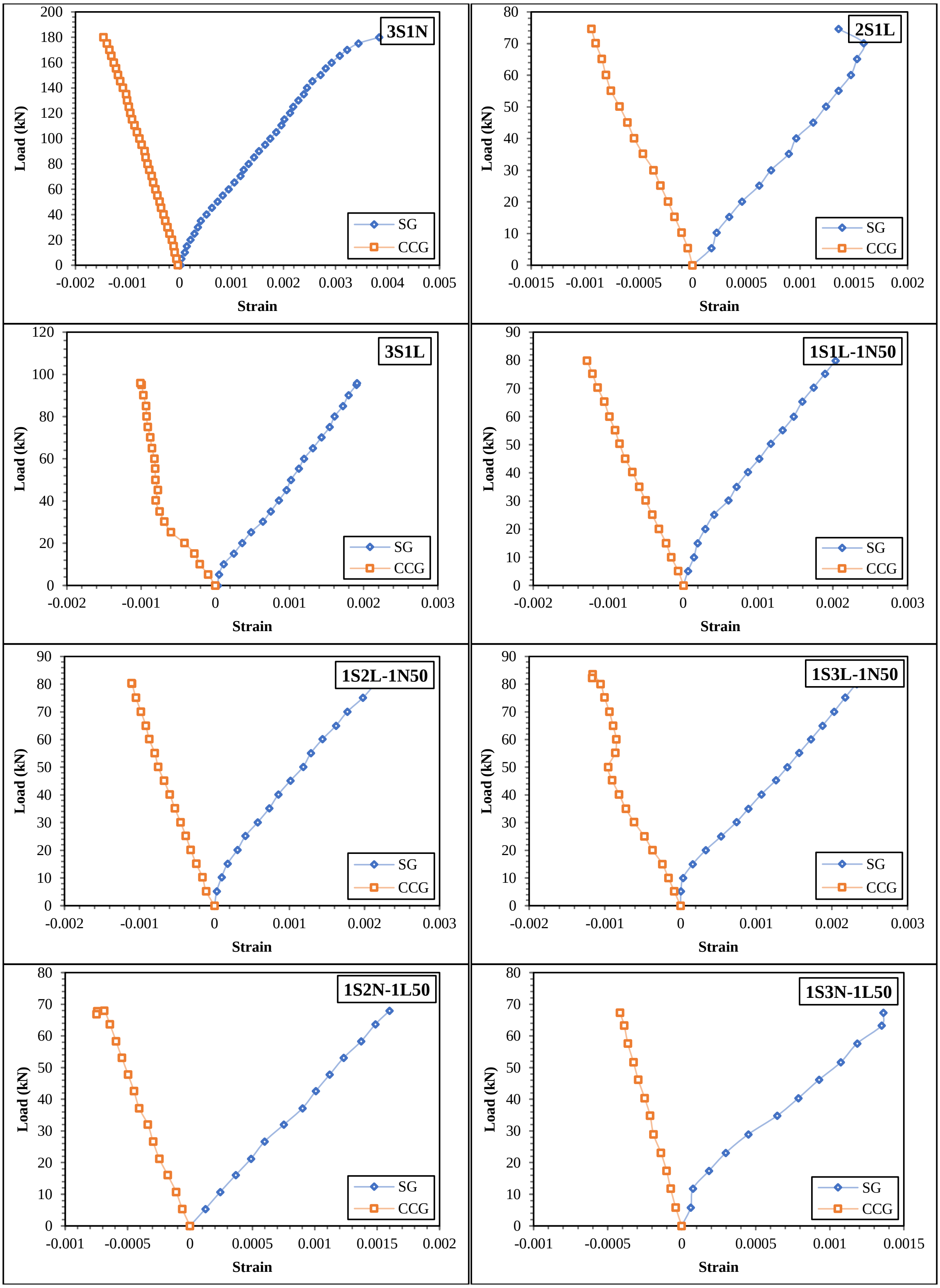


Fig. 10 Load-strain curves continued.

4. Conclusions

Based on the experimental results the following conclusion can be drawn from the finding of this study:

1. All the tested beams failed in a similar mode, due to diagonal tension shear crack.
2. The behavior and trend of the load-deflection response curves for LWC beams is quite similar to that of NWC beams with insignificant increasing in the deflection in two-layer with h_{LW}/h less than 50 % and significant for h_{LW}/h more than 50 %.
3. The shear failure is governed by the lower layer of concrete in the two-layer beams with *a/d* 2.75 and it is compound for *a/d* 2.375 and 2.
4. Decreasing *a/h* from 2.75 to 2.375 and 2 the ultimate capacity increased by 68 % and 111 % respectively for fully NWC beams, and it increased by 73 % and 113 % for two-layer beams, while these percentages change significantly lower for fully LWC beams, the ultimate load capacity increased by 9 % and 40 % by decreasing *a/h* from 2.75 to 2.375 and 2 respectively.
5. The shear stress was calculated using the experimental data then divided by the root square of the compressive strength, $fc`$, as ($V_u/bd\sqrt{fc`}$), which indicates the ability of diagonally cracked concrete to transmit tension and shear. The ratio remains for all configurations higher than 0.17 which is the value recommended by the ACI318-14.

