Comparative Study of Lightweight and Normal Weight Concrete in Flexure

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Title: Comparative Study of Lightweight and Normal Weight Concrete in Flexure.

This investigation represents a comparative study of the flexural behavior of lightweight and normal weight concrete. Both theoretical and experimental moment-curvature characteristics of the tested specimens were used to study the flexural behavior.

A generalized computer program to determine the moment-curvature relationships of a singly reinforced rectangular concrete beam was developed.

For this limited study it was observed that lightweight concrete beams when compared to normal concrete beams achieve comparable moment capacity (about 92% of normal weight concrete) but exhibit higher deflections (about 40% more than normal weight concrete).
COMPARATIVE STUDY OF LIGHTWEIGHT AND NORMAL
WEIGHT CONCRETE IN FLEXURE

by

MOHAMMAD ZAREH

A thesis submitted in partial fulfillment of the
requirements for the degree of

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in
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TO THE OFFICE OF GRADUATE STUDIES:

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DEDICATED
TO
PARVIN, HABIB, BARBARA,
FRUZ, AND ROYA
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CHAPTER I

INTRODUCTION

1.1 Scope of Work

The purpose of this investigation was to study the flexural behavior of lightweight concrete in comparison with normal weight concrete. Both theoretical and experimental moment-curvature relationships were used as a basis for this study.

To develop the moment-curvature \((M-\phi)\) curve a stress-strain relationship was required. Several of these relationships \((1,2)\)* were studied and finally the equation proposed by Desayi and Krishnan \((3,4)\) was chosen. The theoretical \(M-\phi\) curves were developed using an electronic digital computer.

In order to appreciate the advantages and disadvantages of lightweight concrete a knowledge of its physical characteristics would be desirable. Hence, chapter II is devoted to a general review of important properties of lightweight concrete.

1.2 Brief Description of Tests

Four concrete beams were tested, two using lightweight aggregate (expanded shale) and the other two using normal weight aggregate (gravel). In all the specimens natural sand was used.

*Numbers in parenthesis refer to the references at the end of this thesis.
as the fine aggregate.

Two different percentages of high strength reinforcing steel
(ASTM A615) were used; test beams R-1 and L-1 with 0.33 square
inch of steel and R-2 and L-2 with 0.22 square inch. Details
of the test procedure are given in Sec. 4.7.

1.3 Notations

The following notations are used throughout this thesis.
The symbols are defined below and where they appear first in
the text.

\[ a_1 = \text{distance between load points (Fig. 17)} \]
\[ A_s = \text{area of reinforcing steel} \]
\[ b = \text{width of test specimens} \]
\[ b_l = \text{distance between load point and support} \]
\[ C = \text{compression force} \]
\[ c_l = \text{distance between load point and support} \]
\[ d = \text{distance from outer compression fiber to centroid of} \]
\[ \text{tension reinforcement} \]
\[ E_c = \text{modulus of elasticity of concrete} \]
\[ E_s = \text{modulus of elasticity of steel} \]
\[ f_c = \text{concrete stress} \]
\[ f'_c = \text{compressive strength of standard 6in. X 12in. test} \]
\[ \text{cylinders} \]
\[ f''_c = \text{maximum compressive strength of concrete} \]
\[ f_y = \text{yield strength of reinforcing steel} \]
\[ j_d = \text{distance from compression force to centroid of} \]
tension reinforcement

$L =$ span of test specimens

$M =$ bending moment

$P =$ axial load

$R =$ beam reaction

$S =$ horizontal distance between rotation bars

$T =$ tension force

$V =$ vertical distance between dial gauges

$W =$ unit weight of test specimens

$\varepsilon_c =$ concrete strain

$\varepsilon_\sigma =$ strain on concrete corresponding to maximum stress

$\varepsilon_s =$ Strain in reinforcement

$\phi =$ curvature
CHAPTER II

A GENERAL REVIEW OF LIGHTWEIGHT CONCRETE

2.1 General

Freedom of architectural design, together with high compressive strength of concrete, have greatly attributed to its role as one of the major building materials in the world.

