CHAPTER 5

STUDIES ON CONTACT BLAST LOADING AND IMPACT

During impulsive loadings such as blast and impact, the structure is expected to absorb large amounts of energy within a short time. This can be achieved by using a material which possesses large ductility. This helps the structure to undergo large deformations without failure. Steel has good ductility while concrete is known to be brittle. Ferrocement has been reported to be a better material than concrete in terms of the ductility, and it can be expected to have favourable behaviour under impulsive loading environments. To ascertain the behaviour of ferrocement under impulsive loads in comparison with concrete, a test series on structural elements made of ferrocement and reinforced concrete are conducted using blast loading. Reinforced concrete as well as ferrocement slabs are subjected to contact blast and their dynamic response are measured. The process of loading during a contact blast is different from that of an air blast. In contact blast, the transfer of a major portion of blast load occurs through a point while the air blast introduces pressure loading on an area. Both contact blast and impact transfers the load over a very small area. Hence they may be considered as a point load rather than uniformly distributed loads. In order to compare the response of structure during an impact and contact blast, impact experiments are conducted on identical slabs and the responses are measured. Static tests on similar comparison slabs are also conducted in order to assess the stiffnesses of slabs.

5.1 SPECIMEN DETAILS

Slabs of dimensions 900 mm x 600 mm and thickness 20 mm are cast for the proposed static, blast and impact tests. Identical dimensions are used for ferrocement and concrete. Ferrocement slabs are made using 1 : 1.5 cement-sand mortar with two layers of hexagonal woven wire mesh of
1.6 mm diameter and one layer of welded wire mesh of 3mm diameter. Reinforced concrete slabs are cast using a mix of 1 : 1.5 : 3 of cement, sand and broken stone with a water cement ratio of 0.4. A welded wire mesh consisting of 3mm diameter bar at 100 mm spacing in each direction is used as the reinforcement in the concrete slab. Control cubes of mortar and the concrete are cast to find the characteristic compressive strength of the respective materials. The specimens are cured in water for a normal curing period of 28 days before testing.

A support frame is fabricated to support the slab during the static and dynamic tests. This heavy frame gives a knife edge support to all the four edges of the slab both from top and bottom. Thus during a static test, it prevents the corners from lifting up and during a dynamic test, it provides support from top and bottom, arresting the upward or downward movement at the edges.

5.2 EXPERIMENTS

5.2.1 Static test

In order to find the stiffness of the slabs for use in the dynamic calculations connected with the blast and impact tests, static tests are conducted on ferrocement as well as concrete slabs. The slab is mounted on the support frame with a Simplex hydraulic jack of 10 tonne capacity at the top. The concentrated load is applied at the center of the slab and the mid-span deflection is measured using a Baty dial gauge of 50 mm travel accurate enough to measure 0.01 mm. The loading arrangement and the test set-up are shown in Figure 5.1. Both monotonic as well as cyclic loading are applied on the slab. The stiffness of the slab during different cycles of loading in the pre-cracking and post-cracking zones are assessed. The static cyclic load sequence used in the experiment, is shown in Figure 5.2.

5.2.2 Blast test

The explosive charge, mentioned in section 4.1, is fired directly on the slab to find the blast response of the slab. The slab is
FIG. 5.2. LOADING PATTERN FOR STATIC CYCLIC LOADING

MAXIMUM LOAD IN KG IN EACH CYCLE

- - - - - - - - - -

FERROCEMENT

R.C.C.

NO. OF CYCLES

1 2 3 4 5 6 7 8

1040 837 765 540 360 225 90 45
held on the support frame and the blast charge is kept at the midpoint of the slab. The dynamic displacement of the slab is measured using an IEICOS make linear variable differential transformer (LVDT) at the bottom of the slab. Since the loading is transient, deflections are recorded in an Encardio-Rite strip chart recorder through a digital displacementmeter. The loading arrangement and the recording instrumentation are shown in Figure 5.3. The contact blast load is varied by firing charges of weight 5 grams to 25 grams. The slabs are subjected to single blast and repeated blast separately. For single blast testing, each slab is subjected to only one blast of specific magnitude and then removed for examination of the crack pattern etc. The dynamic deflection is recorded during the blast and the permanent set in the slab is measured from the displacementmeter reading after the blast. For repeated blast, a slab is subjected to repeated firings one after the other, the charge being kept on the same spot each time. The dynamic deflections and extent of cracking are noted after every blast. Each type of slab is subjected to three numbers of 25 grams blast. The intensity of blast used is enough to crack the specimens made with ferrocement and reinforced cement concrete. After each blast, permanent deformation in the slab is also noted.

To quantify the contact blast load from each charge separate tests are conducted using load cells. When the charge is fired in direct contact with the load cell i.e. when the charge is fired after directly placing it on top of the load cell, impulsive compressive load is transmitted at the point of contact on the load cell. The charges are burst, keeping them directly on the load cell and the dynamic loads are recorded by the recorder. The load-time history recorded for each blast is integrated to obtain the impulse of each blast. For the blasts from lower charges of 5, 10 and 20 grams, a load cell of 200 kg static capacity is used while for the 25 grams blast, a load cell of 10 tonne static capacity is used. The individual load cell stiffnesses are found from static compression tests. The mass of the load cells are also measured.
FIG. 5.3. ARRANGEMENT FOR BLAST LOADING

