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Torsional Behavior of Light Weight Concrete Beams

Ahmed Noshy[1], Sherif Elwan[2], Haddad Said[3], and Ayman Khalil[4]
1 Assistant Research, Construction Research Institute, National Water Research Center, EGYPT
2 Lecturer, Civil Engineering Department, Higher Institute of Engineering, Cairo, EGYPT
3 Professor, Concrete Structures Department Housing and building Research Center , Cairo, EGYPT
4 Professor, Structural Engineering Department, Ain Shams University, Cairo, EGYPT

الملخص

في السنوات الأخيرة أصبحت الخرسانة خفيفة الوزن مادة إنشائية هامة و تزايد الطلب عليها و ذلك بسبب مميزاتها العملية. يهدف هذا البحث إلى دراسة تأثير العناصر المختلفة على سلوك اللى للكمرات ذات الخرسانة خفيفة الوزن. تعتمد الخرسانة خفيفة الوزن على استبدال جزء من كميه الركام الخشن في الخلطة بحبيات الفوم والتي تؤدى لتقليل وزن المتر المكعب الخرساني من ٢٤ كيلو نيوتن/م٢ إلى ١٨,٥ كيلو نيوتن/م٢. وتعتبر عزوم اللي من الأحمال ذات التأثير عالي الخطورة على الكمرات حيث أنها من الممكن أن تؤدي إلى عملية انهيار قصف في الكمرات ومثل هذا الانهيار يسبب كوارث ويجب تلافيه.

تتضمن الدراسة العملية دراسة سلوك الالتواء على الكمرات من الخرسانة العادية و الخرسانة خفيفة الوزن بإعداد (٦) عينات مصغرة. العينه الاولي ذات قطاع مستطيل من الخرسانة المسلحه العاديه, ثلاث عينات ذات قطاع مستطيل من الخرسانه خفيفه الوزن مختلفين فى نسب الحديد الموجودة بالقطاع و عدد كمرتين من الخرسانه خفيفه الوزن لقطاعات ذات شفه.

وقد تم اختبار العينات وتحليل نتائج الاختبار لمعرفة وتقييم السلوك وقدره تحمل الكمرات المختبرة لعزوم الالتواء.

ABSTRACT

This study presents an experimental investigation in the torsional behavior of reinforced lightweight concrete (LWC) beams. LWC was obtained through the use of polystyrene foam as a partial aggregate's replacement to reduce the concrete dry unit weight from 24.0 kN/m^3 to 18.5 kN/m^3. Major experimental work that has been done on light weight concrete beams was in flexure, shear, bond, unlike torsion so our research will focus on it. Failure of a structural element under torsion is brittle in nature and should be avoided as it compromises the ductile behavior of the structure. This study aims to find out the torsion effect on light weight concrete rather than ordinary concrete for beams, the effect of variation of torsion reinforcement and the effect of cross section shape.

The experimental program includes six beams. Four beams are rectangular cross section. One is ordinary concrete, and the other three specimens are LWC. The other two specimens are flanged LWC beams with T-shaped cross-section. The test results were analyzed to find out and evaluate the behavior and torsion capacity of the tested beams.

Keywords: LWC beams, Torsional behavior, Twist angle, Concrete type, longitudinal reinforcement ratio, transverse steel spacing, strains, deformations and stiffness.

1. INTRODUCTION

Lightweight concrete is not a new material, since it was known at the early days of the Roman Empire (1988). Magnificent ancient structures, like the Sophia Cathedral in Istanbul from the 6th century, were built using lightweight aggregates (1995, cited in 1998). Even in the 2nd Century A.C., the Pantheon vault in Rome, built with mortar made lighter with pumice, reflects the roman engineers' knowledge of lightweight aggregates. St. Peter's Basilica, built 1000 years ago in the Vatican (1960, cited in 1998), also reveals Miguel Angel's surpassing of the 44 m span benchmark using LWC. Nowadays structural LWC