Structural concrete can be divided in two categories: lightweight and normal weight. Basically, lightweight structural concrete is still concrete; a cement and water paste is the binder. Expanded clay, slate, shale, or slag is used as the aggregate instead of gravel. As the name implies lightweight concrete has a lower unit weight, about 2/3 of that of normal weight concrete. This reduction in weight when considered in design of buildings could allow the reduction in sizes of some structural members thereby providing more usable space. This would result in a more suitable and economical structure.

Unfortunately the reduced unit weight of lightweight concrete is accompanied by its higher cost and some different structural properties compared to that of normal weight concrete. Thus, in deciding between lightweight and normal weight concrete, careful consideration should be given to their price and their physical characteristics.
2.2 Historical Background

The modern lightweight aggregate industry (5) was first started in 1917, when Stephen J. Hayde developed a process for heat expansion of shales and clays into lightweight aggregates. These aggregates were used to make concrete of substantial strength and low weight. At about the same time F. J. Straub discovered the use of bituminous coal cinders as an aggregate for manufacture of concrete masonary units.

One of the earliest uses of lightweight concrete (6) was in production of a few ships during World War I, and in a more than one hundred ships and barges during World War II.

After World War II, extensive studies of lightweight aggregates were conducted by the Housing and Home Finance Agency (7), the National Bureau of Standards, and the U. S. Bureau of Reclamation. These studies led to substantial use of lightweight concrete in building frames, bridge decks, and precast products.

From 1950's to present, many multistory structures have been designed utilizing the advantages of reduced dead weight of lightweight concrete.

2.3 Lightweight Aggregates

There are many types of lightweight aggregates available, but not all are structurally suitable. Low density concretes are mainly used for insulation purposes. They have a low unit weight (around 50 pcf) and low compressive strength (ranging from 100 to 1000 psi). Fig. 1 shows a spectrum (6,8) of lightweight concretes.
Structural lightweight concrete as defined by the American Concrete Institute (6) shall have a 28-day compressive strength in excess of 2500 psi and a 28-day unit weight not exceeding 115pcf. Raw materials used in commercial production of structural lightweight aggregates are generally (a) suitable natural deposits of shales, clays, or slates; (b) by-products of other industries, such as iron blast furnace slags or fly ash.

There are several different methods (6) of producing structural lightweight aggregates, e.g., rotary kiln process, sintering process, and machine process.
2.4 Different Processes

Rotary Kiln Process

This process is used mainly with expanded shales and clays which exhibit a bloating characteristic. The raw material is introduced in a rotary kiln and is heated to a temperature varying from 1600° F to 2100° F, depending on the raw material. The aggregate is heated to a point of becoming soft and pliable, but not to a point of complete melting.

The raw material is changed into a product with an internal cellular structure. This cellular structure when cooled becomes a vitreous hard material.

Sintering Process

The raw materials used in sintering process contain some burning fuel. They either contain carbonaceous matter or are mixed with finely ground coal or coke. The material is introduced in special burners where gases are formed causing the expansion of the material and thereby creating its cellular structure.

Machine Process

The slag is melted at temperatures in excess of 2200° F and is rapidly agitated in a machine while adding a controlled amount of water. Then the slag is cooled and crushed. The cellular structure is created by entrapment of the evolved gases.
2.5 Physical Properties of Lightweight Concrete

Compressive Strength

Compressive (6,9) strength comparable to that of normal weight concrete is obtained by the use of lightweight concrete. High compressive strengths of up to 7000 psi are used in the production of structural precast members. However, generally more sacks of cement per cubic yard of concrete are required when manufacturing lightweight concrete instead of normal weight concrete.

Unit Weight

The unit weight (6,9) of lightweight concrete is significantly lower than that of normal weight concrete, due to the cellular structure of the aggregate. The unit weight of lightweight concrete, depending on the type of fine and coarse aggregate used, varies from 90 to 120 pcf. The unit weight is also greatly affected by graduation and particle shape. Higher strength lightweight concrete has a somewhat higher unit weight since more sacks of cement per cubic yard of concrete are used.

Modulus of Elasticity

Static modulus (10) of elasticity is taken as the slope of the secant to the stress-strain curve. Over the years several expressions for modulus of elasticity of concrete have been developed. One that has appeared frequently in codes is \(1000f'_c\). This formula and others, are reasonably accurate for concretes of usual strength made of normal weight aggregates.
However, the increased use of lightweight aggregates and also higher strength concretes created the need for a more accurate expression.