CHARGE ON THE SLAB

LVDT POSITIONING

BLAST

INSTRUMENTATION
5.2.3 Impact test

The aim of conducting the impact tests is twofold. Firstly, the tests are intended to ascertain the superiority of ferrocement over reinforced concrete in resisting impulsive loads. Secondly, it is necessary to compare the response under contact blast load and impact load to find out whether any correlation exists between the two types of loading. The test set up for impact has been shown in Figure 5.1. A falling tup in the form of a steel rod with detachable steel discs of varying weights screwed on to it, is used as the loading head. A guiding frame with a pulley on the top is erected in order to ensure a vertical drop of the hammer on the midpoint of the slab. The slab is held by the support frame on all the edges. The dynamic deflections at the mid-point of the slab are measured using an LVDT kept below the slab. These deflections are recorded in a strip chart recorder. The slabs are tested for single impact and repeated impact. For single impact, each slab is subjected to a single drop of a selected weight from a selected height. The dynamic deflection is recorded and the slab is removed from the support and the crack pattern noted. Each slab is tested for a different impact energy by varying the height of drop and the weight of hammer. For the repeated impact test, the same slab is subjected to repeated drops of constant weight and height until failure. Failure of the slab occurred by the punching of the slab either partially or fully. This test is intended to indicate the ability of the slab to resist the impact loading even after cracking. The cumulative energy required to cause failure of the specimen is determined. This cumulative energy is used as a measure of the energy capacity of the slab. The failure pattern for the ferrocement and concrete slabs are compared for each set of testing. Permanent set of the slab after each drop is also measured using the displacementmeter.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Static test

The following observations are obtained from the static test.

1. Mid-span deflection at each load
2. The first crack load
3. The ultimate load
4. The crack pattern during loading and at failure.

The salient numerical results from the tests are reproduced in Table 5.1. The load deflection behaviour for the two slabs during monotonic loading is shown in Figure 5.4. The same behaviour when loaded under cyclic load is shown in Figure 5.5 and Figure 5.6 for ferrocement and reinforced concrete respectively. These diagrams show distinct nonlinear material behaviour with three zones i.e. pre-cracking, post-cracking and failure. The deflections under cyclic loading show clearly the reduction of the stiffness in subsequent cycles. This stiffness degradation with subsequent cycles of loading is shown in Figure 5.7 and Figure 5.8 for the lower and higher range of loads respectively. It can be seen that for the selected dimensions and reinforcements used in the present experiment, ferrocement has about fifty percent more stiffness during the pre-cracking stage which becomes nearly equal to the stiffness of the reinforced concrete after cracking. This can be attributed to the transfer of the resistance from the composite material to the steel portion of the slab. In ferrocement, once the matrix has cracked, the mesh reinforcement provided in the slab starts resisting the load with large deflections. In reinforced concrete which is made up of conventional reinforcement, the composite material, although having a lesser stiffness initially, continues to resist the load until failure. All the slabs tested showed that the ferrocement had failed at higher load than the reinforced concrete. The first crack load for the ferrocement slab also is higher than that of concrete. The failure crack pattern for the two types of slabs, both at the top and bottom surfaces are shown in Figure 5.9. As far as the static tests are concerned, the cracking is observed to be similar with reinforced concrete exhibiting cracks at slightly lower load level than ferrocement. The in-plane loads developed in the slab owing to a small thickness have allowed the slab to take a dish-like formation at failure. This is evident from the circular cracks observed in the top portion of the slab. The theoretical values for the initial stiffness and ultimate loads are
<table>
<thead>
<tr>
<th>Details</th>
<th>Ferrocement</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>900 x 600 x 20 mm</td>
<td>900 x 600 x 20 mm</td>
</tr>
<tr>
<td>Effective Spans</td>
<td>816 x 500 mm</td>
<td>816 x 500 mm</td>
</tr>
<tr>
<td>Concrete / Mortar</td>
<td>490 kg / sq.cm</td>
<td>330 kg / sq.cm</td>
</tr>
<tr>
<td>First Crack Load</td>
<td>250 kg</td>
<td>170 kg</td>
</tr>
<tr>
<td>Ultimate Load</td>
<td>980-1040 kg</td>
<td>770-840 kg</td>
</tr>
<tr>
<td>Theoretical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Load</td>
<td>834.0 kg</td>
<td>715.2 kg</td>
</tr>
<tr>
<td>Max. Deflection</td>
<td>32.2 mm</td>
<td>26.4 mm</td>
</tr>
<tr>
<td>at Ultimate Load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permanent Deflection after failure</td>
<td>21.0 mm</td>
<td>16.4 mm</td>
</tr>
<tr>
<td>Uncracked stiffness</td>
<td>150-300 kg/mm</td>
<td>150-200 kg/mm</td>
</tr>
<tr>
<td>Theoretical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncracked stiffness</td>
<td>348.0 kg/mm</td>
<td>286.0 kg/mm</td>
</tr>
</tbody>
</table>
FIG. 5.4. STATIC RESPONSE OF SLAB (MONOTONIC)
FIG. 5.5. STATIC RESPONSE OF FERROCEMENT SLAB (CYCLIC)
FIG. 56. STATIC RESPONSE OF R.C.C. SLAB (CYCLIC)
FIG. 5.7. STIFFNESS DEGRADATION IN STATIC CYCLIC LOADING (LOWER)
FIG. 5.8. STIFFNESS DEGRADATION IN STATIC CYCLIC LOADING (HIGHER)
FIG. 5.9. STATIC FAILURE
predicted as shown in the preceding paragraphs.