References

[1] M. A. Nawaz, L. A. Qureshi, B. Ali, and A. Raza, "Mechanical, durability and economic performance of concrete incorporating fly ash and recycled aggregates", SN Applied Sciences, Vol. 2, No. 2, 2020. https://doi.org/10.1007/s42452-020-1960-8

[2] H. K. Adai Al-Farttoosi, O. A. Abdulrazzaq, and H. K. Hussain, "Mechanical Properties of Light Weight Aggregate Concrete Using Pumice as a Coarse Aggregate", IOP Conference Series: Materials Science and Engineering, Vol. 1090, No. 1, p. 012106, 2021. https://doi.org/10.1088/1757-899X/1090/1/012106

[3] W. Nawaz, J. A. Abdalla, R. A. Hawileh, H. S. Alajmani, I. H. Abuzayed, H. Ataya, H. A. Mohamed, "Experimental study on the shear strength of reinforced concrete beams cast with Lava lightweight aggregates", Archives of Civil and Mechanical Engineering, Vol. 19, No. 4, pp. 981-996, 2019. https://doi.org/10.1016/j.acme.2019.05.003

[4] K. -H. Yang, J. -I. Sim, B. -J. Choi, and E. -T. Lee, "Effect of Aggregate Size on Shear Behavior of Lightweight Concrete Continuous Slender Beams", ACI materials journal, Vol. 108, No. 5, pp. 501-509, 2011.

[5] H. K. A. AL-Farttoosi, H. K. Hussain, and O. A. Abdulrazzaq, "Flexural behavior of two-layer beams made with normal and lightweight concrete layers", Periodicals of Engineering and Natural Sciences, Vol. 9, No. 2, pp. 1124-1140, 2021. http://dx.doi.org/10.21533/pen.v9i2.1952.g851

[6] G. Campione and L. La Mendola, "Stress-strain behavior in compression of lightweight fiber reinforced concrete under monotonic and cyclic loads", Transactions on the Built Environment, Vol. 57, pp. 387-396, 2001.

[7] M. -H. Zhang and O. E. Gjørv, "Microstructure of the interfacial zone between lightweight aggregate and cement paste", Cement and Concrete Research, Vol. 20, No. 4, pp. 610-618, 1990. https://doi.org/10.1016/0008-8846(90)90103-5

[8] J. A. Bogas, M. G. Gomes, and S. Real, "Bonding of steel reinforcement in structural expanded clay lightweight aggregate concrete: The influence of failure mechanism and concrete composition", Construction and Building Materials, Vol. 65, pp. 350-359, 2014. https://doi.org/10.1016/j.conbuildmat.2014.04.122

[9] K. H. Mo, U. J. Alengaram, P. Visintin, S. H. Goh, and M. Z. Jumaat, "Influence of lightweight aggregate on the bond properties of concrete with various strength grades", Construction and Building Materials, Vol. 84, pp. 377-386, 2015. https://doi.org/10.1016/j.conbuildmat.2015.03.040

[10] M. Pecce, F. Ceroni, F. A. Bibbò, and S. Acierno, "Steel--concrete bond behaviour of lightweight concrete with expanded polystyrene (EPS)", Materials and Structures, Vol. 48, No. 1, pp. 139-152, 2015. https://doi.org/10.1617/s11527-013-0173-7

[11] B. Xu, D. V. Bompa, A. Y. Elghazouli, A. M. Ruiz-Teran, and P. J. Stafford, "Behaviour of rubberised concrete members in asymmetric shear tests", Construction and Building Materials, Vol. 159, pp. 361-375, 2018. https://doi.org/10.1016/j.conbuildmat.2017.10.091

[12] D. V. Bompa and A. Y. Elghazouli, "Ultimate shear behaviour of hybrid reinforced concrete beam-to-steel column assemblages", Engineering Structures, Vol. 101, pp. 318-336, 2015. https://doi.org/10.1016/j.engstruct.2015.07.033

[13] S. Campana, M. Fernández Ruiz, A. Anastasi, and A. Muttoni, "Analysis of shear-transfer actions on one-way RC members based on measured cracking pattern and failure kinematics", Mag. Concr. Res., Vol. 65, No. 6, pp. 386-404, 2013. https://doi.org/10.1680/macr.12.00142