is a versatile material for modern construction of an utmost importance. The advantages of LWC are its reduced mass and improved thermal and sound insulation properties, while maintaining adequate strength. The reduced weight has numerous advantages, among which the reduced energy demand during construction, the reduced hydrostatic pressure on formwork as well as the fact that water that has been absorbed into the porous structure of lightweight aggregates provides additional water for internal curing. The reduced mass will also reduce the lateral load imposed on the structure during earthquakes, hence, simplifying and reducing the sections of the lateral load carrying system. However, a major structural disadvantage of LWC is that its modulus of elasticity was found to be less than predicted by the relationship proposed by the CUR-Recommendations 39 on LWAC (cited in 2000), which was provided as an addition to the Dutch code VBC (1990, cited in 2000). Although the latter disadvantage means essentially low stiffness, it can be beneficial at times where the property of reduced stiffness may be desirable (2003), among which the situations requiring improved impact or dynamic response and where differential foundation settlement may occur as well as in certain types or configurations of shell roofs. Structural lightweight concrete is therefore widely used all over the world, covering all types of structures, such as high rise buildings, long span bridges, composite steel-concrete construction, precast and prestressed concrete elements, shell roofs and folded plates. It is finally worth mentioning that, according to ACI 213R-03 (2003), structural lightweight concrete is defined as "Structural concrete made with lightweight aggregate; the air-dried unit weight at 28 days is usually in the range of 14.40 to 18.50 kN/m^3 and the compressive strength is more than 17.2 MPa".
Since 2005, an extensive experimental and theoretical research program, aiming at developing structurally and economically efficient LWC as well as establishing design guidelines for all types of structural elements made using this material, is being undertaken at the Department of Structural Engineering of Ain Shams University. The first phase of this program resulted in a new kind of lightweight concrete, which combines the advantages of normal density concrete, through partially replacing the normal weight aggregates with polystyrene foam to the construction industry with a dry

unit weight of 18.50 kN/m^3 , which in turn leads to dead load reduction by 20 % and the associated

decrease in the structure's overall cost, hence, providing a feasible challenge to normal density concrete (NDC).
So, it is important to investigate the strength of LWC due to different internal stresses. One of the major stresses affecting the behavior of concrete beams is the torsional shear stress which is the subject of the present work.

In general, the torsion in structural elements may be classified into two types as follow:
(1) Equilibrium torsion: This occurs in members that depend on torsion to maintain equilibrium.
(2) Compatibility torsion: This occurs due to twist to maintain deformation compatibility in structures.
Only the first type occurs in statically determinate structural and it is essential to provide enough reinforcement to ensure that the member is capable of resisting torsion required by static, whereas both types can occur in statically indeterminate structure. However, if the torsional resistance or stiffness of members has not been taken into account in the analysis of structure, specific calculations for torsion will be necessary, and adequate control of any torsional cracking being provided by the required nominal shear reinforcement.
Torsional stresses have significant effect on beams that it may leads to brittle failure. Torsional moments develop in structural concrete members as a result of anti-symmetrical loading, member geometry, or as a result of structural framing. For example, spandrel beams built integrally with the floor slab are subject to torsional moment resulting from the negative bending moment at the exterior end of the slab. The restraining moment is proportional to the torsional stiffness of the spandrel beam. In complex structures such as helical stairways, curved beams, and eccentrically loaded box beams, torsional stresses dominate the structural behavior. Torsional moment tends to twist the structural member around its longitudinal axis, inducing shear stresses. However, structural members are rarely subjected to pure torsional moment. In most cases, torsional moments act concurrently with bending moments and shear forces.
Demand for more complex structures improves the methods of analysis. New design required a better understanding of the behavior of reinforced concrete members subjected to torsion. In the second half of the twentieth century, research activities helped engineers to understand many aspects of the behavior of concrete members under torsion.

2. EXPERIMENTAL PROGRAM

2.1 Details of the Tested Beams

Six reinforced concrete beams are tested under pure torsion. Four beams are rectangular cross section. One is normal density concrete, and the other three specimens are LWC with dimensions bw / hw= 15/30 cm. The other two specimens are flanged LWC beams with T-shaped cross-section and dimensions bw/hw/bf/tf = 15/30/40/8 cm, as shown in Figure 1. Tested beams are involving the following three major variables:

1- The effect of implementing light weight concrete instead of ordinary concrete.
2- The effect of torsion reinforcement variation.
3- The effect of cross section shape.

