

Experimental Study of the Behaviour of Deep Beams Using Light-Weight Structural Leca Concrete

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ABSTRACT: This paper studies the structural behaviour of deep beams using lightweight concrete. The experimental program consisted of testing twelve simply supported deep beams specimens tested under static two-point loading. The dimensions were (1300×150×400) mm. Light expanding clay aggregate (LECA) was used to product lightweight concrete. Test variables were depth of deep beams, lightweight concrete density, ratio of main reinforcement, ratio and shape of web reinforcement and shear span to depth ratio (a/h). Effects of these variables on behaviour of lightweight deep beam were studied, the behaviour including Crack patterns, first crack load; ultimate loads and reserve strength, load-deflection response, flexural strains distribution and shear strains.

KEYWORDS: Deep beam, lightweight concrete, LECA, strain gage, crack pattern

I. INTRODUCTION

Reinforced concrete deep beams are widely used in buildings, bridges and infrastructures. Deep beams are applying as foundation wall or raft slab, shear walls in building, and it is also used in water tank structure. The beam with shear span to depth ratio (a/d) less than 1 is classified as Deep beam and a beam with a/d ratio exceeding 2.5 as ordinary beam. The assumption "plane section before bending remains plane after bending" which valid for ordinary beam; it is not valid for deep beam and the distribution of flexural strain along depth at mid span is nonlinear. Deep beams begin to crack at loads ranging from 1/3 to 1/2 ultimate load.[1] Currently, the major codes and manuals that contain some discussion of deep beams including the American ACI Building Code, the draft Euro code EC/2, the Canadian Code, and the CIRIA Guide No. 2. The CIRIA Guide No. 2 gives the most comprehensive recommendations and is the only one that covers the buckling strength of slender beams.[2, 4] According to ACI Building Code 318-11, Deep beams are members loaded on one face and supported on the opposite face so that compression struts can develop between the loads and the supports, and have either: Clear spans, l_n , equal to or less than four times the overall member depth; or Regions with concentrated loads within twice the member depth from the face of the support.[3]

Structural lightweight aggregate concrete is an important and versatile material in modern construction. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types.[5] The primary use of structural lightweight concrete is to reduce the dead load of a concrete structure, which then allows the structural designer to reduce the size of columns, footing and other load bearing elements. Structural lightweight concrete mixtures can be designed to achieve similar strengths as normal weight concrete. In buildings, structural lightweight concrete provides a higher fire-rated concrete structure. The porosity of lightweight aggregate provides a source of water for internal curing of concrete strength and durability. This does not preclude the need for external curing. [6] The lightweight aggregates, for use in structural concrete, are manufactured from natural materials are: expanded clay, shale, and slate. They are obtained by heating suitable raw materials in a rotary kiln to incipient fusion (temperature of 1000 to 1200°C). Often, the raw material is reduced to the desired size before calcining, but crushing after expansion may also be applied. Oven-dry particles of lightweight aggregate of the expanded clay or shale variety have an apparent specific gravity in the range of 1.2 to 1.5 for coarse aggregate and between 1.3 and 1.7 for fine aggregate. The bulk density of the aggregate is 650 to 900 kg/m³ when

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made by the sinter strand process, and 300 to 650 kg/m³ when made in a rotary kiln. These aggregates produce concrete with a density usually within the range of 1400 to 1800 kg/m³. [7] In this study, light expanded clay aggregates (LECA) are used in production structural lightweight concrete.