5.3.1.1 Theoretical initial uncracked stiffness

Based on plate theory [29], the stiffness of the ferrocement and reinforced concrete slabs are calculated using the values of flexural rigidity in the uncracked state. The expression for the central deflection of a simply supported plate of dimensions 'a' and 'b', when subjected to a central concentrated load of 'P' is given by

\[
\omega_{\text{max}} = \frac{4P}{\pi^4 a b D (\frac{1}{a^2} + \frac{1}{b^2})^2}
\]

...(5.1)

where

\[
D = \frac{E h^3}{12 (1-\nu^2)}
\]

...(5.2)

where

P = central concentrated load on the slab,
\(a, b\) = effective dimensions of the slab,
D = flexural rigidity of the slab,
h = thickness of the slab,
E = Young's Modulus and
\(\nu\) = Poisson's ratio.

The values of Young's modulus for the two materials are calculated from the expression [32],

\[
E = 5700 \sqrt[3]{f_{\text{ck}}}
\]

...(5.3)

where

\(f_{\text{ck}}\) = characteristic strength of the material in N/mm\(^2\).

\(= 48.07\ N/\text{mm}^2\) (480 kg/cm\(^2\)) for ferrocement;

\(= 32.37\ N/\text{mm}^2\) (330 kg/cm\(^2\)) for reinforced concrete,

from the cube compressive strength.

With these values of \(f_{\text{ck}}\), the Young's modulus is found as

\[
E = 39519.54\ N/\text{mm}^2\ (4.03 \times 10^5\ \text{kg/cm}^2)\] for ferrocement and
E = 32431.48 N/mm^2 (3.31 x 10^5 kg/cm^2) for reinforced concrete.

The slab dimensions are

a = 816 mm ,

b = 500 mm. and

h = 15 mm neglecting the clear cover,

Assuming a Poisson's ratio (ν) of 0.15, the flexural rigidity of the slab is found as

D = 11.371 x 10^6 N mm (1.159 x 10^5 kg cm) for ferrocement and

D = 9.331 x 10^5 N mm (0.095 x 10^5 kg cm) for reinforced concrete.

The uncracked stiffness of the two slabs are hence calculated as

\[ K_{\text{ferrocement}} = \frac{P}{w} = \frac{4abD}{a^2 + b^2 \left(\frac{1}{a} + \frac{1}{b}\right)} \]

\[ = 3420 \text{ N/mm} \]

\[ = 348.0 \text{ kg/mm} \]

Similarly for reinforced concrete,

\[ K_{\text{RCC}} = 2806 \text{ N/mm} \]

\[ = 286.0 \text{ kg/mm} \]

5.3.1.2 Theoretical ultimate load

The static ultimate load is calculated from the flexure theory of the reinforced concrete assuming an under reinforced section so that the failure occurs by the yielding of the reinforcement.

A. Ferrocement

Effective dimensions of the slab = 816 mm x 500 mm

Thickness of the slab = 20 mm

Effective cover of reinforcement = 6.5 mm

Effective depth = 20 - 6.5 = 13.5 mm

Characteristic strength = 490 kg/sq.cm

Yield stress of steel = 2500 kg/sq.cm
As given in [33], the volume percentage of reinforcement is worked out as

\[
V_f = \frac{V_m}{V_i} \quad \ldots (5.4)
\]

\[V = \gamma_m \cdot h \cdot \text{area}, \quad \ldots (5.5)\]

\[\gamma_m = \text{density of steel} = 7860 \text{ kg/m}^3\]

\[h = \text{thickness of ferrocement section} = 0.02 \text{ m.}\]

\[V_i = N \cdot W_m \times \text{area}, \quad \ldots (5.6)\]

\[N = \text{no. of layers} = 2\]

\[W_m = \text{unit weight of mesh} = 0.1435 \text{ kg/m}^2.\]

Substituting these values,

\[V_f = \frac{2 \times 0.1435}{7860 \times 0.02} \times 100 = 0.183\]

\[\therefore \text{Effective area of reinforcement} = \eta \cdot V_f \cdot A, \quad \ldots (5.7)\]

\[\eta = \text{Global efficiency factor} = 0.3, \text{ for wire mesh.}\]

\[V_f = 0.183, \text{ as above and}\]

\[A = \text{area of section} = 100 \times 2 = 200 \text{ cm}^2\]

\[\therefore A_{st} = 0.3 \times 0.183 \times 200 / 100 = 0.110 \text{ cm}^2\]

For the welded mesh reinforcement,

\[V_f = \frac{N \pi d_b^2}{4h} \left( \frac{1}{D_l} + \frac{1}{D_t} \right), \quad \ldots (5.8)\]

\[N = \text{no. of layers} = 1,\]

\[d_b = \text{diameter of mesh wire} = 0.3 \text{ cm.}\]
h = Thickness of section = 2.0 cm.,
$D_l =$ longitudinal spacing of mesh = 10 cm. and
$D_t =$ lateral spacing of mesh = 10 cm.
Substituting these values,

$$V_f = \frac{1 \times \pi \times 0.3^2}{4 \times 2} \times \left( \frac{1}{10} + \frac{1}{10} \right) \times 100$$

= 0.7065

$A_{st} = \eta V_f \frac{A}{V}$

= $0.5 \times 0.7065 \times 100 \times \frac{2}{100}$

= 0.7065 cm$^2$

Hence the total area of steel = 0.110 + 0.7065 = 0.8165 cm$^2$

The ultimate moment of resistance $M_u$ is given by

$$M_u = 0.87 f_y A_{st} d \left( 1 - A_{st} \frac{f_y}{b d f_{ck}} \right)$$

...(5.9)

With the values as listed above,

$M_u = 2323.46$ kg cm/m

= 23.23 kg cm/cm

From the yield line theory of plates [29], the ultimate central concentrated load is given by

$$P_u = M_u \times 4 \left( \frac{a}{b} + \frac{b}{a} \right)$$

...(5.10)

where a and b are the dimensions of the slab.