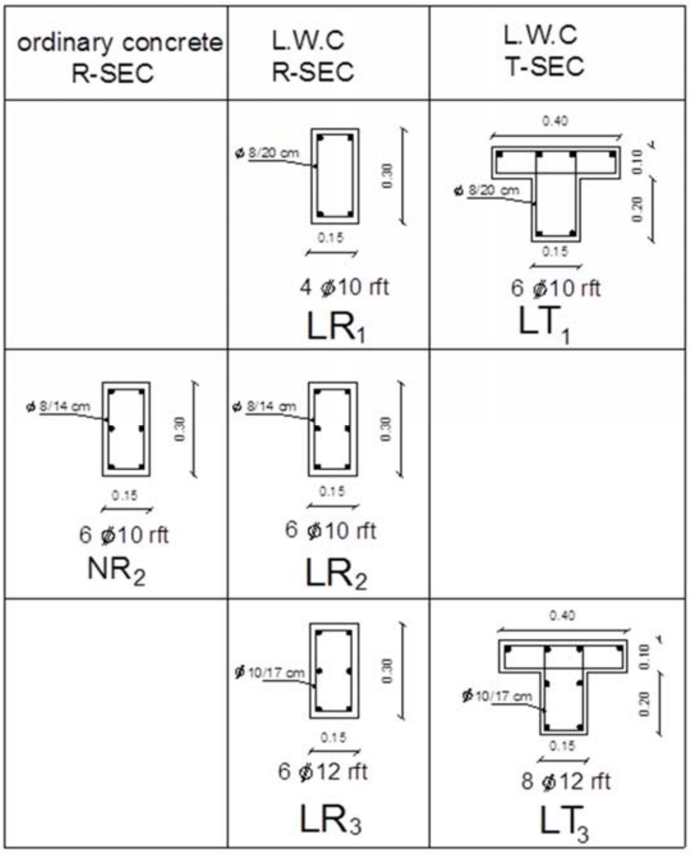


Figure 1 : Details of tested Beams of the experimental program.

The over-all lengths of all beams were 2600 mm and the supported length was 1400 mm and 30% additional stirrups were used at each end of all beams to be safe against failure during test. The middle portion is the beam effective length. It was the test zone with length 1200 mm .

Schematic arrangement of loading for the tested beams is shown in Figure 2. Using steel brackets at each end of the tested beams, one bracket being clamped against torsion and the other being free to twist. The component parts of the test rig were designed and fabricated for a maximum torque of 100Kn.m, and to suite the points of fixation of the strong test bed arranged at 1000 mm intervals in both directions.

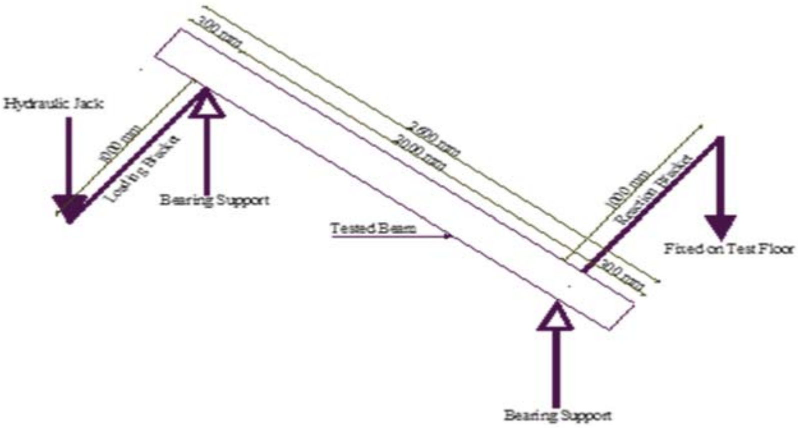


Figure 2: Schematic Diagram of Loading for Beams Under Torsion.

The torsion was applied by hydraulic jack at the end of an outrigger arm and supported on reaction steel frame with four columns fixed on the test bed. Special bearings under the end of the specimen were used to ensure that the test beam was restrained against twisting only at the fixed end. The front view of the experimental set-up is shown in Figure 3.

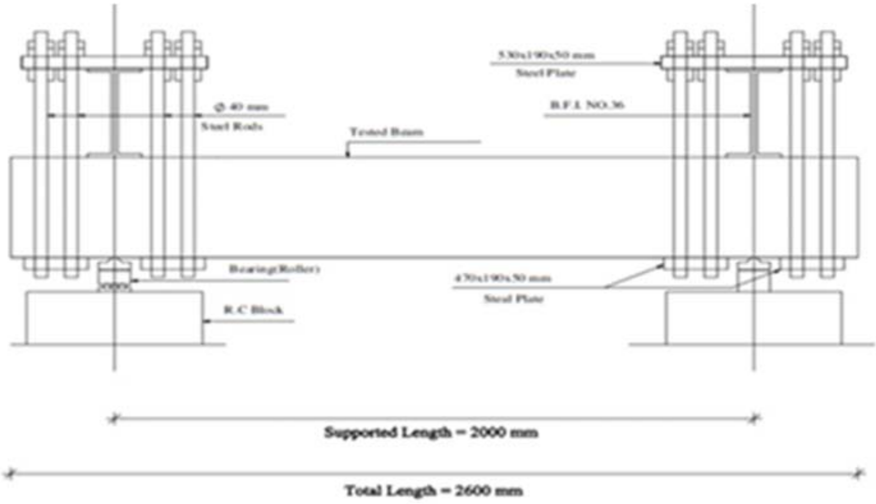


Figure 3 : Front View of Experimental Set-Up.