II. MATERIALS AND METHODS

A total of twelve deep beams were tested. The beams were divided into two groups, control beams group and test beams. Table (1) shows a description about the specimens details and the variables. All beams were of rectangular cross section, all beams have length of 1300mm and width of 150 mm, ten beams have depth of 400mm and two beams have depth of 460 mm and 520 mm. For all beams the clear span between the supports was 1000 mm. The top longitudinal reinforcement bar was 10 mm diameter while the bottom main reinforcement were varied from 10 mm to 12 mm diameter, deformed steel bars extended over the entire length of the beam and anchored adequately at the ends with 90° bends not less than 17.5 times diameter of bars. Horizontal and vertical web reinforcements were used varied from 6 mm to 8 mm diameter deformed steel bar. To avoid local bearing, rubber pads were seated at loading and supporting points. Control beams and tested beams are designed according to CIRIA guide 2 which gives 3ø10 mm for main reinforcement, ø6 at 150mm for vertical web reinforcement and ø6 at 200 mm for horizontal web reinforcement. Control beams (CB) consist of two beams, one of them with normal weight concrete and the other with lightweight concrete. Test beams (TB) consist of ten beams, the variables were the effect of depth to study size effect (two beams), effect of density (two beams), effect of main and web reinforcement (four beams), and effect of shear span to depth ratio (a/h) (two beams) .

Table (1) Description of specimens and test variables

I	specimen Symbol	Dimension mm (L × h × b)	Density kg/m ³	Main reinf.	Web reinf. Vertical	Web reinf. Horizontal	a/d	Variable
1	CB1	1300*400*150	NW	3 ø10	ø6@150	ø6@200	0.5	Control beam
2	CB2	1300*400*150	1600	3 ø10	ø6@150	ø6@200	0.5	Control beam
3	TB1	1300*460*150	1600	3 ø10	ø6@150	ø6@200	0.435	Increase depth
4	TB 2	1300*520*150	1600	3 ø10	ø6@150	ø6@200	0.385	Increase depth
5	TB 3	1300*400*150	1700	3 ø10	ø6@150	ø6@200	0.5	Increase Density
6	TB 4	1300*400*150	1800	3 ø10	ø6@150	ø6@200	0.5	Increase Density
7	TB 5	1300*400*150	1600	3 ø12	ø6@150	ø6@200	0.5	Increase Main Reinf.
8	TB 6	1300*400*150	1600	3 ø10	ø8@150	ø6@200	0.5	Increase Vertical Reinf.
9	TB 7	1300*400*150	1600	3 ø10			0.5	Without Web Reinf.
10	TB 8	1300*400*150	1600	3 ø10	Ø8@150		0.5	Inclined Web Reinf.
11	TB 9	1300*400*150	1600	3 ø10	ø6@150	Ø6@200	0.75	Increase a/d
12	TB 10	1300*400*150	1600	3 ø10	Ø6@150	Ø6@200	1	Increase a/d

Materials used in experimental investigations are available in local market, which include cement, natural gravel, natural silica sand, water, and deformed reinforcement bars except light expanding clay aggregate (leca) which was imported from Iran. Light expanded clay aggregate (LECA) was used as lightweight coarse aggregate. In the present study the leca of gradation (4-10) mm was used because it is suitable for the production of structural lightweight concrete.

III. EXPERIMENTAL PROGRAM

A trial mixes were designed, cast, and tested before deciding which mixes that will be used in experimental program; the purpose was to get mixes that satisfy structural lightweight concrete requirements (density between 1440-1840 kg/m³ and compressive strength more than 17.5 mpa). For each mix three concrete cubes were cast and tested to obtain the density and compressive strength. The quantities of materials required for one cubic meter of concrete for all trial mixer in addition to the densities and compressive strength are given in Table (2), for mix (M1) the ratios of all

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material took from previous researches (used only LECA as course aggregate), in mix (M2) the cement content and fine aggregate content were increased while the LECA content and water ratio were decreased. In mix (M3) the fine aggregate content were increased and 15% of course aggregate volume replaced with normal weight gravel , mix (M4& M5) were same mix (M3) with increased gravel volume to 20% & 25% and decreased LECA volume to 80% & 25% respectively.