Adrian Pauw (11) analyzed a large number of test data for concrete of different densities and arrived at the following empirical equation.

$$E_C = 33W \sqrt{f_c'}$$

Where $E_C =$ elastic modulus, psi
$W =$ unit weight, pcf
$f_c' =$ concrete compressive strength, psi

The above formula gives the values of modulus of elasticity for both lightweight and normal weight concrete and is adopted by the current American Concrete Institute Code.

For this study Pauw's empirical formula was used to determine the theoretical modulus of elasticity of the tested specimens.

Creep

Creep is the dimensional change or increase in strain of concrete due to a sustained load. There have been numerous research programs involved in determining the creep properties of lightweight concrete.

Creep strain of lightweight concrete (6) varies from about equal to double that of normal weight concrete. Tests have shown that the use of higher strength concrete, steam curing, or the use of sand to replace lightweight fines
reduces this variation.

**Shear**

Lightweight concrete (12,13) in relation to normal weight exhibits lower tensile strength, especially when subjected to air drying. Because shear capacity of structural members is directly related to the diagonal tension resistance of the concrete, i.e., its tensile strength, a lower shear strength is attributed to lightweight concrete.

**Durability**

In addition to laboratory tests, the use of lightweight concrete (6,10) in bridge decks has shown that lightweight concrete has an equal or better resistance against freezing and thawing compared to that of normal weight concrete.

**Bond**

In comparative tests of lightweight and normal weight concretes there appears to be slightly (6,10) lower pull-out capacity for lightweight concrete. However, the difference is small enough so that the American Concrete Institute Code allows the same capabilities for both concretes.

**Fire Endurance**

Due to its lower (6,10) thermal conductivity, lightweight concrete is more fire resistant than normal weight concrete.
Summary

Modulus of elasticity of lightweight concrete is about 1/2 to 3/4th that of normal weight concrete.

Creep and shrinkage vary from about equal to double that of normal weight concrete.

Lightweight concrete when air dried shows less diagonal tension resistance.

Lightweight concrete is a better insulator and has more fire resistance.
CHAPTER III

THEORETICAL MOMENT CURVATURE RELATIONSHIP

3.1 Stress-Strain Relationships

To determine the theoretical moment-curvature curve a stress-strain relationship is required. However, due to nonlinear stress-strain characteristics of concrete, many empirical formulas (1, 2) have been proposed.

In 1951 Hognestad (14) proposed a stress-strain relationship for concrete in flexure. Hognestad's proposed curve, which has been widely accepted, is shown in Fig. 2.

\[
f_c = f_c'' \left[ 2 \frac{\varepsilon_c}{\varepsilon_0} - \left( \frac{\varepsilon_c}{\varepsilon_0} \right)^2 \right]
\]

Fig. 2. Hognestad stress-strain curve for concrete in flexure.
The ascending portion of the curve is represented by the formula:

\[ f_c = f_c'' \left[ \frac{2 \varepsilon_0}{2f_c''/E_c} - \left( \frac{f_c''/E_c}{\varepsilon_0} \right)^2 \right] \]

Where \( \varepsilon_0 = 2f_c''/E_c \)

\[ f_c'' = 0.85f_c' \]

The descending portion of the curve is defined by a straight line which starts at the maximum stress value and falls to a value of \( 0.85f_c'' \) at a strain of 0.0038. This is the ultimate strain where concrete is assumed to fail.

Desayi and Krishnan (3), in 1964, proposed a new simplified equation. This equation represents both the ascending and the descending part of the stress-strain curve. Desayi and Krishnan's proposed stress-strain relationship is shown in Fig. 3.

![Stress-strain curve](image)

**Fig. 3.** Desayi and Krishnan stress-strain curve for concrete in flexure.
Where $\varepsilon_c = 2f''_c/E_c$

$f''_c = 0.85f'_c$

Due to their simplicity and their use by other researchers, the stress-strain equations proposed by Hognestad and the one by Desayi and Krishnan were first chosen for this study. Both of these equations were used in a computer program and the resulting moment-curvature curves were plotted. The ascending portion of the curves using Desayi and Krishnan's equation was remarkably close to that of Hognestad's.