The ultimate load for the ferrocement slab considering failure due to flexure is thus calculated as

$P_u = 208.5$ kg.

However, the slab being thin, it deflects to about 1.5 times its thickness before failure. This introduces in-plane load resistance in the slab as the slab is clamped at all the edges. Hence consideration of the small deflection theory in such a case leads to a much smaller ultimate load than the actual one [29]. Hence large deflection theory including the in-plane resistance of the slab should be applied for finding the true ultimate load of the slab.
However, as the procedure for applying the large deflection theory is more involved, an approximate factor based on the comparison of small deflection and large deflection theories as given in [29] is applied to the ultimate load found by considering flexure alone. This factor for the ratio of maximum deflection to thickness ratio of 1.5, for the simply supported condition is about 4.0.

The theoretical ultimate load of ferrocement slab

\[ \text{Load} = 208.5 \times 4.0 \]
\[ = 834.0 \text{ kg.} \]

B. Reinforced concrete

Effective dimensions of the slab = 816 mm x 500 mm
Thickness of the slab = 20 mm
Effective cover of reinforcement = 6.5 mm
Effective depth = 20 - 6.5 = 13.5 mm
Characteristic strength = 330 kg/sq.cm
Yield stress of steel = 2500 kg/sq.cm

As already worked out the volume percentage of reinforcement is given as
\[ V_r = 0.7065 \text{ for welded mesh.} \]

Hence the total area of reinforcement

\[ A_r = 0.7065 \times 100 \times 2 \times 0.5/100 \]
\[ = 0.7065 \text{ sq.cm.} \]

Similar to the calculations carried out for ferrocement, the ultimate moment of resistance is found as

\[ M_u = 1992.2 \text{ kg cm /m} \]
\[ = 19.92 \text{ kg cm /cm} \]

The ultimate load for flexure is given as

\[ P_u = 178.8 \text{ kg.} \]

Using the correction factor for the in-plane loading, the theoretical ultimate load is

\[ P_u = 178.8 \times 4.0 \]
\[ = 715.2 \text{ kg.} \]
5.3.2 Blast Test

The response of the ferrocement and concrete slabs for the blast loading has been measured in terms of the dynamic deflections at the mid span. The maximum dynamic deflection for each blast is extracted from the deflection history recorded in the strip chart recorder. These observations are tabulated in Table 5.2. Figure 5.10 and Figure 5.11 show the blast response of reinforced concrete and ferrocement slabs respectively when subjected to four different charges i.e. 5 grams, 10 grams, 20 grams and 25 grams. The dynamic deflections are found to increase with the increase in quantity of charge. The variation of maximum dynamic deflection with quantity of charge for the two types of slabs is shown in Figure 5.12. From this, ferrocement slab is found to be more ductile by about 20%. From the values of Table 5.2 and from Figure 5.12, it can be noted that, the maximum deflection for ferrocement slab is lesser than reinforced concrete slab for the 5 grams and 10 grams blast. This shows that the ferrocement has a higher stiffness before cracking. For the 20 and 25 grams blasts, ferrocement has deflected more than reinforced concrete showing about 20-25% higher ductility after cracking.

The permanent set after each blast is plotted in Figure 5.13. Permanent set for the two types of slabs are almost the same. No cracking has been observed in the slabs for the blasts using 5 grams and 10 grams charges. The crack pattern observed for the 20 grams and 25 grams blast is shown in Figure 5.14. As can be seen from the figures, ferrocement has shown higher crack resistance than concrete.

The results of the repeated blast tests are also shown in Table 5.2. The maximum dynamic deflections during repeated blast are shown in Figure 5.15 and the permanent set observed during this loading is compared in Figure 5.16. Higher energy absorption and ductility of ferrocement is shown by approximately 80% larger dynamic deflections than reinforced concrete for the same number of blasts. The cracking due to the repeated blast is shown in Figure 5.17. It can be seen that the
### Table 5.2 BLAST TEST RESULTS

<table>
<thead>
<tr>
<th>CHARGE</th>
<th>MAX. DYNAMIC DEFLECTION</th>
<th>PERMANENT SET AFTER LOADING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in mm</td>
<td>in mm</td>
</tr>
<tr>
<td></td>
<td>Ferrocement</td>
<td>RCC</td>
</tr>
<tr>
<td>1. Single Blast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>7.0</td>
<td>8.5</td>
</tr>
<tr>
<td>10</td>
<td>8.0</td>
<td>10.4</td>
</tr>
<tr>
<td>20</td>
<td>18.0</td>
<td>16.5</td>
</tr>
<tr>
<td>25</td>
<td>28.0</td>
<td>20.0</td>
</tr>
<tr>
<td>2. Repeated blast</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25-1</td>
<td>28.0</td>
<td>20.0</td>
</tr>
<tr>
<td>25-2</td>
<td>54.0</td>
<td>30.0</td>
</tr>
<tr>
<td>25-3</td>
<td>54.0</td>
<td>22.0</td>
</tr>
</tbody>
</table>
FIG. 5.10. BLAST RESPONSE OF R.C.C. SLAB