Table (2) properties of trail mixes

Mix No.	Cement (kg)	Water (kg)	Fine Agg. (kg)	Course Agg. (kg)		Density (kg/m ³)	Compressive strength (MPa)
				Gravel	Leca(4-10)		
M1	350	160	630	-	340	1405	16.2
M2	400	180	680	-	320	1435	17.9
M3	400	170	600	230	270	1600	21,3
M4	400	170	600	306	253	1707	23.1
M5	400	170	600	382	237	1810	24.5

Timber forms with plywood face were used in casing beams, the interior face of forms were coated with oil prior casting and before the reinforcement cage was placed in position, plastic spacers were used to maintain the concrete covers. Tilting drum mixer was used, the interior surface of the mixer drum was cleaned and moistened before use. LECA required for mixes were soaked in water for 24 hr and then spread on dry place to obtain LECA in saturated surface dry (SSD) condition and the mix water was computed as if LECA were non-absorbent. The dry ingredients were added in the following order, about one half of the coarse aggregate, all the fine aggregate, all the cement, and finally the remaining part of the coarse aggregate. Then the water was added and mixing was started. The period of mixing ranged from two to three minutes so that a homogenous mix was obtained. After the mixing process was completed, concrete was poured in the forms and then compacted mechanically by using a standard pencil vibrator to ensure the proper placement and consolidation of the concrete in and around the reinforcement cage, The top surface of concrete was leveled and smoothly finished after casting was completed using hand trowel . During the casting of beams, three (150 x150x150) mm cubes and two (100 x 200) mm cylinders were made for each mix. After cleaning and lubricating the molds, concrete was cast and compacted and then cured under the same conditions of beams. Table (3) shows the average compressive and tensile strength of both normal and lightweight concrete for all beams and its mixes. Mix (M3) was used to cast all lightweight concrete deep beams excepted TB3 which was cast with mix (M4) and TB4 which was cast with mix (M5). For normal concrete one mix (MN) were used (Cement 1: Sand 1.5: Gravel 3) Water/ cement ratio (W/C ratio= 0.55). The quantities of cement, fine aggregate and course aggregate based on dry weights. Mix was designed to give a compressive strength of about 30 N/mm² at age of 28 days and slump of about 8 cm. This mix was used to cast the control beam (CB1).

Table (3): Concrete strength of the tested specimens

I	Specimen	Mix	f_{cu} (N/mm ²)	f_t (N/mm ²)
1	CB1	MN	32.5	2.506
2	CB2	M3	21.1	1.602
3	TB1	M3	21.1	1.602
4	TB2	M3	21.1	1.602
5	TB3	M4	22.9	1.732
6	TB4	M5	24.65	1.833
7	TB5	M3	21.1	1.602
8	TB6	M3	21.1	1.602
9	TB7	M3	21.1	1.602
10	TB8	M3	21.1	1.602
11	TB9	M3	21.1	1.602
12	TB10	M3	21.1	1.602

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A TML foil strain gauge type PFL-30-11-3L was used in this work. This type is mainly used for strain measurement in concrete. Strain gages were used to determine concrete flexural strains along mid span and concrete shear strain in the shear span along the inclined line between load and support. Table (4) and figure (1) shows the locations of strain gauges on deep beam specimens. These locations are allocated to measure the concrete strains along beam depth and diagonals lines within shear span to investigate the flexural and shear behaviour respectively. The strain gages for deep beams were instrumented; and then they were carried to the load cell which was automatic compression testing machine with a capacity of (600 kN) that used to apply the load.

Table (4): Strain gauges locations on specimens

Specimen	location	direction	NO.	Distance(mm)			
CB1,CB2,TB3, TB4,TB5,TB6, TB7,TB8	Left side	Perpendicular to inclined line between support and load	3	From support			
				80	224	368	
	Right side	Parallel with inclined line	2	100	350		
CB1,CB2	Mid span	Parallel with beam length	4	From bottom			
				80	160	240	320
TB1	Left side	Perpendicular to inclined line between support and load	3	From support			
				80	250	420	
	Right side	Parallel with inclined line	2	100	400		
	Mid span	Parallel with beam length	4	From bottom			
				80	180	280	380
TB2	Left side	Perpendicular to inclined line between support and load	3	From support			
				80	280	480	
	Right side	Parallel with inclined line	2	100	460		
	Mid span	Parallel with beam length	4	From bottom			
				80	200	320	440
TB9	Left side	Perpendicular to inclined line between support and load	3	From support			
				80	250	420	
	Right side	Parallel with inclined line	2	100	400		
	Mid span	Parallel with beam length	4	From bottom			
				80	160	240	360
TB10	Left side	Perpendicular to inclined line between support and load	3	From support			
				80	280	480	
	Right side	Parallel with inclined line	2	100	460		
	Mid span	Parallel with beam length	4	From bottom			
				80	160	240	320