Since Desayi and Krishnan's equation represents both the ascending and the descending part in a single expression it was subsequently used as the basis for comparison in the analysis of test results.

3.2 Moment Curvature Relationship

The relationship between bending moment and the resulting deformation of flexural members is characterized by their moment-curvature curves.

![Fig. 4. Curvature and moment](image)
As is shown in Fig. 4 angle $\phi$ measured by the concrete and steel strains represents the curvature of a specimen.

Moment is taken as the product of compression or tension force (C or T) times the moment arm designated as $jd$. Fig. 5 shows a typical moment-curvature curve.

![Typical moment-curvature curve](image)

**Fig. 5.** Typical moment-curvature curve
3.3 Development of the Theoretical Moment Curvature Relationship

A trial and error method was employed with the aid of an electronic digital computer. The method of solution involved the arbitrary selection of outer fiber tensile strain ($\varepsilon_S$) for a given concrete strain ($\varepsilon_C$). Using the stress-strain relationship, tension and compression forces were determined. When these two forces became equal, then it was evident that the right strains were selected. The corresponding $\varphi$ and $M$ were computed. This operation was repeated for different values of $\varepsilon_C$. Finally a moment-curvature curve was determined. The detailed procedure is given in the following section.

3.4 Computer Analysis of Moment Curvature

The program to determine the moment-curvature curve was written in FORTRAN language and was run at the Portland State University Computer Center on IBM 1130 computer.

For the purpose of analysis the cross-section and the corresponding stress and strain diagrams were divided into a number of rectangles of equal depth. As shown in Fig. 6 a linear strain distribution was assumed.

An iterative procedure was used for the solution of each point on the moment-curvature. However, an exact solution i.e., tension force equal to compression force, was not expected to result. Each point was obtained within a predetermined error. To allow a relatively fast convergence in the program, an error limit of one half of one per cent of compression force ($C$) was taken.
The program was written for the analysis of flexural members with only tensile reinforcing. The use of different subroutines in the program allows for future modifications with relative ease. The logic diagram of the program, named SOLVE, is given in figures 7 thru 11.

For the complete listing of the program see Appendix.

Fig. 6. Finite element approximation
Input Data, Area of reinforcing steel, steel yield strength, concrete cylinder strength, weight of specimen, effective depth, and effective width of specimen.

Write The name of the stress-strain relationship used.

Write All input data.

Calculate $E_c$ and $f_c''$.

Choose $\epsilon_r$ and $\epsilon_c$.

Call subroutine TC.

Is control card less than 1?

Yes: Call subroutine STRS1.

No: Choose new $\epsilon_r$.

Is $T = C \pm 0.005 \times C$?

Yes: Go To 90.

No: Call subroutine STRS2.

Fig. 7. SOLVE - Logic diagram to calculate tension and compression forces.
Calculate centroid of stress diagram

Calculate moment arm

Calculate moment

WRITE Concrete and steel strains, concrete stress, tension and compression force, moment arm, curvature, and moment

Is strain = 0.0038

Increase $\varepsilon_c$

END

Go To 18

**Fig. 8.** SOLVE - Logic diagram to calculate moment
SUBROUTINE TC

Start

Calculate curvature

Determine tension force T

Return

Fig. 9. SUBROUTINE TC - Logic diagram to calculate tension force and curvature.
SUBROUTINE STRS1

Start

Calculate stress-strain relationship using Desayi and Krishnan equation

Calculate the area of stress diagram

Calculate compression force

Return

Fig. 10. SUBROUTINE STRS1- Logic diagram to calculate compression force using Desayi and Krishnan stress-strain equation.
SUBROUTINE STRSZI

Start

Calculate stress-strain relationship using Hognestad equation

Calculate the area of stress curve

Calculate compression force

Return

Fig. 11. SUBROUTINE STRS2 - Logic diagram to calculate compression force using Hognestad stress-strain equation.
CHAPTER IV

MATERIALS, INSTRUMENTATION AND TEST PROCEDURE

4.1 Reinforcing steel

All reinforcing consisted of #3 (3/8 inch diameter) bars of high strength deformed steel bars conforming to ASTM A615.

A coupon approximately 18 inches long was cut from each steel specimen. The coupons were tested to failure in a Richle 300 kips testing machine at U. S. Army Corp of Engineers Material Laboratory, Troutdale, Oregon. The yield strength of #3 bars ranged from 69,000 to 70,000 psi.