FIG. 5.11. BLAST RESPONSE OF FERROCEMENT SLAB
FIG. 5.12 MAXIMUM RESPONSE FOR SINGLE BLAST

CHARGE IN GMS

DEFLECTION IN MM

FERROCEMENT

R.C.C
FIG. 5.13. PERMANENT SET DUE TO SINGLE BLAST
FIG. 5.14. CRACKING DUE TO SINGLE BLAST
FIG. 5.15 MAXIMUM RESPONSE FOR REPEATED BLAST
FIG. 5.16. PERMANENT SET FOR REPEATED BLAST

DEFLECTION IN MM

- FERROCEMENT
- R.C.C

NO. OF BLASTS (5 GMS)
FIG. 5.17. FAILURE DUE TO REPEATED LOADING
cracking in ferrocement is considerably lesser than in concrete.

The load-time history recorded from the blast tests on load cells are shown in Figure 5.18 and Figure 5.19. Based on these load histories, the impulse of the blast was calculated as the total area of the load-time graph. The relative intensity of each blast is worked out from the impulse of the blast. These values are given in Table 5.3. These impulse values are used to relate the intensity of each blast for the response studies on the slabs.

5.3.2.1 Theoretical blast deflections

For the computation of maximum dynamic deflection for the blast loading, a single degree of freedom system is assumed with an appropriate static stiffness of the slab. This system is subjected to the force-time history of blast obtained from the blast test on the load cell. These forces are applied as accelerations on to the single degree system using the mass of the load cell. A computer program [34] to find the response of a single degree of freedom system subjected to time varying accelerations using numerical integration applying finite difference technique is used to find the dynamic response. The calculations are done as follows.

Model calculation for 25 grams blast on ferrocement slab:

Weight of the load cell used for force measurement = 4.8 kgf

\[ \text{Mass of the load cell} = \frac{4.8}{9810} \]

\[ = 4.8929 \times 10^{-4} \text{ kg sec}^2 /\text{mm} \]

From the force-time history given in Table 5.3, force values are divided by this mass to get the accelerations produced by the blast. The properties of the single degree of freedom system are worked out as below.

Weight of the ferrocement slab = 28 kgf

\[ \text{Mass of the slab} = \frac{28}{9810} \]

\[ = 2.854 \times 10^{-3} \text{ kg sec}^2 /\text{mm} \]

In order to find a suitable slab stiffness for calculating the natural frequency, the range of variation of stiffnesses in the static testing has
FIG. 5.18. LOAD CELL RESPONSE FOR BLAST LOADING-5, 10, 20 GMS

QUANTITY OF BLAST CHARGE

1. 5 GMS
2. 10 GMS
3. 20 GMS

FORCE IN KG

TIME IN SEC
FIG. 5.19. LOAD CELL RESPONSE TO BLAST LOADING - 25 GMS
### Table 5.3 RESULTS OF BLAST TESTS ON LOAD CELL

<table>
<thead>
<tr>
<th>CHARGE</th>
<th>LOAD CELL DETAILS</th>
<th>MAXIMUM FORCE (kg)</th>
<th>IMPULSE Kg cm sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>capacity = 200 kg</td>
<td>90.9</td>
<td>7.56</td>
</tr>
<tr>
<td></td>
<td>weight = 1.4 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>stiffness = 5000 kg/mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>same as above</td>
<td>119.4</td>
<td>12.62</td>
</tr>
<tr>
<td>20</td>
<td>same as above</td>
<td>148.0</td>
<td>20.96</td>
</tr>
<tr>
<td>25</td>
<td>capacity = 10 tonnes</td>
<td>727.0</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>weight = 4.8 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>stiffness = 92310 kg/mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
been taken into account. A sample value thus arrived is given by

\[ \text{Stiffness of the slab} = 150 \text{ kg/mm for ferrocement} \]
for 25 grams blast

\[ \therefore \text{Natural frequency} = \sqrt{\frac{150}{2.854 \times 10^{-3}}} \]
\[ = 229.0 \text{ rad/sec.} \]

\[ \text{Damping ratio} = 0.1 \text{ (assumed)} \]

With these values of the single degree of freedom system, the accelerations are applied on the system and the displacement response is obtained. These results are shown in Table 5.4.

5.3.2.2 Energy absorption in blast

From the deflection-time history recorded from the blast tests, an energy absorption constant is worked out taking into account the appropriate stiffness of the slab. This is taken as a measure of the energy absorption in the specimen and is worked out for each blast for comparison. In a single degree axially loaded member of axial stiffness 'k', the energy stored for an induced axial deformation of \( \delta \) will be given by

\[ U = k \delta^2 \]  \hspace{1cm} \text{(5.11)}

Applying the similar theory for the tested slab with the bending stiffness and the bending deflection as corresponding quantities, the energy absorption constant for the blast is defined to be

\[ E_c = \int_{0}^{t^+} k \delta^2 \, dt \]
\[ \text{(5.12)} \]

where \( t^+ \) is the duration for the positive deflection phase of the response of the slab.