Strains of deep beams were measured using a mobile data acquisition system. The data acquisition system used in this study includes Laptop Lenovo G580 computer, strain indicator has 16 channels, Type Data Taker (data logger) DT85 – Australian origin 2010 (which can receive data from an array of strain gauges installed on the deep beam) and accompanying software. The frequency of measurement of the device is specified by the user with maximum speed of one data point per second. The deflection of tested beams was measured via using dial gauge with magnetic holder. The capacity of the dial gauge was 30 mm with accuracy of 0.01 mm.

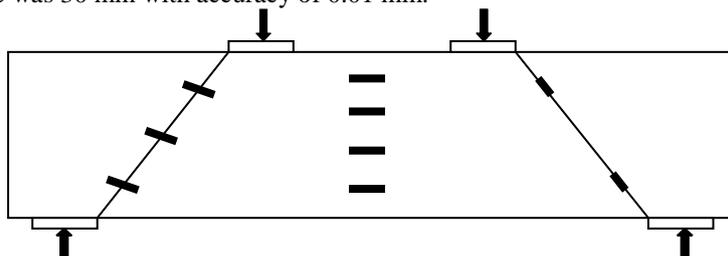


Figure (1): General locations of strain gauges on specimens

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IV. GENERAL BEHAVIOR OF DEEP BEAM AND CRACK PATTERN

All tested deep beams failed in shear with a little effect or no bearing failure for concrete close supports and load points (No local crushing failure). End anchorage of the main bars functioned properly during testing and does not affect the failure mode of the deep beams. Flexure cracks were observed near the mid span of the deep beams at about (26.6% - 38.8%) of failure load, those flexure cracks did not substantially grow during the subsequent increment of loading. When the load was increased, diagonal web cracking (inclined cracks) started at the mid depth in parallel of critical path between support and load point in mid of shear spans at about (40.5% - 58.5%) of failure load. There were also other cracks appeared parallel to it. When additional load was applied, one of inclined cracks became more prominent than the others, and propagated towards the loads and support points, eventually this crack caused the shear failure of the beam. The failure mode was diagonal splitting failure.

V. EFFECT OF VARIABLES ON DIAGONAL CRACKING LOAD AND ULTIMATE LOAD

First diagonal Cracking load and ultimate load are considered as good measure for the sake of studying the behavior of deep beam. Diagonal cracking load defined as the load at which the first inclined crack can be detected in the shear span of deep beam (the diagonal tension crack develop fully in the shear span). Ultimate load defined as the load at which deep beam failed in shear by one or more of shear cracks and its value detected during the test by observing the gauge of the machine. The cracking load is much lesser than the ultimate load. The beams exhibited high shear strengths after diagonal cracking. The difference between the ultimate shear load and the diagonal cracking load is considered as the reserve strength of deep beams. The ratio of the ultimate shear load V_u to the diagonal cracking load V_{cr} , was calculated to estimate the reserve strength of deep beams. The values of cracking loads and ultimate loads and the ratios of ultimate load to cracking load are listed in Table (5).

Table (5) loads and deflections at first and failure stages.

