Experimental and Theoretical Analysis of Reinforced Light-Weight Concrete Sections under Eccentric Loads

Dr. Omar A. EL-Nawawy, Dr.Amr H. Zaher, Dr.Amgad A.Talaat &Eng. Ahmed S. Mostafa

Abstract— Due to technology and research development on concrete compressive strength over the last years, the use of lightweight concrete (LWC) has proved to be most popular in terms of economy, superior strength, stiffness and durability. However, strength and ductility are generally inversely proportional. Lightweight concrete is a brittle material causing failure to occur suddenly under excessive applied loads. It is also well known, that axial compression concrete elements (i.e. axially compressed) rarely occurs in practice. The stress concentrations caused by eccentric loading, further reduce the strength and ductility of high-strength concrete columns.

This paper presents an experimental-theoretical and analytically (Ansys 14.0) study to investigate the general deformational behavior of eccentrically loaded light-weight reinforced concrete (LWRC) columns. Six medium scale LWRC columns with 150 mm width, 250 mm depth, and 1200 mm height connected with two end cantilevers were tested under eccentric loads. Different types of light-weight materials were used.

The experimental study includes also testing of one medium scale LWRC beam with cross section (150 x 250) mm, 1200 mm length and span 1100 was tested under the effect of two vertical concentrated loads.

The obtained experimental results were combined with some other available data, in order to formulate some recommendations for designers and researchers concerning the analysis, design and construction of LWRC elements.

Ansys 14 has provided useful insight for future application of a finite element package as a method of analysis. To ensure that the finite element model is producing results that can be used for study, any model should be calibrated with good experimental data. This will then provide the proper modeling parameters needed for later use.

Key words— Light-weight concrete, Columns, Eccentric loading, Strains, Beams, Codes.

I. INTRODUCTION

Most of current concrete researches focus on using high-strength concrete mixes, by which is meant a cost effective material that satisfies demanding performance requirements, including durability [1]. Light-weight concrete (LWC) is very important to the construction industry due to its cost effective and numerous advantages. The primary advantage of using LWC is to reduce the dead load of the concrete structure, which allows the structural designer to reduce the size of carrying columns, footings and other load bearing elements [2].

Furthermore, the reduced mass will reduce the lateral load that will be imposed on the structure during earthquakes, hence simplifying and reducing the lateral load carrying system [3]. Structural light-weight concrete mixes can be designed to achieve similar strengths as normal weight concrete. The same is true for other mechanical and durability performance requirements. Structural lightweight concrete provides a more efficient strength-to-weight ratio in structural elements. In most cases, the marginally higher cost of lightweight concrete is offset by size reduction of structural elements, less reinforcing steel and reduced volume of concrete which result in lower overall cost [4].

Light-weight foamed concrete is a new kind of Lightweight concrete, which combines the advantages of normal density concrete, cellular concrete and self-compacting concrete through partially replacing the normal weight aggregates with polystyrene foam, hence, leading to concrete unit weight reduction while maintaining adequate strength. The latter material can therefore be produced using standard methods familiar to the construction industry with a dry unit weight of 18.5 kN/m3, which in turn leads to dead load reduction of 15 – 20 % and the associated decrease in the structure’s overall cost, hence, providing a feasible challenge to normal density concrete (NDC) [5].

The comparison shows that the reinforced concrete columns made of natural lightweight aggregates can be used in structures if they include appropriate transverse reinforcement and have a good mix design [6].

The LWAC column has the incentive of size effect. Therefore, the size effect should be considered in the design of LWAC columns [7].

II. EXPERIMENTAL PROGRAM

The experimental program includes testing of three types of columns in order to perform five stages of loading from pure axial load up to pure bending moments. The details of tested columns are as follows:

A. Column Group No. (1):

Columns (C1-C3) of effective cross section 15 x 25 cm, overall length 120 cm, and 25 x 35 cm heads of height 20 cm, and effective loading length of 70 cm, with longitudinal reinforcement 4 φ 10 mm in corners and 5 φ 8/m closed stirrups with spacing 20 cm and the additional reinforcement. Details are given in figure (1).