The above integral is actually the area of the response diagram for the slab in the positive deflection portion. The rebound of the slab is not considered in calculating the energy absorption. The sample
Table 5.4 BLAST RESPONSE OF SDOF SYSTEM

<table>
<thead>
<tr>
<th>Charge</th>
<th>Stiffness gms of slab</th>
<th>Natural Freq. kg/mm rad/s</th>
<th>Theoretical response mm</th>
<th>Experimental response mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrocement</td>
<td>5 150-300 229-323.9</td>
<td>2.3-4.95</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10 150-300 229-323.9</td>
<td>7.8-15.3</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 150-300 229-323.9</td>
<td>10.8-20.8</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25 150-300 229-323.9</td>
<td>13.7-28.2</td>
<td>28.0</td>
<td></td>
</tr>
</tbody>
</table>

2. Reinforced concrete

<table>
<thead>
<tr>
<th>Charge</th>
<th>Stiffness gms of slab</th>
<th>Natural Freq. kg/mm rad/s</th>
<th>Theoretical response mm</th>
<th>Experimental response mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 150-162.5 222.8-231.9</td>
<td>4.9-5.4</td>
<td>8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 150-162.5 222.8-231.9</td>
<td>15.0-16.0</td>
<td>10.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 150-162.5 222.8-231.9</td>
<td>20.2-21.9</td>
<td>16.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 150-162.5 222.8-231.9</td>
<td>27.5-29.5</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The calculation for the energy absorption of ferrocement for 5 grams blast is shown in Table 5.5. The energy absorption values calculated for the various blasts on ferrocement and reinforced concrete slabs are tabulated in Table 5.6. The energy absorption constant for the two types of slab are also plotted in Figure 5.20. It is seen that the ferrocement has absorbed larger energy in the higher order blasts of 20 grams and 25 grams. This shows that ferrocement has about 25% higher energy absorption during blast.

5.3.3 Impact test

The observations recorded in the impact test on ferrocement and concrete slabs include the dynamic deflections at mid-span, the permanent deflection after impact and the cracking in the slab after each impact. These readings have been recorded for different impact energy applied to the slabs. These observations are presented in Table 5.7. The dynamic deflection history recorded for the ferrocement slab and the concrete slab are shown in Figure 5.21 and Figure 5.22 respectively. The maximum dynamic deflection for the two types of slabs in relation to the impact energy is plotted in Figure 5.23. The maximum dynamic deflection is found to vary as indicated in the figure for different input energy. In all the single impact responses, reinforced concrete slab deflected more than the ferrocement.

However, no significant information is derived from the permanent deflections recorded during the single impact test and reproduced in Figure 5.24. The deflections for the two types of slabs are nearly the same. The cracking in ferrocement slab was considerably lesser than concrete as shown in Figure 5.25.

The maximum deflection for each impact in the repeated impact test is plotted in Figure 5.26. The deflections of ferrocement slab are lesser in the initial stages and became more than the concrete slab near failure. This indicates that the increased ductility in ferrocement slab enables it to undergo large deformations near failure without fracture. The plot of permanent set in the slab after each impact is shown in
Table 5.5 SAMPLE CALCULATION OF ENERGY ABSORPTION CONSTANT

Blast test

Material: Ferrocement
Charge: 5 grains

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Deflection ((\delta)) (mm)</th>
<th>Stiffness of slab (k) (kg / mm)</th>
<th>(k \delta^2) (kg mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>3.0</td>
<td>50.0</td>
<td>450.0</td>
</tr>
<tr>
<td>0.02</td>
<td>4.5</td>
<td>50.0</td>
<td>1012.5</td>
</tr>
<tr>
<td>0.03</td>
<td>6.25</td>
<td>50.0</td>
<td>1953.125</td>
</tr>
<tr>
<td>0.04</td>
<td>7.0</td>
<td>50.0</td>
<td>2450.0</td>
</tr>
<tr>
<td>0.05</td>
<td>6.75</td>
<td>50.0</td>
<td>2278.125</td>
</tr>
<tr>
<td>0.06</td>
<td>6.5</td>
<td>50.0</td>
<td>2112.5</td>
</tr>
<tr>
<td>0.07</td>
<td>5.5</td>
<td>50.0</td>
<td>1512.5</td>
</tr>
<tr>
<td>0.08</td>
<td>4.5</td>
<td>50.0</td>
<td>1012.5</td>
</tr>
<tr>
<td>0.09</td>
<td>3.0</td>
<td>50.0</td>
<td>450.0</td>
</tr>
<tr>
<td>0.10</td>
<td>1.0</td>
<td>150.0</td>
<td>150.0</td>
</tr>
<tr>
<td>0.11</td>
<td>0.0</td>
<td>-</td>
<td>0.00</td>
</tr>
</tbody>
</table>

\[
\sum k \delta^2 = 13381.25
\]

\[
\therefore \text{Energy absorption constant} = \sum k \delta^2 \, dt = 13381.25 \times 0.01
\]

\[
= 133.81 \text{ kg mm sec.}
\]
Table 5.6 ENERGY ABSORPTION CONSTANT IN BLAST LOADING

<table>
<thead>
<tr>
<th>Charge in grams</th>
<th>Energy Absorption in kg mm sec</th>
<th>Ferrocement</th>
<th>RCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>133.81</td>
<td>209.54</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>170.93</td>
<td>255.9</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>551.53</td>
<td>489.3</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>1057.92</td>
<td>795.53</td>
<td></td>
</tr>
</tbody>
</table>
FIG. 520 ENERGY ABSORPTION IN BLAST