Reinforcing details are shown in Fig. 12. Specimen R-1 and L-1 were reinforced with three #3 bars. The other two specimens were reinforced with two #3 bars. All reinforcing bars were placed on plastic chairs to secure their vertical position and were tied together by wires to prevent any horizontal movement.

Typical Beam Elevation

Fig. 12. Test specimen details
4.2 Concrete Materials

A. Normal weight concrete

Oregon Portland Cement Type III (high early strength) was used. Cement was stored indoors in bags throughout the test.

Coarse aggregate consisted of Willamette River gravel of 3/4 inch maximum diameter. For fine aggregate, a well graded Willamette River sand was used.

B. Lightweight concrete

Coarse aggregate consisted of expanded shale, mined near Banks, Oregon, and produced by a rotary kiln process.

Fine aggregate and cement were the same type used for normal weight concrete.

The concrete mix was designed to give a seven day cylinder strength of 4500 psi with approximately a two inch slump. The mix data for lightweight and normal weight concrete are shown in tables 1 and 2.

4.3 Forms

Forms were constructed of 3/4 inch exterior plywood, were thoroughly varnished, and were oiled before each use. Careful removal and reassembly allowed the use of one form for all four specimens.
**TABLE I**

**MIX DESIGN FOR LIGHTWEIGHT CONCRETE TEST BEAMS**

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>CEMENT</th>
<th>SAND</th>
<th>EXP. SHALE</th>
<th>WATER</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT</td>
<td>41.8</td>
<td>110.3</td>
<td>42.6</td>
<td>19.0</td>
<td>213.7</td>
</tr>
</tbody>
</table>

water/cement ratio = 0.455

**TABLE II**

**MIX DESIGN FOR NORMAL WEIGHT CONCRETE TEST BEAMS**

<table>
<thead>
<tr>
<th>MATERIALS</th>
<th>CEMENT</th>
<th>SAND</th>
<th>GRAVEL</th>
<th>WATER</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEIGHT</td>
<td>44.0</td>
<td>84.4</td>
<td>153.2</td>
<td>19.0</td>
<td>300.6</td>
</tr>
</tbody>
</table>

water/cement ratio = 0.432
4.4 Casting and Curing

A drum type mixer was used. Due to its size, two separate batches had to be made in order to cast one beam and six 6 X 12 standard cylinders. Special care was taken to make the two batches as nearly identical as possible. Three standard 6 X 12 test cylinders from each batch were cast in steel forms and were thoroughly compacted by hand tapping.

The concrete beams were placed in two lifts with each lift thoroughly compacted by hand tapping and by means of a 1 3/8 inch diameter vibrator head. After casting, exposed surfaces of all specimens were given a smooth finish with a steel hand trowel.

The test specimens and the test cylinders were kept moist and covered with a waterproof sheet for 24 hours after casting. When forms were removed, the specimens were moist cured until two days prior to testing.

4.5 Specimen Dimensions

Since no over-head crane was available in the laboratory, the weight of the test beams was a controlling factor in the size of the specimens. The width of beams were chosen to assure a flexural failure. Fig. 12 shows test specimen details.

4.6 Testing Equipment and Instrumentation

The test beams were loaded as shown in Fig. 13. The concentric load P was applied to a 100 kip capacity load cell
Fig. 13. Typical loading for test specimens

Fig. 14. Typical test set up
by means of a simplex hand operated hydraulic pump and ram arrangement. Fig. 14 shows the testing frame and a typical test set up.

To facilitate observation of the tensile face of the beam, it was tested upside down. The applied load was recorded from a Daytronic Model 711 dial indicator connected to the load cell.

The point loads and roller supports were simulated by use of steel rollers and base plates (Fig. 15). The supports were placed approximately six inches from each end of the beam, thus reducing the span length of the beam to exactly five feet.

The concrete strain was measured by dial gauges attached at top and bottom of the rotation bars. These bars were fabricated from steel angles and were placed at each side of the test specimen (Fig. 14).

4.7 Test Procedure

All loads were applied at 0.5 to 1.0 kip increments. After each loading increment, dial gauges were read and recorded.