The general view of the loading and the reaction brackets are shown in Figure 4 and 5 respectively.

Figure 4: General view of the Loading Bracket.

Figure 5: General view of the Reaction Bracket.

2.2 Materials Properties and Casting

Two types of steel were used in this study. The first type was proof-strength steel with grade 36/52. These bars were used as longitudinal reinforcements and stirrups. The second type was mild-strength steel with grade 24/36. These bars were used as stirrups. All the previous reinforcement had a constant modulus of elasticity, Es = 200 GPa.
Two concrete mixes were used for the specimens. The first mix was for the LWC specimens and the second mix was for the NDC specimen. In order to achieve the

concrete; polystyrene foam, silica fume and super plasticizer were added to the mix. The mix proportions / m^3 for the LWC and the NDC are shown in table 1.

Table 1 : Mix proportions for the LWC beams

	Cement (kg/m^3)	Silica fume (kg/m^3)	Coarse aggregate (kg/m^3)	Sand (kg/m^3)	Polystyrene foam (liter/m^3)	Super plasticizer (liter/m^3)	w/c ratio
LWC	450	40	630	630	330	13.5	0.308
NDC	320	----	1050	680	----	----	0.64

The steel cages of the specimens were placed in the formwork shown in Figure 6. Concrete was cast in the formwork for the five LWC specimens at the same day and from the same concrete batch. On the other hand, beam NR2 was also cast in the same formwork at the same day, but using a second batch for NDC. After casting, the concrete of beam NR2 was compacted in the form using a poker vibrator, while the other five LWC beams did not require compaction. The specimens were then cured with plenty of water and covered with burlap for one week. For control purposes, six standard concrete cubes were cast alongside the beams and were tested at the same day as the beams, in order to provide values of the 28-days concrete characteristic compressive strength, f_{cu}, in the range of (25-30) N/mm^2.

Figure 6: Formwork of the tested beams

2.3 Measurements and Instrumentation

Measurements of loads, strains and rotations were recorded. All instrumented readings were monitored and recorded using data logger system through which the signals were conditioned, and stored on PC computed hard disk.

2.3.1 Steel Strains

Electrical resistance strain gauges type, KFG-l0-120-Cl-11, were used. The gauge length was 10 mm and the gauge factor was (±2.11) while the gauge nominal resistance was 120 ohms. Two gauges were fixed on longitudinal bars (ϵ_{L1} & ϵ_{L2}). Three gauges were fixed on stirrups (ϵ_{st1}, ϵ_{st2}& ϵ_{st3}). The gauges were fixed using special adhesive material at

prescribed critical locations in the test region. The locations of the various strains are shown in Figure 7.
The critical strain gauges for longitudinal and stirrups are ϵ_{L1}& ϵ_{st1} respectively

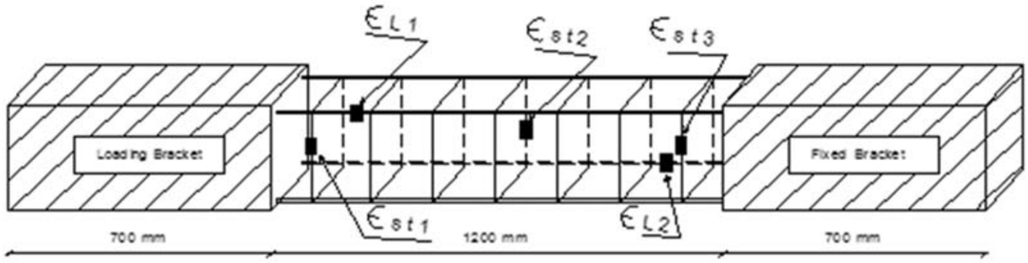


Figure 7 :The location of strain gauges

2.3.2 Rotation Measurements

The rotation of the test region will measured at three different sections. The first measured rotation (θ_1) was calculated by the slope between the vertical displacement at the end of loading bracket and its length. The other two measured rotations (θ_2) and (θ_3) were calculated by two LVDTS spaced at 500 mm were used. The rotation was calculated by dividing the vector summation of the vertical displacement, measured by the two LVDTS, by 500 mm apart from each other. Figure 8 shows the arrangement of LVDTS used to measure the rotation. The critical section of measured rotation is (θ_2).