<table>
<thead>
<tr>
<th>CHARGE IN CMS</th>
<th>R.C.C</th>
<th>FERROCEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ENERGY ABSORPTION IN KGM SEC

600  800  600  1200

200  400  600  800  1200
Table 5.7 IMPACT TEST RESULTS

1. Single Impact

<table>
<thead>
<tr>
<th>Weight Dropped (kg)</th>
<th>Height of drop (cm)</th>
<th>Impact energy (kg cm)</th>
<th>Maximum Deflections (mm)</th>
<th>Ferrocement</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.035</td>
<td>50</td>
<td>651.75</td>
<td>10.0</td>
<td>11.0</td>
<td></td>
</tr>
<tr>
<td>10.095</td>
<td>75</td>
<td>757.125</td>
<td>13.0</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>10.095</td>
<td>100</td>
<td>1009.5</td>
<td>20.0</td>
<td>32.4</td>
<td></td>
</tr>
<tr>
<td>10.095</td>
<td>125</td>
<td>1261.875</td>
<td>34.4</td>
<td>Failed</td>
<td></td>
</tr>
<tr>
<td>13.035</td>
<td>100</td>
<td>1303.5</td>
<td>40.0</td>
<td>--</td>
<td>---</td>
</tr>
<tr>
<td>13.035</td>
<td>125</td>
<td>1629.375</td>
<td>Failed</td>
<td>--</td>
<td>---</td>
</tr>
</tbody>
</table>
### Table 5.7 (Continued)

2. Repeated Impact

<table>
<thead>
<tr>
<th>Cumulative Impact Energy (kg cm)</th>
<th>Maximum Deflection (mm)</th>
<th>Permanent Set (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC</td>
<td>RC</td>
</tr>
<tr>
<td>757.125</td>
<td>13.0</td>
<td>24.0</td>
</tr>
<tr>
<td>1514.25</td>
<td>22.0</td>
<td>25.0</td>
</tr>
<tr>
<td>2271.375</td>
<td>20.0</td>
<td>25.0</td>
</tr>
<tr>
<td>3028.5</td>
<td>27.0</td>
<td>20.0</td>
</tr>
<tr>
<td>3785.625</td>
<td>31.0</td>
<td>22.0</td>
</tr>
<tr>
<td>4542.75</td>
<td>25.0</td>
<td>Failed</td>
</tr>
<tr>
<td>5299.875</td>
<td>Failed</td>
<td>---</td>
</tr>
</tbody>
</table>
FIG. 5.21 IMPACT RESPONSE OF FERROCEMENT SLAB
FIG. 5.22. IMPACT RESPONSE OF R.C.C. SLAB

APPLIED IMPACT ENERGY

1. 651.75 KG CM
2. 757.125 KG CM
3. 1009.5 KG CM
FIG. 5.24. PERMANENT SET FOR SINGLE IMPACT
FIG. 5.25. CRACKING DUE TO SINGLE IMPACT
FIG. 5.26. MAXIMUM RESPONSE FOR REPEATED IMPACT
Figure 5.27. Though the deformations are nearly the same for the two materials, the permanent deflection of ferrocement just before failure is much larger than that of concrete. The cumulative energy required to fail the specimen in the repeated impact test and the impact energy required for failure in single impact test have been indicated in Table 5.7. It is seen that ferrocement has approximately 50% more energy absorption both in single impact and repeated impact. The cracking and the failure pattern in repeated blast has been included in Figure 5.17. The failure in the two materials has a marked difference indicated by perforation in reinforced concrete and only scabbing and spalling in ferrocement. The wire mesh reinforcement in ferrocement has helped in keeping the material together even after failure.

5.3.3.1 Theoretical impact deflection

For the analytical computation of maximum dynamic deflection during impact, a single degree of freedom impact model is used with an axial stiffness equal to the bending stiffness of the slab. An impact formula is applied with the values of height and weight used in each test. The maximum dynamic deflection is computed from the impact formula as

\[
\delta_d = \frac{P}{k} \left( 1 + \frac{1}{4} \left( 1 + \frac{2h}{P} \frac{k}{P} \right) \right) \quad \text{...}(5.13)
\]

where

- \( \delta_d \) = dynamic deflection of the slab due to impact
- \( P \) = weight dropped
- \( h \) = height of drop
- \( k \) = static stiffness of the slab

The values thus calculated are shown along with observed experimental values in Table 5.8. It can be seen from the table that the computed values of maximum impact response in terms of dynamic deflection correlate reasonably well with the experimental results.
FIG. 5.27. PERMANENT SET FOR REPEATED IMPACT
Table 5.8 IMPACT RESPONSE OF SDOF SYSTEM

<table>
<thead>
<tr>
<th>Weight dropped (kg)</th>
<th>Height of drop (cm)</th>
<th>Stiffness of slab (kg/mm)</th>
<th>Max. dynamic Deflection (mm)</th>
<th>Observed Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrocement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.035</td>
<td>50</td>
<td>50.0</td>
<td>16.4</td>
<td>10.0</td>
</tr>
<tr>
<td>10.095</td>
<td>75</td>
<td>50.0</td>
<td>17.5</td>
<td>12.5</td>
</tr>
<tr>
<td>10.095</td>
<td>100</td>
<td>37.5</td>
<td>23.5</td>
<td>20.0</td>
</tr>
<tr>
<td>10.095</td>
<td>125</td>
<td>20.0</td>
<td>36.0</td>
<td>31.5</td>
</tr>
<tr>
<td>13.035</td>
<td>100</td>
<td>15.9</td>
<td>41.2</td>
<td>40.0</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.035</td>
<td>50</td>
<td>50.0</td>
<td>16.4</td>
<td>11.0</td>
</tr>
<tr>
<td>10.095</td>
<td>75</td>
<td>33.33</td>
<td>21.7</td>
<td>24.0</td>
</tr>
<tr>
<td>10.095</td>
<td>100</td>
<td>16.0</td>
<td>36.1</td>
<td>32.0</td>
</tr>
</tbody>
</table>
5.3.3.2 Energy absorption in impact