B. Column Group No. (2):

Specimens (C4-C6) of effective column cross section 15 x 25 cm, overall length 120 cm, and 25 x 35 cm heads of height 40 cm, and effective loading length of 40 cm, with longitudinal reinforcement 4 φ 10 mm in corners and 5 φ
8/m closed stirrups with spacing 20 cm and the additional reinforcement. Details are given in figure (2).

C. Beam Test:

A flexural loading beam (C7) is of dimensions 15 x 25 cm, longitudinal reinforcement 4 φ 10 mm and 5 φ 8/m closed stirrups with spacing 20 cm. The effective span is 110 cm and the overall length is 120 cm. Details of the beam are given in figure (3).

The seven specimens were made from lightweight foam concrete.

III. EXPERIMENTAL DETAILS

Characteristics of used materials:

The properties of the materials used for preparing ordinary and lightweight concrete composites tested in this study are: aggregates, cement, silica fume, water, foam, super-plasticizer, and reinforcement steel [6].

Aggregates:

The fine aggregates used in this work were all of siliceous graded natural sand. It has a fineness modulus of 3.35 and apparent specific gravity of 2.62.

Course aggregates used were all composed of siliceous gravel and having a general particle shape of a combination of round and sub-angular with max nominal size 10 mm and the surface texture is more or less smooth and uniform.

Cement:

The cement used in all of the experimental work was ordinary Portland cement of physical and chemical properties in compliance with E.S.S. 373, 1984.

Water:

Clean drinking fresh water free from impurities was used for mixing and curing.

Silica fume:

The silica fume used in all experimental work was ordinary silica fume.

Super plasticizer:

A high water reducer or a super-plasticizer was added to the concrete composites to improve the workability of the fresh composite and at the same time converse its compactness without increasing the water content.

The super-plasticizer used in this study was of a liquid form under trade Name, ADDICRETE BVS which is in compliance with ASTM C494, 1982 of type V with doses about 2.8%. It permits a reduction of 24% of the water content in concrete mixture when used in these doses.

Reinforcing steel:

The longitudinal reinforcement of columns of diameter 10 mm was of high grade steel while the 8 mm were of mild steel.

Mix Composition

The quantities required by weight for one cubic meter of concrete for the L.W.C columns are as given in table (1).

<table>
<thead>
<tr>
<th>Table (1): Material quantities the L.W.C columns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
</tr>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Gravel</td>
</tr>
<tr>
<td>W/C ratio</td>
</tr>
<tr>
<td>Plasticizer</td>
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<tr>
<td>Silica fume</td>
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<tr>
<td>Polystyrenes Foam</td>
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</table>

IV. PREPARATION OF SPECIMENS

Forms:

Wooden forms were designed and prepared to allow for simple and correct placing of concrete. The steel bars were tied with the stirrups forming reinforcement cages corresponding to that required for columns. Electrical strain gauges of 10 mm length and 120 ohm resistance were fixed on the steel bars, in order to follow the reinforcement strains during loading. The strain gauges were covered with silicon sealant to protect them during casting and consolidation of concrete.

The forms were coated with a thin layer of oil to facilitate their removal after hardening of concrete.

The reinforcement cages were then placed in the forms and lifted by small blocks to permit appropriate concrete cover.

V. MIXING AND CURING

Dry materials were mechanically mixed in a drum mixer for two minutes then water and super-plasticizer were added to the mix and cast in the forms just after mixing.

The batch consisted of 34 kg cement, 9.5 kg water, 48 kg sand, 48 kg gravel, 1 liter super-plasticizer and 0.38 kg foam with approximately three batches to cast each column. The cast concrete was then vibrated with an electrical needle vibrator and hence, the final concrete surface was smoothed. The forms were removed after 24 hours from casting and columns were moistened continuously with water for 7 days and kept in laboratory atmosphere until they were tested after 4 to 6 weeks.

Standard specimens were prepared during casting columns to obtain the mechanical properties of the used concrete. These specimens consisted of 12 cube specimens (15.8 cm side) and 2 cylindrical specimens (15 cm diameter and 30 cm height). The specimens were cast in layers and each layer was compacted by rod. After 24 hours, the specimens were demoulded and kept under water until they were tested. Six cubes were tested in compression to get the 7 days strength while the other cubes were tested to get the 28 days compressive strength. One cylinder was tested in...
uniaxial compression to determine the cylindrical strength and the compressive modulus of elasticity while the other cylinder was tested to obtain the splitting tensile strength of concrete. All cylinders were tested after 28 days from casting and all tests were carried out in accordance with the standard Egyptian specifications. Table (2) shows the average values of the obtained results.

