*IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*
*e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 15, Issue 2 Ver. IV (Mar. - Apr. 2018), PP 79-92*
*www.iosrjournals.org*

# Impact Resistance of Reinforced Concrete Beams Encased By Ferro cement

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**Abstract:** *Strengthening reinforced concrete beams by a thin layer of ferrocement gives favourable properties such as smaller crack spacing and width, greater toughness which increases their impact load capacity, excellent bond in contact surface, and superfluity of formwork.*
*The purpose of the experimental program in the present work is to show the effect of combination of conventional reinforced concrete beam encased by a thin layer of ferrocement.*
*In this work, the first part of the experimental program covers the effect of some variables that affect the application of ferrocement in strengthening of reinforced concrete beams that are subjected to impact loads. The effect of number of layers of wire mesh, thickness of ferrocement, shape of encasement, amount, fastening and distribution of skeletal steel, mortar strength and nature of bond between concrete and ferrocement are considered. In addition, two reinforced concrete beams were constructed with low compressive strength to investigate the behavior of ferrocement with more than one type of concrete mix subjected to impact load. 300 specimens and 1400 laboratory tests were needed to choose the nine parameters, that lead to study fourteen conditions through twenty rectangular reinforced concrete beams with dimension of 150x200x3000 mm. For example to study of the nature and effect of contact surface between the reinforced concrete beam and the skin of ferrocement, five micro beams were needed, the first beam with normal contact surface, the second with rough surface. Grease, polymer bonding agent and epoxy resin bonding agent were used for the other three beams. Testing thirty-five specimens led to choose the two most suitable conditions to study the full-scale beams according to the engineering requirement and economy.*
*From the load/ or deflection versus number of the blows relationship, the usefulness of ferrocement encasement to improve the impact load resistance of rectangular reinforced concrete beams was observed. The reinforced concrete beams encased by ferrocement elements developed an impact resistance, which is up to 8 times that of the bare reinforced concrete beams, and the strength is almost dependent on the detailing of ferrocement composite.*

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Date of Submission: 14-04-2018 Date of acceptance: 30-04-2018

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## I Introduction

Structure integrity is the important factor in design of multi-storey building, this is due to the initiation of progressive collapse caused by some abnormal loading such as dynamic loads, which are caused by wind, explosions, impact and other sources. Dynamic load may be defined as loads of which the magnitude, direction, or position vary rapidly with time, eventually results in the collapse of a whole building. For the new structure, experience has shown that the overall integrity of structure can be substantially enhanced by main changes in the detailing of the reinforcement. The methods that satisfy the integrity requirement for reducing the abnormal loads for new structures are strengthening the joints used between panels by using additional dies system and strengthening of exiting reinforced concrete member, with different techniques which give a great deal to offer in the improvement of the performance of the various constructions under their ultimate strength or abnormal loading. The effective resistance of any structure to impact is mainly dependant upon its ability to absorb energy and the more ductile target has a higher ability to absorb energy. The ductility ratio is defined as the ratio of the ultimate deflection ($\Delta_u$) to the deflection at yield ($\Delta_y$). For the purpose of design, the proper allowable value of the ductility ratio usually depends on the type and function of the structure, the amount of damage that can be tolerated and how many times the design load is expected to occur. The ductility ratio should not be less than or equal to (1) if no damage is to be allowed and would be taken about (3 to 5) for moderate damage which implies considerable yielding of steel and cracking of concrete, but no significant impairment of the resistance to fracture loading.

Ferrocement is very adequate to resist the impact, due to its higher ability of absorbing impact energy as compared with the conventional reinforced concrete.

The impact resistance increases as the ductility tensile strength and specific surface areas of the meshes are increased. The damage is localized at the impact zone and no spalling of large mortar fragments occurs. This was attributed to the fact that the multiple layers of mesh held the mortar fragments together and kept the integrity of the target. The steel reinforcement of higher content and/or higher specific surface has higher impact resistance. Also the steel content increases the impact resistance. Up to optimum content of mesh reinforcement gives the higher impact resistance. The methods of reducing the effect of abnormal loads for new structure include, strengthening the joints used between pre-cast panels, using additional dies system consisting of transverse, longitudinal, vertical and peripheral dies.