During the testing operation for two specimens (R-1 and R-2) some mis-alignment was noticed. In such instances, the loads were reduced to the starting point and after correction was made the test operation was resumed.
Fig. 15. Typical test beam roller supports
CHAPTER V

ANALYSIS OF TEST DATA AND CONCLUSION

5.1 Curvature

The curvature of test beams was determined by the use of rotation meters. The placement of rotation bars at each side of the specimen provided two curvature values for each load increment. The average of the two curvature values were used in the analysis. The method of calculation is outlined below.

\[ \phi = \frac{[\varepsilon_c] + [\varepsilon_x]}{S \times \sqrt{V}} \]

Where \( S \) = horizontal distance between rotation bars

\( V \) = vertical distance between dial gauges
5.2 Moment

Figure 17 shows the loading, shear, and moment diagrams.

Since the maximum variation in the length $a_1$, $b_1$, and $c_1$ was only $1/8$ of an inch, then they were assumed equal and the maximum moment was simply calculated as $\frac{PL}{6}$.
5.3 Failure Characteristics

The first visible tension cracks occurred generally about 1/5 of the ultimate applied load. As the load was increased, the depth of the cracks became visible at the ends of the specimens. Lightweight concrete specimens developed large shear cracks before failure, but in the normal weight specimens the failure occurred by the extension of tension cracks into the compression zone (Figs. 18 and 19).

It should be noted that the test beams were not loaded to complete failure. Loading was stopped at the point where the load dial indicator would not advance with additional pumping of the jack. This procedure provided additional safety protection to the personnel and the equipment.

5.4 Test Analysis

Due to the tension resistance of concrete, the initial portion of the experimental moment-curvature curves show a higher slope compared to that of theoretical results. This is because the theoretical M-\( \xi \) curves are developed with the assumption that concrete section is cracked and does not carry any tension. The computer program used to develop the theoretical moment-curvature relationship can be modified to incorporate the tension strength of concrete with that of reinforcing steel. This would give a somewhat closer comparison between the experimental and the theoretical results.

After the initial rise, the experimental results approach the
Fig. 18. Specimen R-1 and L-1 after test was completed.

Fig. 19. Specimen R-2 and L-2 after test was completed.
theoretical curve, cross it, and drop to just below the ultimate moment. Figs. 20 thru 27 show the theoretical and the observed M-Ø curves for the test beams.

Test specimens (R-1 and R-2) compared to (L-1 and L-2) had a somewhat higher (about 6%) compressive cylinder strength. However, this small variation in $f_c$ had a very small effect on the M-Ø curves. Therefore it was ignored.

Both the lightweight concrete test beams (L-1 and L-2) show comparable ultimate moment to that of normal concrete beams (R-1 and R-2). However, as can be seen from Figs. 20 thru 27 the lightweight concrete specimens developed much higher deflection.

Lightweight concrete used in this study (lightweight aggregate and natural sand) had a lower unit weight (about 27% of normal weight concrete). This unit weight reduction, assuming all other parameters to be equal, would result in a more economical structure.

5.5 Conclusions

Based on this limited study the following conclusions seem warranted.

1. Lightweight concrete and normal weight concrete test beams show comparable moment capacity (about 92% of normal weight concrete).

2. Under the same loading conditions, lightweight concrete compared to normal weight concrete gives a larger deflection (about 40% more than normal weight concrete).
3. The lower unit weight of concrete, assuming all other parameters to be equal, would result in a more economical structure.

4. A generalized computer program to determine the moment-curvature relationships of a singly reinforced rectangular concrete beam was developed. This computer program could be used with different stress-strain relationships by simply replacing the appropriate subroutine.

5. The computer program developed here-in can be easily modified for different shapes of cross sections. Similarly, it can be adopted to include the tensile stress-strain characteristics of concrete.
Fig. 20. Moment-curvature curves for specimen R-1

\[ \frac{M}{bd^2} \text{ ksi} \]
Fig. 21. Moment-curvature curves for specimen L-1
Fig. 22. experimental moment-curvature for specimens R-1 and L-1
Fig. 23. Theoretical moment-curvature for specimen R-1 and L-1

\[ \frac{M}{bd^2z} \]

\[ \theta \relax 0.001 \]

\[ 0.0000 \]

\[ 0.0001 \]

\[ 0.0002 \]

\[ 0.0003 \]

\[ 0.0004 \]

\[ 0.0005 \]

\[ 0.0006 \]