Table (2): Mechanical properties of L.W.C columns mix (kg/cm²)

<table>
<thead>
<tr>
<th>Cube strength</th>
<th>Cylindrical compressive strength</th>
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<tbody>
<tr>
<td>7 days</td>
<td>175</td>
</tr>
<tr>
<td>28 days</td>
<td>240</td>
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<td>190</td>
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</table>

VI. LOADING OF COLUMNS

Two sides of each column are white painted, one day before testing, to facilitate the tracing of cracks during loading. At the day of testing, the column was mounted and adjusted in machine. The columns were all loaded in increments up to failure.

The tested columns were instrumented to measure their mechanical behavior after each load increment using the following tools, see Fig. (4).

a. Strains: The concrete strains were measured using mechanical strains gauges (extensometer) of 50 mm gauge and 0.01 mm accuracy. The distance between demec points mounted on the painted sides of the specimen was measure in three rows. The main reinforcement strains were measured with the electrical strain gauges fixed on them. The electrical strain gauges were coupled to a strain indicator.

b. Lateral deflections: They were measured using 5 LVDT 100 mm capacity and 0.01 mm accuracy and were arranged to measure the deflection distribution through out the column height.

c. Cracks: After each load increment the cracks are traced and marked on the painted sides of the specimen according to their priority of occurrence.

VII. BEHAVIOR OF THE TESTED SPECIMENS

The seven tested models behaved in a different manner and the following remarks were noticed:

- **Cracking, Crack Pattern and Failure Load**

For the tested columns, the first crack for the first three columns appeared at a load level about 0.8 of the ultimate load (the failure load) while for the other columns the first crack appeared at a load level about 0.5 of the ultimate load.

Table (3) shows the load at which the first crack appeared, the failure load and the eccentricity used for all specimens. Figures (5) to (10) show the crack patterns of the tested columns. Figure (11) shows the interaction (Load-Moment) diagram.

From the previous table and the mentioned figures the following marks can be included.

1- The ratio of first crack load to failure load for small eccentricity columns is more than for big eccentricity columns and this can be attributed to the difference of the behavior of light weight concrete due to compression only and due to compression and moment.

2- Increasing the eccentricity for the columns (C2-C6); the main cracks get higher near the middle, then as the load increased the cracks propagated in a diagonal manner until they reached the other side of column.

3- For the first three columns (C1-C3) the first crack appeared in the lower middle of the columns and as a load increased, the cracks propagated upwards in almost a vertical manner and For the next three specimens (C4-C6) the first crack appeared in the lower middle of columns and as a load increased, the crack propagated upwards in a diagonal manner with an inclination angle of about 55-65 degrees approximately. This may be attributed to the effect of increasing the loading eccentricity.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Eccentricity (cm)</th>
<th>Crackin g load (ton)</th>
<th>Crackin g Moment (m.t)</th>
<th>Failure Load (ton)</th>
<th>Failure Moment (m.t)</th>
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<tbody>
<tr>
<td>C1</td>
<td>0</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
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<td>C2</td>
<td>4.4</td>
<td>30</td>
<td>50</td>
<td>60</td>
<td>70</td>
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<td>C3</td>
<td>6.9</td>
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<td>45</td>
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<td>60</td>
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<td>C4</td>
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<td>C5</td>
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<td>C6</td>
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<td>6</td>
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<tr>
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4-It was observed that all the columns tested have low ductility and this may be attributed to the high cube strength fcu of the concrete used.

- **DEFLECTIONS**
  
  As mentioned before, central lateral deformations of the tested models were measured on each model to predict the deflected shape of the tested model.

  The experimental load central deflection curves, on tension side of all tested specimens, are shown in figures (12) to (17).

  From these figures, the following remarks could be concluded.

  1- The load-deflection curves for models (C1-C6) were nearly linear at the early stages of loading (from zero up cracking of concrete), after which there was a bigger increase in deflection because of the great decrease in stiffness due to excessive cracking.