2.3.3 Test Procedure

Before testing any beam and after aligning it within the testing frame, all the instruments positioned and hooked with the data logger system. The electrical instrumentation readings were initialized to zero using software (LAB VIEW) .
The torsion moment was applied using double acting hydraulic jacks connected to automatic control hydraulic pump. The hydraulic pump, which was connected to the jack producing torque was totally controlled by [lab view] software through electrical control valves. To control the torque produced by the hydraulic jack a LVDTs were used to record the vertical displacement at the end of loading bracket.

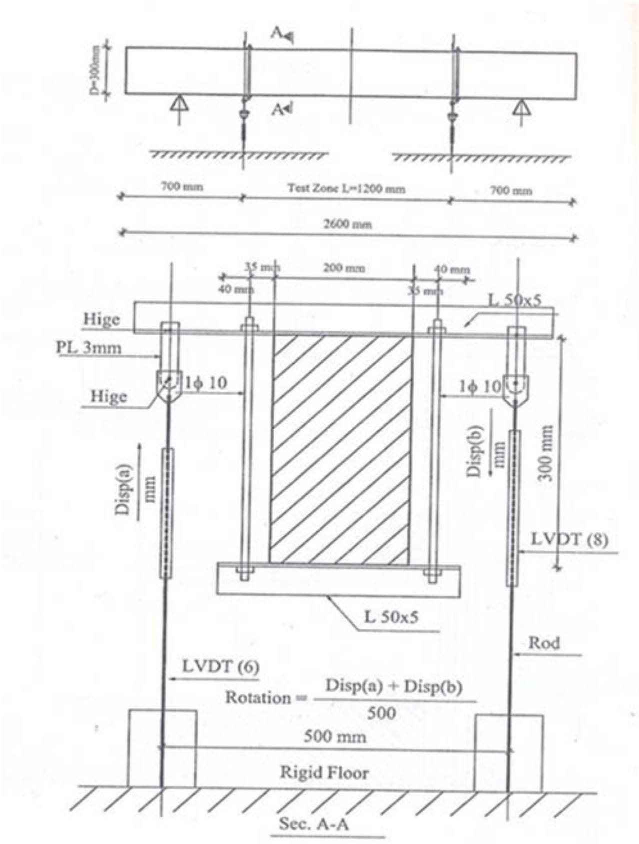


Figure 8: Rotation Measuring Device.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1Cracking patterns

The tested reinforced concrete beams subjected to loading up to cracking behave as plain concrete beam without reinforcement. The stresses in the reinforcement are quite small, and the torque-twist curve is identical to that of a plain concrete beam. After first crack appearance the reinforcement stresses increase remarkably. Sum of small cracks appear with the increase in loading. Cracks' widths increase with the increase in the applied torque till failure. The crack pattern of the tested beams were observed and marked during each test with respect to equivalent load stage. All cracks occurred with in test zone area as shown at Figure 9. The initial observed cracks were diagonal and parallel to the diagonal compressive stresses. Since the shear stresses due to torsion are quite large, cracks started to develop along the beams length. After the initial cracks formation and new cracks began to develop propagating towards the beams edges as the applied torque increased.