Strengthening of existing reinforced concrete member with different techniques has a great deal to offer for improvement in the performance of the various constructions under their ultimate strength or abnormal loading. The technique of adding extra reinforcement is widely used, for tension as well as for compression zones in the flexural members, also for axially loaded members. There are many techniques for adding extra reinforcement, fixing of steel plates procedure can be carried out while the structures are in use and it can be used for flexure and shear strengthening, bolting is another technique to fix the additional reinforcement, the additional concrete overlying the old concrete with or without additional and/or transverse steel bars, external post-tensioning by means of high-strength strands or bars is used and using special strengthening form.

In order to overcome the limitations of traditional strengthening methods, using a thin layer of ferrocement gives favourable properties such as smaller crack spacing and width, greater toughness which increases its impact load capacity, excellent bond in contact surface, and superfluity of formwork. Other advantages of this method are that the shrinkage of the ferrocement is neutralized by the wire mesh, and that the wire mesh acts as a shear reinforcement without connecting it to reinforced concrete beam.

There has been very little research on the combined effect of conventional reinforced concrete beams that are encased with a thin layer of ferrocement on the impact resistance of the concrete. The present research deals with the ability of a thin layer of ferrocement encased rectangular reinforced concrete beams that are subjected to the impact load to enhance the ductility and impact resistance. The experimental program covers the effect of variables that affect the application of ferrocement. Hence, the present investigation is concerned with the effect of number of layers of wire mesh, effect of thickness of ferrocement element, effect of skeletal steel and its distribution, effect of mortar strength, effect of shape of encasement, effect of fastening the skeletal steel, effect of the nature of contact surface between reinforced concrete beam and ferrocement and effect of ferrocement strengthening on various concrete strength.

## II Experimental Work:

The first part of the experimental program covers the effect of some variables that affect the application of ferrocement in strengthening of reinforced concrete beams that are subjected to impact loads. The effect of number of layers of wire mesh, thickness of ferrocement, shape of encasement, amount, fastening and distribution of skeletal steel, mortar strength and nature of bond between concrete and ferrocement are considered.

In addition, two reinforced concrete beams were constructed with low compressive strength in order to investigate the behaviour of ferrocement with more than one type of concrete mix and subjected to impact loads. 300 specimens and 1400 laboratory tests were carried out to choose the upper nine parameters, that led to study fourteen conditions before construction of the twenty rectangular reinforced concrete beams. For example to test the nature and effect of contact surface between the reinforced concrete beam and the skin of ferrocement, five micro beams were required, the first beam with normal contact surface, the second with rough surface, grease, polymer bonding agent and epoxy resin bonding agent for the other three beams. Testing of thirty-five specimens led to choosing two conditions which were more suitable to study with full-scale beams according to the engineering requirements and economy. They are the normal and rough surface. Hence, for any chosen parameter many micro samples were required to choose the best beams encasement.

## III Materials

1. Cement: The cement used was ordinary Portland cement having the chemical composition and physical properties as given in Table (1).
2. Fine aggregate: Natural sand was used, the grading is given in the Table (2).
3. Coarse aggregate: Natural aggregate with (4.75-19mm) nominal size was use, the grading is given in the Table (3).

**Tables (1) Chemical composition and physical properties of the ordinary Portland cement used during the present work**

| No. | Chemical Component | Projects cement % | IQS 5 limits |
|---|---|---|---|
| 1 | CaO | 61.8 | |
| 2 | $SiO_2$ | 22.0 | |
| 3 | $Al_2O_3$ | 5.04 | |
| 4 | $Fe_2O_3$ | 3.16 | |
| 5 | $SO_3$ | 2.64 | 2.8* |
| 6 | MgO | 2.97 | 5.0* |
| 7 | Loss on | 1.20 | 4.0* |
| 8 | Insoluble residue | 0.60 | 1.5* |
| 9 | L.S.F | 0.86 | 1.02-0.66 |
| **No.** | **Physical Test** | **Results** | **IQS 5 limits** |
| 1 | Fineness | 335 $m^2$/kg | 230 $m^2$/kg ** |
| 2 | Initial setting time | 2:15 (hrs : min) | 45 min** |
| 3 | Final setting time | 3:30 (hrs : min) | 10 hrs** |
| 4 | Comp. strength (3 day) | 186 kg/$cm^2$ | 150 kg/$cm^2$** |
| 5 | Comp. strength (7 day) | 281 kg/$cm^2$ | 230 kg/$cm^2$** |
| 6 | Soundness | 0.2 % | 0.8%* |