[14] M. Z. Jumaat, U. J. Alengaram, and H. Mahmud, "Shear strength of oil palm shell foamed concrete beams", Mater. Des., Vol. 30, No. 6, pp. 2227-2236, 2009. https://doi.org/10.1016/j.matdes.2008.09.024

[15] E. Yasar, C. D. Atis, A. Kilic, and H. Gulsen, "Strength properties of lightweight concrete made with basaltic pumice and fly ash", Materials Letters, Vol. 57, No. 15, pp. 2267-2270, 2003. https://doi.org/10.1016/S0167-577X(03)00146-0

[16] R. M. Korol and K. S. Sivakumaran, "Energy absorption potential of light weight concrete floors", Canadian Journal of Civil Engineering, Vol. 39, No. 11, pp. 1193-1201, 2012. https://doi.org/10.1139/l2012-107

[17] K. Onoue, H. Tamai, and H. Suseno, "Shock-absorbing capability of lightweight concrete utilizing volcanic pumice aggregate", Construction and Building Materials, Vol. 83, pp. 261-274, 2015. https://doi.org/10.1016/j.conbuildmat.2015.03.019

[18] P. Shafigh, H. Bin Mahmud, M. Z. Bin Jumaat, R. Ahmmad, and S. Bahri, "Structural lightweight aggregate concrete using two types of waste from the palm oil industry as aggregate", Journal of Cleaner Production, Vol. 80, pp. 187-196, 2014. https://doi.org/10.1016/j.jclepro.2014.05.051

[19] M. Limbachiya, M. S. Meddah, and Y. Ouchagour, "Performance of Portland/Silica Fume Cement Concrete Produced with Recycled Concrete Aggregate", ACI Materials Journal, Vol. 109, No. 1, pp. 91-100, 2012.

[20] C. -W. Tang, T. Yen, and H. -J. Chen, "Shear behavior of reinforced concrete beams made with sedimentary lightweight aggregate without shear reinforcement", Journal of Materials in Civil Engineering, Vol. 21, No. 12, pp. 730-739, 2009. https://doi.org/10.1061/(ASCE)0899-1561(2009)21:12(730)

[21] U. J. Alengaram, M. Z. Jumaat, H. Mahmud, and M. M. Fayyadh, "Shear behaviour of reinforced palm kernel shell concrete beams", Construction and Building Materials, Vol. 25, No. 6, pp. 2918-2927, 2011. https://doi.org/10.1016/j.conbuildmat.2010.12.032

[22] A. C. I. Committee, "Building code requirements for structural concrete (ACI 318-08) and commentary", 2008.

[23] I. Iskhakov, Y. Ribakov, K. Holschemacher, and T. Mueller, "Experimental investigation of full scale two-layer reinforced concrete beams", Mechanics of Advanced Materials and Structures, Vol. 21, No. 4, pp. 273-283, 2014. https://doi.org/10.1080/15376494.2012.680673

[24] I. Iskhakov, Y. Ribakov, and K. Holschemacher, "Experimental investigation of continuous two-layer reinforced concrete beams", Structural Concrete, Vol. 18, No. 1, pp. 205-215, 2017. https://doi.org/10.1002/suco.201600027

[25] A. R. Krishnaraja and S. Kandasamy, "Flexural performance of hybrid engineered cementitious composite layered reinforced concrete beams", Periodica Polytechnica Civil Engineering, Vol. 62, No. 4, pp. 921-929, 2018. https://doi.org/10.3311/PPci.11748

[26] M. Velmurugan, S. Kesavraman, and A. Radhakrishnan, "Experimental study on flexural behaviours of ECC and concrete composite reinforced beams", International Journal of Civil Engineering and Technology, Vol. 8, No. 2, pp. 282-288, 2017.

[27] W. J. Ge, A. F. Ashour, X. Ji, C. Cai, and D. F. Cao, "Flexural behavior of ECC-concrete composite beams reinforced with steel bars", Construction and Building Materials, Vol. 159, pp. 175-188, 2018. https://doi.org/10.1016/j.conbuildmat.2017.10.101

[28] S. J. Mohsin and N. S. Mohammed, "Nonlinear analysis of hybrid reinforced concrete beams under flexural load", IOP Conference Series: Materials Science and Engineering, Vol. 737, No. 1, pp. 1-10, 2020. https://doi.org/10.1088/1757-899X/737/1/012022

[29] P. Dybeł and D. Wałach, "Evaluation of the Development of Bond Strength between Two Concrete Layers", in IOP Conference Series: Materials Science and Engineering, Vol. 245, No. 3, 2017. https://doi.org/10.1088/1757-899X/245/3/032056