L-1

R-1
Fig. 24. Moment-curvature curve for specimen R-2
Fig. 25. Moment-curvature curve for specimen L-2
Fig. 26. Experimental moment-curvature curves for specimens R-2 and L-2
Fig. 27. Theoretical moment-curvature curves for specimens R-2 and L-2.
REFERENCES


APPENDIX

LISTING FOR THE COMPUTER PROGRAM - SOLVE

This program calculates the M-Ø relationship using either Hognestad or Desayi and Krishnan stress-strain equation.

REAL MOMNT, MARM
COMMON DEPTH(60), STRN(60), STRS(60), AREA(60), SUM(60)

Read input data

5 READ(2,100) AS, FY, FCP, WT, D, WIDTH
READ(2,8) ICON
IF(ICON=1) 6, 9, 500
6 WRITE(5,12)
GO TO 14
9 WRITE(5,16)
14 WRITE(5,110) AS, FY, FCP, WT, WIDTH
NP = 41
I = 0
J = 0
EC = WT ** 1.5 * (33.0 * FCP ** 0.5)
FCPP = 0.85 * FCP
10 I = I + 1
18 STRN1 = I * (0.0001)
20 J = J + 1
STRN2 = J * (-0.0001)

Call subroutine TC

CALL TC (NP, EC, FCPP, STRN1, STRN2, D, AS, FY, CVTR, T, &DTOP)
IF(ICON=1) 21,22, 500

Call subroutine STRS1

21 CALL STRS1 (NP, EC, FCP, DTOP, WIDTH, C)
GO TO 23

Call subroutine STRS2

22 CALL STRS2 (NP, EC, FCPP, DTOP, WIDTH, C, STRN1)
23 IF(T+C) 80, 90, 70
47

70 IF(T+0.995*C) 90, 90, 85
80 IF(T+1.005*C) 81, 90, 90
85 EBOT = STRN2
    STRN2 = 2 * STRN2
    ETOP = STRN2
C
C    Call subroutine TC
C
    CALL TC (NP, EC, FCP, STRN1, STRN2, D, AS, FY, CVTR, &T, DTOP)
C
C    Call subroutine STRS1
C
200 CALL STRS1 (NP, EC, FCPP, DTOP, WIDTH, C)
    GO TO 210
C
C    Call subroutine STRS2
C
205 CALL STRS2 (NP, EC, FCPP, DTOP, WIDTH, C, STRN1)
210 IF(T+C) 310, 90, 300
300 IF(T+0.995*C) 90,90, 85
310 IF(T+1.005*C) 320, 90, 90
320 STRN2 = (EBOT + ETOP)/2.0
C
C    Call subroutine TC
C
    CALL TC (NP, EC, FCP, STRN1, STRN2, D, AS, FY, CVTR, &T, DTOP)
    IF(ICON-1) 325, 328, 500
C
C    Call subroutine STRS1
C
C    CALL STRS1 (NP, EC, FCPP, DTOP, WIDTH, C)
    GO TO 329
C
C    Call subroutine STRS2
C
328 CALL STRS2 (NP, EC, FCPP, DTOP, WIDTH, C, STRN1)
329 IF(T+C) 340, 90, 330
330 IF(T+0.995*C) 90, 90, 360
340 IF(T+1.005*C) 350, 90, 90
350 ETOP = STRN2
    GO TO 320
360 EBOT = STRN2
    GO TO 320
81 ETOP = STRN2
    STRN2 = STRN2/2.0
    EBOT = STRN2
C
C    Call subroutine TC
CALL TC (NP, EC, FCP, STRN1, STRN2, D, AS, FY, CVTR, 
&T, DTOP)
IF(ICON=1) 362,365, 500