Specimen	First cracking load	Diagonal Cracking Load V_{cr} (kN)	Ultimate Load V_u (kN)	V_u / V_{cr}	Deflection at first Cracking	Maximum Deflection
CB1	51	77	180	2.33	0.6	3.1
CB2	39.5	60	135	2.25	0.52	2.5
TB1	44	75.5	145	1.92	0.55	2.35
TB2	59	89	152	1.71	0.5	2.1
TB3	43	63.5	141.5	2.23	0.55	2.5
TB4	45	68	145.5	2.14	0.53	2.45
TB5	44	59	141	2.39	0.52	2.2
TB6	38	58.5	143	2.44	0.49	2.7
TB7	36	57	100	1.75	0.5	2.1
TB8	42	63	154	2.44	0.55	2.9
TB9	33.5	47	115	2.45	0.55	2.7
TB10	27	38.5	95	2.47	0.5	2.85

When depth was increased by 15% & 30%, diagonal cracking loads increased by 26% & 48%, ultimate load increase by 7.4% & 12.6%, and reserve strength decrease by 33% and 52% respectively. This mean that the load capacity of deep beam increases when depth is increased, also reserve strength in small size deep beam is greater than that in big size deep beam. In other word, deep beam with large depth has the probability of exhibiting a brittle failure. The effect of concrete density was studied using normal and lightweight concrete. It is observed that using LWC in deep beam instead of NWC (CB1 & CB2) decreased diagonal cracking load, ultimate load, and reserve strength. Also increasing the density of lightweight concrete from 1600 kg/m³ (CB1) to (1707 & 1810) kg/m³ (TB3, TB4) increased diagonal cracking load, the ultimate load and decrease reserve strength. The increment of main tensile reinforcement ratio (TB5) by 45% (ρ increase from 0.0042 to 0.0061) caused rising in the ultimate load by 4.4% and reduction in reserve strength by 14%. No effect has been observed on diagonal cracking load. The effect of web reinforcement was studied with three deep beams (TB6, TB7, and TB8). By observation, it has been found that when vertical web reinforcement

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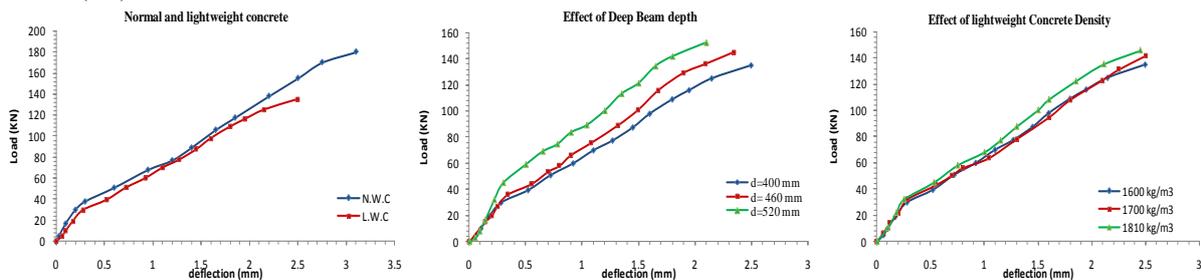
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increased from $\phi 6$ at 150mm to $\phi 8$ at 150mm the ultimate load increased by 6% and the reserve strength increased by 19%. For deep beam (TB7) which without web reinforcement, ultimate load reduced by 26% decreased and reserve strength decrease by 50%. When inclined web reinforcement $\phi 8$ at 150mm was used with TB8, ultimate load increase by 14% and reserve strength increase by 19%. As a result, ultimate load and reserve strength directly proportional with the ratio and shape of web reinforcement. Cracking load was slightly effected by web reinforcement. Increasing shear span to depth ratio (a/h) to 0.75 (TB9) and 1 (TB10) caused a decrease in diagonal cracking load by 21.7% and 35.8%, ultimate load decreased by 18.5% and 29.6%, and reserve strength increased by 20% and 22% respectively.