  2- For all models, it was noticed that increasing eccentricity causes increase of central deflection and this can be attributed to the increase in moment acting on the models.

- **LONGITUDINAL STEEL STRAINS**
  
  The curves in Fig. (18) to (23) Show the load steel-strain variations, at mid span section, through the load history for the seven tested models. From these curves, it is clear that before cracking, the behavior of steel strain was almost linear. Also, just before failure of the models, all the steel strain gauges were damaged so they did not give readings to be recorded.

- **LONGITUDINAL CONCRETE STRAINS**
  
  The concrete strains were measured through the columns lengths to determine the strain distribution through the each column length from zero up to failure load.

  The curves in Fig. (24) to (29) Show the longitudinal concrete strains near mid span section of all the tested models at different load levels.

  From these curves the following remarks can be included:

  1. The moment-longitudinal concrete strain curve was almost linear, before cracking, for all models.

  2. For columns from C1 to C6 the failure concrete strain was almost 0.0042 (more than normal strength concrete) and this may be attributed to the low cube strength fcu of the concrete.

- **DETAILING OF MODEL FOR COLUMN**
  
  An eight-node solid element is used to model the concrete. The element dimensions are selected after many trials to maintain the positions of the reinforcement and the dimensions of the concrete cover. The dimensions of the element are 50 x 50 x 50 mm., 25 x 25 x 50 mm., 25 x 25 x 25 mm. The clear height of the column consist of 24 elements which will equal to 1200 mm, the length is divided to 5 elements which will equal to 250 mm, the width is divided to 3 element which will equal to 150 mm, the cover dimension equal one element which will equal to 25 mm. The model dimensions are the same of the experimental tested column, which are 1200 mm height, 250 length, and 150 MM WIDTH AND. The model mesh and the elements dimensions are shown in Fig. (30) to (35).

- **REINFORCEMENT OF COLUMN**
  
  The longitudinal reinforcement is four bars of nominal diameter; 10mm. these bars represent 0.9 % reinforcement ratio. The concrete cover is 25 mm. The stirrups had a nominal diameter; 8mm, and shape is closed box form. These stirrups are arranged uniformly along the column height with internal spacing of 200 mm. As shown in Fig. (36) to (37).

- **LOADS AND BOUNDARY CONDITIONS**
  
  Displacement boundary conditions are needed to constrain the model to get a unique solution. To ensure that the model acts the same way as the experimental column, boundary conditions need to be applied where the supports and loadings exist. The upper support is modeled in such a way that a hinge is created. A single line of nodes are given constraint in the UX, and UZ directions, applied as constant values of 0. The lower support is modeled as a roller. All nodes in column based are given constraint in the UY directions, applied as constant values of 0 by doing this; the column will be allowed to rotate at the support. The support condition is shown in Fig. (38). The force, P, applied at the column head depend on the position of eccentric load. The force applied at each node on the plate. As Shown in Figure (39).

- **CRACKING AND FAILURE LOADS**
  
  The elastic limit was considered to be load at which the first crack appeared in the specimen (cracking load). This load limit was calculated with accuracy 5 ton for specimens (C1-C6) and 1 ton for specimen (B), which was limited by the number of load increments used from zero up to failure load. Figure (40) to (45) shows the crack pattern of the analysis test.

- **VIII. FINITE ELEMENT METHOD**
  
  The finite element method for linear or nonlinear analysis of non-homogeneous structures such as reinforced concrete is well known and is documented in many references.

  The finite element analysis of an elastic continuum starts with the subdivision of the original system into an assemblage of discrete elements connected at the nodes, assuming compatibility along the element boundaries.

- **IX. CONCLUSIONS**
  
  1. The observed value of the first cracking loads for all values of load eccentricity (e/t) almost same with theoretical analysis.
2. The observed value of the failure loads for load eccentricity \( (e/t) = 0 \) to 0.276 were greater than those obtained from the theoretical analysis about 13%, for load eccentricity \( (e/t) = 0.376 \) to 1.056 were greater than those obtained from the theoretical analysis about 5% and for \( (e/t) = \infty \) was greater than those obtained from the theoretical analysis about 25%.