C Call subroutine STRS1

362 CALL STRS1 (NP, EC, FCPP, DTOP, WIDTH, C)
GO TO 368

C Call subroutine STRS2

365 CALL STRS2 (NP, EC, FCPP, DTOP, WIDTH, C, STRN1)
368 IF(T+C) 375, 90, 370
370 IF(T+0.995*C) 90, 90, 320
375 IF(T+1.005*C) 81, 90, 90
90 CONTINUE
DO 92 K= 1,NP
92 SUM(K) = 0.0
DO 95 K = 2,NP
95 SUM(K) = SUM(K-1) * STRS(K-1) * DPTH(K-1)
DO 97 K = 1,NP
97 STRS(K) = STRS(K) + STRS(K-1)
CNTRD = SUM(NP)/STRS(NP)
MARM = (D - (DTOP-CNTRD))
MOMNT = (-T+C) * 0.5 * MARM
WRITE(5,130) STRN1, STRN2
WRITE(5,140) STRS(1)
WRITE(5,150) T, C, MARM, CVTR, MOMNT
IF(STRN1- 0.0038) 10,5,5
8 FORMAT (II)
12 FORMAT (///, 3X, " M-Ø CALC. USING KRISHNAN AND DESAYI 
& EQUATION ")
16 FORMAT (///, 3X, " M-Ø CALC. USING HOGNESTAD EQUATION ")
100 FORMAT (6F12.0 )
110 FORMAT (3X, " AS = ", F8.4, " IN.*2 ", 3X, " FY = ", 
&F8.0, " PSI ", 3X, " FCP = ", F8.0, " PSI ", //, 3X, 
&3X, " WIDTH = ", F6.2, " IN. ", //)
130 FORMAT (3X, " CONCRETE STRAIN = ", F9.7, 5X, " STEEL 
& STRAIN = ",F10.7)
140 FORMAT (3X, " CONCRETE STRESS = ", F12.4, //)
150 FORMAT (5X, " T = ", F12.0, " C = ", F12.0, " MARM = ", 
& F12.6, //, 5X, " CVTR = ", F12.6, " MOMENT = ", F12.2, //)
500 CALL EXIT
END
SUBROUTINE TC

This subroutine calculates the curvature and the tension force.

SUBROUTINE TC (NP, EC, FCP, STRN1, STRN2, D, AS, FY, & CVTR, T, DTOP)
COMMON DPTH(60), STRN(60), STRS(60), AREA(60), SUN(60)
ES = 29400000.0
27 CVTR=(STRN1-STRN2)/D
DTOP = STRN1/CVTR
DO 40 K = 1,NP
DPH(K) = DTOP - (DTOP * (K-1))/40.0
40 STRN(K) = (STRN1 * DPTH(K))/DTOP
T = STRN2 * ES * AS
T1 = -AS * FY
IF(T1-T) 43, 43, 42
42 T = T1
43 RETURN
END

SUBROUTINE STRS1

This subroutine calculates the compression force using Desai and Krishnan stress-strain equation.

SUBROUTINE STRS1
COMMON DPTH(60), STRN(60), STRS(60), AREA(60)
23 DO 25 K = 1,NP
25 AREA(K) = 0.0
DO 10 K = 1,NP
A = EC * STRN(K)
B = (A/(2.0 * FCPP)) * (A/2.0 * FCPP)
10 STRN(K) = AREA(K-1) + (STRS(K-1) + STRS(K)) * (DTOP * & 0.0125)
C = AREA(NP) * WIDTH
RETURN
END
SUBROUTINE STRS2

This subroutine calculates the compression force using Hognestad stress-strain relationship.

SUBROUTINE STRS2 (NP, EC, FCPP, DTOP, WIDTH, C, STRN1)
COMMON DPTH(60), STRN(60), STRS(60), AREA(60)
Do 25 K = 1,NP
25 AREA(K) = 0.0
IF(STRN1-(2.0 * FCPP/EC)) 30, 30, 50
30 Do 40 K = 1,NP
A = EC * STRN(K)
B = (A/(2.0 *FCPP)) * (A/2.0*FCPP))
40 STRS(K) = (A-FCPP * B)
GO TO 70
50 STRS(1) + FCPP - 0.15 * FCPP * ((STRN1 - (2.0 * FCPP & /EC))/(0.0038 - (2.0 * FCPP/EC)))
DO 60 K = 1,NP
60 STRS(K) = (STRS(1) * DPTH(K))/DTOP
70 DO 80 K = 2,NP
80 AREA(K) = AREA(K-1) + (STRS(K-1) + STRS(K) * (DTOP * & 0.0125)
C = AREA(NP) * WIDTH
RETURN
END