VI. EFFECT OF VARIABLES ON LOAD - DEFLECTION RESPONSE

Deflections were measured in this study at mid span of deep beam using dial gauge. In general, all deep beams exhibited similar overall behavior, which was characterized by a nearly bilinear response. The load-deflection relationship is linear before the appearance of the first cracking in concrete. After first cracking of concrete, the slope of load-deflection curves decreased and nonlinear relationship begins due to inelastic deformation in concrete after cracking, this continue until reaching ultimate load. After ultimate load, deflection is increased rapidly with constant or drop in loading. For deep beams with lightweight concrete, the initial slope of load-deflection curve in the elastic range is flatter than deep beam with normal weight concrete, it is due to lower modulus of elasticity for lightweight concrete. After the crack appeared in the concrete, deflection for normal weight concrete deep beam is more than lightweight concrete deep beam therefore; maximum deflection for lightweight concrete deep beam is less compared to deep beam with normal weight concrete. See Table (5)

The load-deflection curves of each deep beam are shown in Fig (2). It can be seen that with increased depth of deep beams (TB1 and B2), the maximum deflections at ultimate load decreased. Deep beam which have 520 mm depth exhibited smaller deflections at ultimate load and their failure is relatively brittle. The density increment of lightweight concrete have little effect on maximum deflection and the behavior of load deflection curve. Increasing the amount of main tensile reinforcement (TB5) decreases deflection at ultimate load and effect on deflection slightly before first crack appeared. But after first cracking, it can be observed that the increase of deflection is faster for deep beam with low amount of main reinforcement. By increasing the amount of vertical web reinforcement (TB6), there is a little effect on the value of maximum deflection. In the deep beam without web reinforcement (TB7), the value of maximum deflection was decreased. When inclined web reinforcement was used (TB8), the value of maximum deflection increased clearly. By observing load-deflection curves, it can be noticed that curve after cracking become flatter for deep beams with low amount of web reinforcement. Therefore, the deep beams with high amount of web reinforcement behave stiffer than those with low web reinforcement. This stiffness was improved when used inclined web reinforcement and be small without web reinforcement. This means that web reinforcement have little effect on deep beam stiffness before appearance of diagonal cracks, but after the appearance of diagonal cracking, this effect will be pronounced and be the dominant on deep beam stiffness. When the shear span to depth ratio (a/h) was increased maximum deflection and reduced the deep beam's stiffness before and after cracking. It is observed when (a/h) increased from 0.5 to 0.75 and 1 (TB9 and TB10) maximum deflection increased from 2.5mm to 2.7mm and 2.85mm respectively. The slope of load deflection curve before and after cracking for deep beam with (a/h) of 0.5 is larger than those with (a/h) of 0.75 and 1.