Cracks in Front Face of **NR2**

Cracks in Back Face of **NR2**

Cracks in Front Face of **LR1**

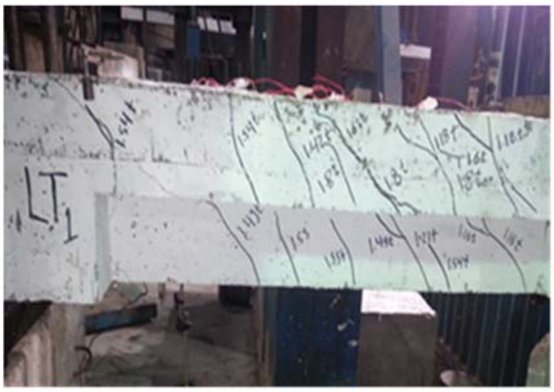
Cracks in Back Face of **LR1**

Cracks in Front Face of **LR2**

Cracks in Back Face of **LR2**

Cracks in Front Face of **LR3**

Cracks in Back Face of **LR3**



Cracks in Front Face of **LT1**

Cracks in Back Face of **LT1**

Cracks in Front Face of **LT3**

Cracks in Back Face of **LT3**

Figure 9 : Crack Pattern for all tested beams

Typical torsional diagonal cracks developed around the parameter faces of the tested beam. The average inclination angle of the cracks (at the four faces) to the beam longitudinal axis ranged from 48° to 58°. At the maximum torque the width, number, and length of cracks increased with the increase in the twist angle. Figure 10 shows the typical spiral-cracking pattern for all tested beams.

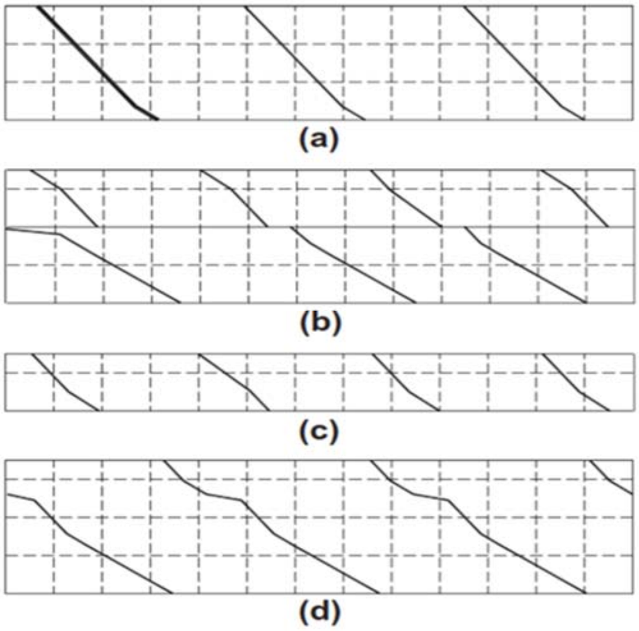


Figure 10: Typical cracking pattern for all tested beams (a) top, (b) front, (c) bottom, and (d) back.

In next part, the observed behavior of the six beam specimens will presented. Among the experimental results recorded were vertical displacement at the end of loading bracket, angle of twist, longitudinal steel strains, stirrup strains at different load stages, and the torsion moment design for this beam at the yield strain as shown at Table 2**.**

Table 2 : Comparison among tested beams results

Beam name	Fcu N/mm^2	First crack		Failure stage		Mt design (kN.m)	Maximum Vertical displacement Cm
		Mt (kN.m)	θcr degree	Mt (kN.m)	θF degree		
NR2	29	4.68	0.59°	9.38	5.65°	6.5	7.34
LR1	26.5	3.24	0.38°	8.22	4.23°	5.9	7.58
LR2	29	4.32	0.37°	9.18	4.48°	6.65	6.54
LR3	31	5.92	0.42°	11.67	6.1°	9.9	6.95
LT1	29.5	5.2	0.24°	14.48	3.41°	10.5	6.1
LT3	30.5	8.28	0.48°	18.63	3.67°	13.5	6.47

3.2 Failure loads

The cracking torque for beam (NR2) is higher than the cracking torque for beam (LR2) by 8.3% . The failure torque for beam (NR2) was higher than the failure torque for beam

(LR2) by 2.2% . The failure torque for beam (LR2) was higher than the failure torque for beam (LR2) by 10.5% and is lower than the failure torque for beam (LR3) by 27.1%. The cracking torque for beam (LR2) is higher than the cracking torque for beam (LR1) by 25% and is lower than the cracking torque for beam (LR3) by 37%. The cracking torque for beam (LT1) is higher than the cracking torque for beam (LR1) by 60% . The failure torque for beam (LT1) was higher than the failure torque for beam (LR1) by 76% . The cracking torque for beam (LT3) is higher than the cracking torque for beam (LR3) by 39.8% . The failure torque for beam (LT3) was higher than the failure torque for beam (LR3) by 60% .

3.3 Twist Angle

The applied torque - the twist angle curves for the six beams were linear, elastic with small angle of twist and the slope of each curve is slightly different for each of the sections, due to the uncracked stiffness of the beams. After first cracking, the cracks propagated diagonally. The relationship changed between the applied torque and the twist angle behaved in a non-linear plastic way. The torque-angle of twist slope decreased indicating a decrease in the stiffness up to the ultimate. The torque loading excessive decrease in stiffness due to cracking had resulted in a quick approaching to failure load. The rotation continued to increase even with the applied load out increasing as shown at Figure 11.