As described in the section 5.3.2.2, the energy absorption constant is worked out in order to compare the responses of the two types of slabs. The values of the energy absorption constant for different impacts are tabulated against the input impact energy in each case in Table 5.9 and are also shown in Figure 5.28. The energy absorption calculated from the response history of impact gives 25% higher value for concrete. This can be explained by the fact that the stiffness of the ferrocement is higher than concrete initially which reduces and becomes nearly equal to the concrete value after cracking and when failure is approached.

From the plotted values of energy absorption constant for ferrocement with respect to input impact energy (Figure 5.29), an empirical quadratic relation has been arrived between the two quantities as

\[ u_2 = 2.077 x u_1 - 7.738 \times 10^4 u_1^2 \]  

...(5.14)

where \( u_2 \) = input impact energy and 
\( u_1 \) = energy absorption constant.

5.4 CONCLUSIONS

Based on the experiments carried out on the ferrocement and concrete slabs and the results obtained from the tests, the following conclusions are arrived at.

5.4.1 Energy absorption

From the results of the single impact test, it is established that the impact energy required to cause failure of ferrocement is about 30% more than that of concrete. Similarly in the repeated impact test, it is found that the total cumulative energy up to failure is approximately
Table 5.9 ENERGY ABSORPTION CONSTANT IN IMPACT

<table>
<thead>
<tr>
<th>S No</th>
<th>Weight dropped (kg)</th>
<th>Height of drop (cm)</th>
<th>Maximum Deflection (cm)</th>
<th>Input Energy (kgcm)</th>
<th>Energy Absorption (kgms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>13.035</td>
<td>50</td>
<td>1.0</td>
<td>664.79</td>
<td>340.31</td>
</tr>
<tr>
<td>2.</td>
<td>10.095</td>
<td>75</td>
<td>1.2</td>
<td>769.24</td>
<td>742.09</td>
</tr>
<tr>
<td>3.</td>
<td>10.095</td>
<td>100</td>
<td>2.0</td>
<td>1029.69</td>
<td>524.22</td>
</tr>
<tr>
<td>4.</td>
<td>10.095</td>
<td>125</td>
<td>3.15</td>
<td>1293.6</td>
<td>974.95</td>
</tr>
<tr>
<td>5.</td>
<td>13.035</td>
<td>100</td>
<td>4.0</td>
<td>1355.64</td>
<td>1565.9</td>
</tr>
</tbody>
</table>

Ferrocement

1. 13.035 50 1.0 664.79 340.31
2. 10.095 75 1.2 769.24 742.09
3. 10.095 100 2.0 1029.69 524.22
4. 10.095 125 3.15 1293.6 974.95
5. 13.035 100 4.0 1355.64 1565.9

Reinforced Concrete

1. 13.035 50 1.1 666.09 372.22
2. 10.095 75 2.4 781.35 975.29
3. 10.095 100 3.2 1041.8 662.7
FIG. 5.28, ENERGY ABSORPTION IN IMPACT
FIG. 5.29. RELATION BETWEEN INPUT ENERGY AND ENERGY ABSORPTION

\[ U_2 = 2.007 U_1 - 7.738 U_1^2 \]
20% more than that of concrete. However the energy absorption calculated, based on the response history of impact gives 25% higher value for concrete since the deflection at mid-span is influenced by local shear deformations. Ferrocement has 15% larger crack resistance than concrete as indicated by the number of cracks produced by the same impact in both the specimens.

From the single blast tests conducted on ferrocement and concrete slabs, the results indicate that Ferrocement has 32% more energy absorption than reinforced concrete. The ductility of ferrocement also found to be 40% higher than concrete as seen from the maximum dynamic deflections during single and repeated blasts. Based on the number of cracks produced due to blast loads, the higher crack resistance of ferrocement is confirmed.

5.4.2 Contact blast and impact

The results of the tests using the two types impulsive load viz. blast and impact indicate there are many similarities in the response of structures subjected to the two types of loadings. Even though it will not be possible to equate totally the characteristics of these loadings, it is possible, in certain aspects to replace contact blast by impact. The dynamic deflection history recorded for the two types of loadings are found to be similar. The variation of maximum deflection in relation to the input energy also is similar. Similar observations have been made for the variation of permanent set after loading. The crack pattern in the two load cases are seen to be nearly the same.

An empirical quadratic relation between the input impact energy and the energy absorption of ferrocement slab is proposed as

\[ u_2 = 2.077 \times u_1 - 7.738 \times 10^4 u_1^2 \]

...(5.14)

where

- \( u_2 \) = input impact energy in kgcm
- \( u_1 \) = energy absorption constant in kgmm sec.
The assumption of the slab acting as a single degree of freedom system in resisting impact and blast loads has proved to give sufficiently accurate results as far as the maximum response is concerned.