3. For load eccentricity \( (e/t) = 0 \) to 0.276, the steel strain values are greater than those obtained from the theoretical analysis about 25% and for load eccentricity \( (e/t) = 0.376 \) to 1.056, the steel strain values obtained from the theoretical analysis are almost same before cracking and smaller than that measured experimentally about 13% after cracking.

4. For load eccentricity \( (e/t) = 0 \) to 0.176, the concrete strain values obtained from the theoretical analysis were smaller than that measured experimentally about 3%, for load eccentricity \( (e/t) = 0.276 \) to 0.376, the concrete strain values obtained from the theoretical analysis were smaller than that measured experimentally about 12% and for load eccentricity \( (e/t) = 0.54 \) to 1.056, the concrete strain values obtained from the theoretical analysis were smaller than that measured experimentally about 20%.

5. For load eccentricity \( (e/t) = 0.376 \) to 1.056 the maximum concrete compressive strain was grater than that measured experimentally, this may attributed to in big eccentricity the effect of moment appear and due to the stiffness of the actual column could be lower than what the finite element models predict, which cause lower concrete strain in big eccentricity. The reason of lower stiffness in experimental test may be refer to micro cracks. Micro cracks produced by drying shrinkage and handling are present in the concrete to some degree. These would reduce the stiffness of the actual columns, while the finite element model do not include micro cracks.

6. The finite element models has lower ultimate load than the experimental work. This variation of cracking and ultimate load was acceptable due to there is a variation of concrete strength in experimental work affect the behavior of tested columns.

REFERENCES


Fig (2): Typical dimension and reinforcement of columns C4, C5, C6

Fig (3): Typical dimensions and reinforcement of beam C7

Fig (4): Schematic Arrangement of the Test Set-up
Fig. (11): Load-Moment diagram for tested columns

Fig. (12) Moment – Maximum deflection curve of e/t=0.176

Fig. (13) Moment – Maximum deflection curve of e/t=0.276

Fig. (14) Moment – Maximum deflection curve of e/t=0.376

Fig. (15) Moment – Maximum deflection curve of e/t=0.54

Fig. (16) Moment – Maximum deflection curve of e/t=1.056
Fig. (17) Moment – Maximum deflection curve of $e/t = \infty$

Fig. (18) Moment – Maximum steel strain curve of $e/t = 0.176$

Fig. (19) Moment – Maximum steel strain curve of $e/t = 0.276$

Fig. (20) Moment – Maximum steel strain curve of $e/t = 0.376$

Fig. (21) Moment – Maximum steel strain curve of $e/t = 0.54$

Fig. (22) Moment – Maximum steel strain curve of $e/t = 1.056$
Fig. (23) Moment – Maximum steel strain curve of $e/t=\infty$

Fig. (24) Moment – Maximum concrete strain curve of $e/t=0.176$

Fig. (25) Moment – Maximum concrete strain curve of $e/t=0.276$

Fig. (26) Moment – Maximum concrete strain curve of $e/t=0.376$

Fig. (27) Moment – Maximum concrete strain curve of $e/t=0.54$

Fig. (28) Moment – Maximum concrete strain curve of $e/t=1.056$
Fig. (29) Moment – Maximum concrete strain curve of e/t=∞

Fig (30) – The model mesh and the elements dimensions e/t=0.00

Fig (31) – The model mesh and the elements dimensions e/t=0.176

Fig (32) – The model mesh and the elements dimensions e/t=0.276

Fig (33) – The model mesh and the elements dimensions e/t=0.376

Fig (34) – The model mesh and the elements dimensions e/t=0.54
Fig (35) – The model mesh and the elements dimensions 
e/t=1.056

Fig (36) Details of Steel Reinforcement for Group (I)

Fig (37) Details of Steel Reinforcement for Group (II)

Fig (38) – Support condition

Fig (39) – The applied loads

Fig (40) the crack pattern for specimen has e/t = 0.0
Fig (41) the crack pattern for specimen has $e/t = 0.176$

Fig (42) the crack pattern for specimen has $e/t = 0.276$

Fig (43) the crack pattern for specimen has $e/t = 0.376$

Fig (44) the crack pattern for specimen has $e/t = 0.54$

Fig (45) the crack pattern for specimen has $e/t = 1.056$