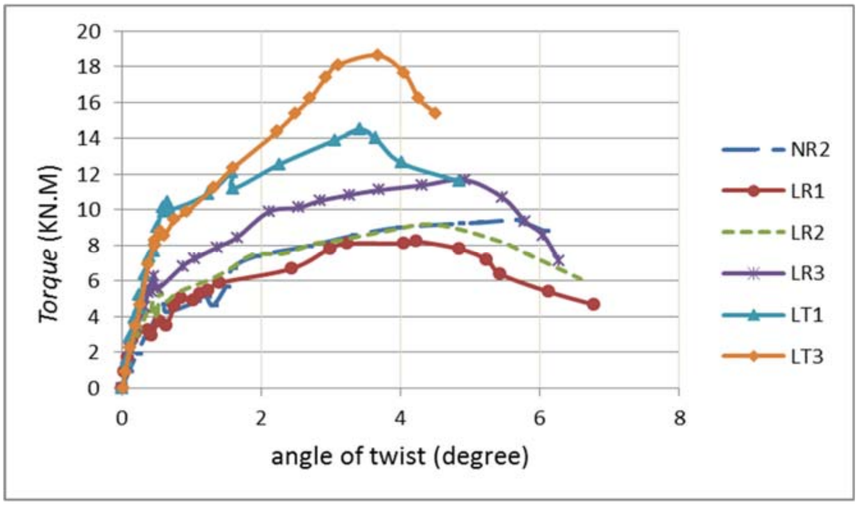


Figure 11 : Torsional Moment- angle of twist for all tested beams.

The twist angle at first crack for beam (NR2) is higher than that of beam (LR2) by 60%. The twist angle at failure for beam (NR2) is higher than that of beam (LR2) by 26.1%. The twist angle at first crack for beam (LR2) is lower than that of beam (LR1) by 2.7% and also lower than that of beam (LR3) by 13.5% . The twist angle at failure for beam (LR2) is higher than that of beam (LR1) by 5.5% and also lower than that of beam (LR3) by 9.8%. The twist angle at first crack for beam (LT1) is lower than that of beam (LR1) by 58%. The twist angle at failure for beam (LT1) is lower than that of beam (LR1) by

24%. The twist angle at first crack for beam (LR3) is lower than that of beam (LT3) by 14%. The twist angle at failure for beam (LR3) is higher than that of beam (LT3) by 34%. The twist angle at failure for beam (LR3) is higher than that of beam (LT3) by 34%.

3.4 Longitudinal Steel Strains

The reinforcement stresses are quite small, the measured strain values are insignificant and the relation was near linearity before first cracking . At this stage the beam behaves as a plain concrete beam without reinforcement up to first cracking.
After cracking, the behavior of the beam changed. The Longitudinal steel became more effective in resisting the torsional moment. A significant increase in longitudinal steel strain values is observed with silent increase in torque beyond first cracking as shown at Figure 12.