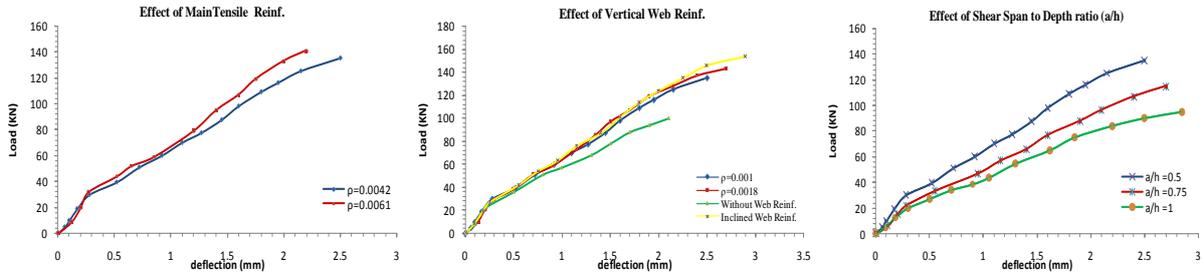


Figure (2): Experimental Load-deflection curves

VII. EFFECT OF VARIABLES ON FLEXURAL STRAIN

The variations of flexural strain were measured at mid span of the deep beam for six specimens. The aim was to study the effect of lightweight concrete, beam depth, and shear span to depth ratio (a/h) on the distribution of flexural strain. As shown in figure (3), it can be observed that behavior of flexural strain distribution in both lightweight and normal weight concrete deep beams is non-linear. At failure, strains in extreme tension and compression zone are greater for NWC deep beam, that is due to the load capacity of NWC deep beam (CB1) is more than LWC deep beam (CB2). Also it can be seen that when the shear span to depth ratio(a/h) increases (CB1,TB9,) the nonlinearity of flexural strain behavior decreases, strains in tension and compression zone increase in spite of the drop in load capacity. Large depth deep beam exhibited more pronounced deviation of the strain pattern at mid-span and strains decreases with the increase of deep beam depth in spite of an increase in load at failure.

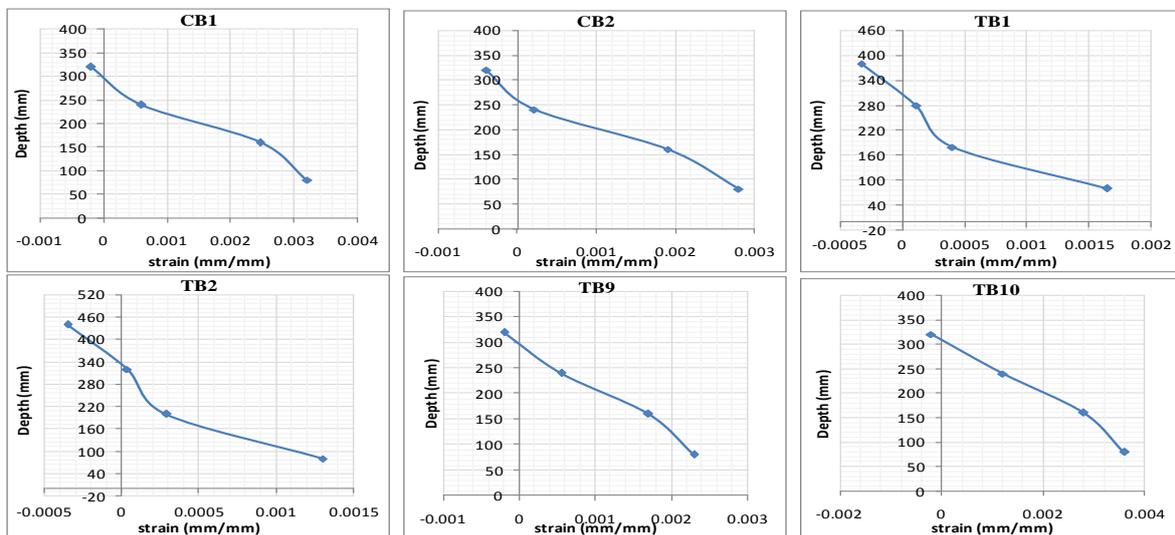


Figure (3): Flexural strain distribution along mid span

VIII. EFFECT OF VARIABLES ON SHEAR STRAIN

Shear strain variation in shear span region measured experimentally by electrical strain gauge along the diagonal cracking line between loading point and support plates for all specimens. For all deep beams, three strain gauges were attached on left side perpendicular to crack path . These gauges used to shear strain measurement. Additional two strain gauges were attached to right side parallel to inclined line. The main purpose of those gauges was to measure the compressive strain in strut (compression member described in STM). Figure(1) and Table (4) shows the location of strain gauges on specimens. Loads- shear strain plots for all deep beams are shown in figure (4), the right curves represent the shear strain versus load calculated by gauges(1,2,3) and the left curves represent the compression strain

versus load calculated by gauge (3,4). For all specimens, it was observed that shear strain before first diagonal cracking was very small and increased rapidly after diagonal crack developing. Gauge (1) was affected at first by cracks and its reading increased directly after first diagonal crack. Sometimes gauges were cut due to cracks passing through it. Shear strain behavior of LWC beam are similar to NWC beam. It has been observed that at failure, the compressive strain in strut was relatively small and not exceed (0.0012).

IX. CONCLUSIONS

Based on the test results the following main conclusions can be drawn:

- The general behavior of deep beams under loading, progressing of cracks, and failure mode of lightweight concrete are considerably similar to these of normal weight concrete.

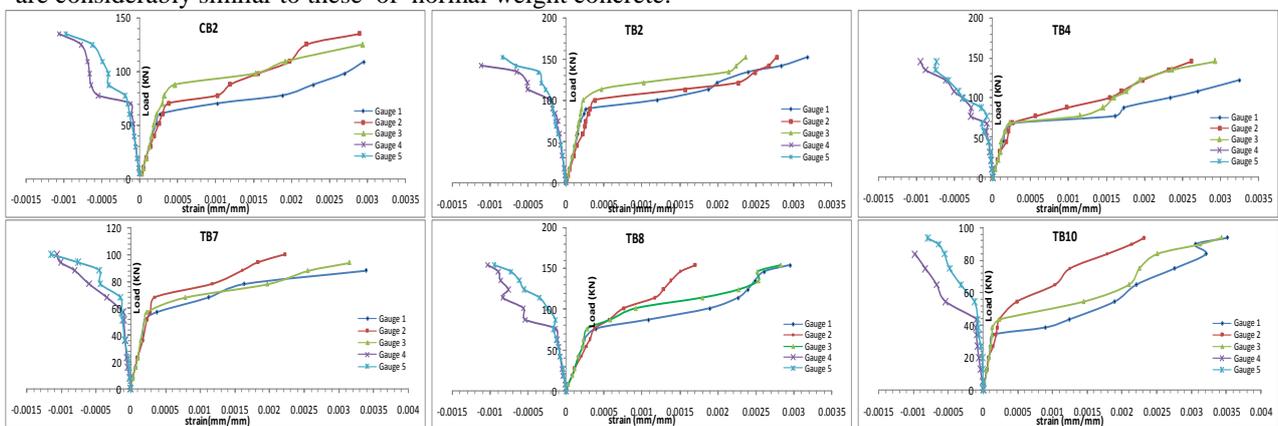


Figure (4): load versus shear and compression strains at shear span

- The using of LWC instead of NWC decreased first diagonal cracking and ultimate loads. For deep beams with lightweight concrete, the initial slope of load-deflection curve in the elastic range is flatter than deep beam with normal weight concrete due to lower modulus of elasticity for lightweight concrete. However, maximum deflection for LWC deep beam was lesser.
- Increasing the density of lightweight concrete was increased load capacity and effected slightly on beam deflection.
- In large depth LWC deep beam, the ultimate load was increased and the deflection was decreased. Shear strength provided by deep beams after appearance of first diagonal crack (reserve strength) are greater in deep beam with small depth, i.e. large depth deep beam exhibited brittle failure.
- The increment of main tensile reinforcement caused rising in load carrying capacity of LWC deep beam and reduction in maximum deflection.
- The increasing of vertical web reinforcement ratio improved the behavior of LWC deep beam by increasing ultimate load, maximum deflection and stiffness after first cracking. This improvement raised with using inclined web reinforcement and dropped in beam without web reinforcement.
- When shear span to depth ratio (a/h) was increased, there was increasing in maximum deflection and beam strength after cracking (reserve strength) and reduction in the first cracking and ultimate loads were decreased.
- The flexural strains distribution at midspan of LWC deep beams are nonlinear same as in NWC deep beam. This nonlinearity increased in large depth beam and reduced with increase shear span to depth (a/h) ratio.
- Shear strains in shear span between support and load plates were very small before diagonal cracks development. When diagonal cracks appeared, it was rapidly increased and reached to extreme value.
- The initial slope of load - shear strain plots for LWC deep was flatter than that for NWC deep beam. Strain in LWC beams are the greatest in spite of the lower load capacity; that was due to the lower modulus of elasticity of LWC.
- The failure was not caused by concrete crushing in compression strut between support and load. Compression strain in strut was relatively small and not exceeds (0.0012).

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