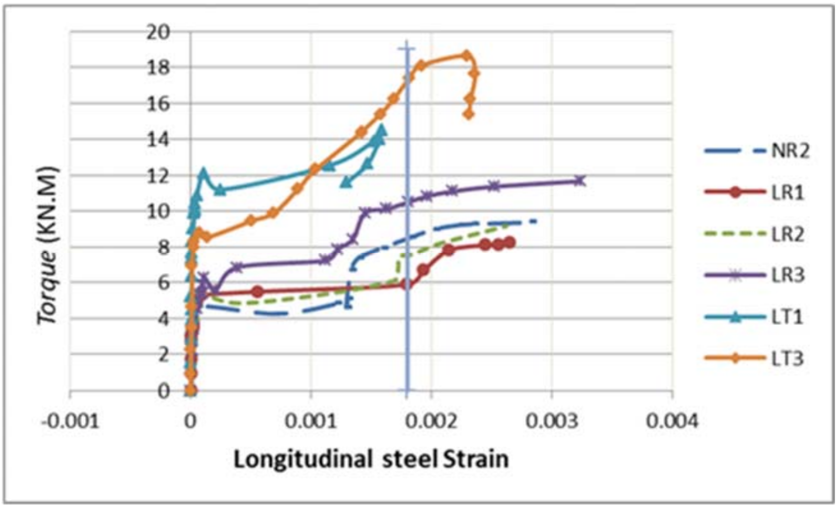


Figure 12: Torque - Longitudinal steel Strain Curve for all tested beams .
The longitudinal steel of beam (NR2) reached yield at an applied torque of 8.5 kN.m. The longitudinal steel of beam (LR1) reached yield first at an applied torque of 5.9 kN.m, the longitudinal steel of beam (LR2) reached yield at an applied torque of 7.5 Kn.m and the longitudinal steel of beam (LR3) reached yield first at an applied torque of 9.9 kN.m. The longitudinal steel of beam (LT1) didn’t reach yield till failure. The longitudinal steel of beam (LT3) reached yield at an applied torque of 17.2 kN.m .

3.5 Stirrups Strains

The stresses in the stirrups are quite small, the measured strains are insignificant at the three sections and the relation between the applied torque and stirrups steel strain was near linearity before first cracking. The beam behaves as a plain concrete beam without reinforcement. After cracking, the stirrups steel became more effective in resisting the torsional moment. A large increase in stirrups steel strain values is observed with slight increase in torque as shown at Figure 13.

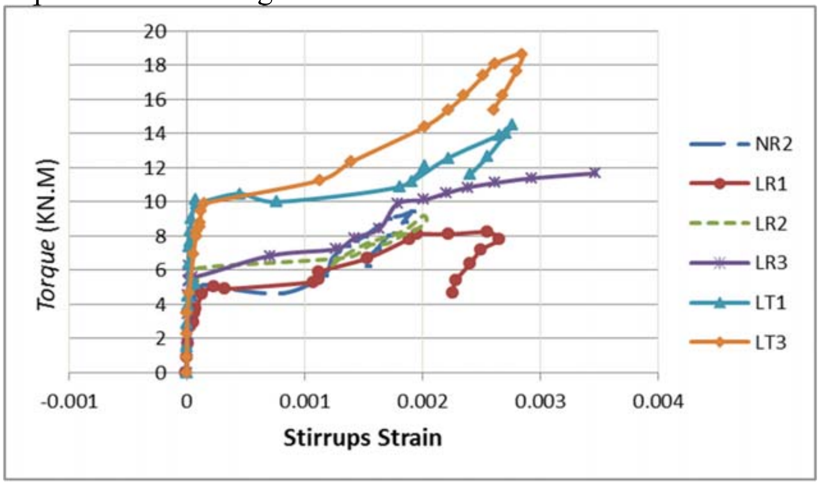


Figure 13: Torque - Stirrups Strain Curve for all tested beams .

The stirrups steel of beam (NR2) reached yield first at an applied torque of 6.5 kN.m. The mild stirrups steel of beam (LR1) reached yield first at an applied torque of 6 kN.m, the mild stirrups steel of beam (LR2) reached yield at an applied torque of 6.65 Kn.m and the high stirrups steel of beam (LR3) reached yield at an applied torque of 10.5 kN.m. The mild stirrups steel of beam (LT1) reached yield first at an applied torque of 10.5 kN.m and the high stirrups steel of beam (LT3) reached yield at an applied torque of 13.5 kN.m.

4. Conclusions

As a result of this investigation, the following conclusions were drawn:

- Beams cast using ordinary reinforced concrete and lightweight concrete experienced similar failure modes when tested under pure torsion loads.
- Beams casted using light weight concrete can be used as an alternative to ordinary reinforced concrete beams taking into consideration that its own weight is lower about 25 % and torsional capacity is lower approximately by about 10 % than that of ordinary concrete beams.

- The observed cracks were diagonal and occurred at the mid span of all tested beams. The average inclination angle of the cracks (at the four faces) to the beam longitudinal axis ranged from 48° to 58°.

- The stresses in the longitudinal steel and stirrups before the first crack are quite small so the measured strain values are insignificant. The behavior is linear and similar for all beams up to first cracking.
- The effect of changing the quantity of steel reinforcement appear after first crack that a big increase in steel strain values with a little increase in torque.
- The percentage of reinforcement within a section is set no or minor brittle failure to the concrete such reinforcement quantity allows the yield to occur first.
- Increasing the cross section properties (Ao , Ph) about 50% lead to big increasing in the cracking torque and ultimate torque exceed 50% compared with increasing the quantity of steel reinforcement which has slightly effect on cracking load and lead to reasonable increasing in the ultimate torque.

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