**Table (2) Grading of fine aggregate used in the present work**

| Sieve size ( mm) | Percent passing | |
|---|---|---|
| | *Passing %* | *IQS 45* |
| 10.0 | 100 | 100 |
| 4.75 | 100 | 90-100 |
| 2.36 | 95 | 75-100 |
| 1.18 | 75 | 55-90 |
| 0.60 | 48 | 35-59 |
| 0.30 | 18 | 8-30 |
| 0.15 | 5 | 0-10 |
| 0.075 | 3.5 | 5 Maximum |

**Table (3) Grading of coarse aggregate used in the present work**

| Sieve size ( mm) | Percent passing | |
|---|---|---|
| | *passing %* | *IQS 45* |
| 37.5 | 100 | 100 |
| 20 | 100 | 95-100 |
| 10 | 35 | 30-60 |
| 5 | 6 | 0-10 |
| 0.075 | 0 | 3 Maximum |

## IV Steel Reinforcements

Deformed steel bars with diameters of 9.9 mm as well as plain steel bars with diameter of 5 mm were used in the present work. These bars were tested in tension according to ASTM A370-87 a. Woven hexagonal wire mesh was used, the average diameter was 0.7 mm. The mechanical properties of wire mesh, skeletal reinforcement and deformed bars are given in Table (4). A chemical test was carried out on a sample taken from wire mesh to determine the chemical composition. The test results indicate that the main material of the wire mesh is iron with some ratio of metallic material as given in Table (5).

**Table (4) Properties of wire mesh and steel bar reinforcement**

| Type of reinforcement | Dia. mm | Yield stress ($f_y$) N/$mm^2$ | Ultimate strength ($f_u$) N/$mm^2$ | Modulus of elasticity ($E_s$) N/$mm^2$ |
|---|---|---|---|---|
| Wire mesh | 0.7 | 310 | 520 | 67000 |
| Skeletal | 5 | 490 | 582 | 199810 |
| Longitudinal | 9.9 | 370 | 560 | 194700 |

**Table (5) Chemical properties of wire mesh**

| Fe % | Cr % | Cu % | Mn % | Ni % | C % | S% | Si % |
|---|---|---|---|---|---|---|---|
| 99.4429 | 0.0090 | 0.0450 | 0.3850 | 0.0360 | 0.0536 | 0.0187 | 0.0098 |

**Mix Design:**

For reinforced concrete beams two different concrete mixes were used to give high and normal strength of concrete, the first was 0.4w/c 1:1.2:2.6 and the second was 0.6w/c 1:1.5:3, with slump of 80 mm for the first mix and collapse for the second.

For ferrocement, three different mortar mixes, cement/sand ratio, were used to give different strengths of mortar, 1:2, 1:3 and 1:5, with w/c = 0.6 for all mixes.

**Mixing Procedure**

The mixing of concrete and mortar was carried out in a rotary pan type mixer of 0. 2 $m^3$ capacity. In all the mixes of concrete the aggregates and cement were first mixed dry for about 60 seconds and after the addition of water, for further 120 seconds.

After mixing, the concrete was poured into lightly oiled steel moulds in three layers and well compacted by a table vibrator for about 20 seconds for each layer to give adequate compaction. The specimens were then covered with polythene sheets supported on trestles and lifted undistributed until the moulds were stripped after (24 hours).

With each beam the following specimens were cast to determine the properties for the hardened concrete.

1. Three 152×152×152 mm cubes for compressive strength ($f_{cu}$).
2. Three 152×305 mm cylinders for the compressive strength ( $f_c'$ ).
3. Three 100 × 100 ×500 mm prisms for modulus of rupture ($f_r$).
   The same procedure was used for mixing the mortar. Each beam encasement included the following specimens of hardened mortar [31].
4. Three 75 × 150 mm cylinders for compressive strength ( $f_{cf}'$ ).
5. Three 50×50×50 mm cube for compressive strength ( $f_{cuf}'$ ).
6. Three 40×40×160 mm prisms for modulus of rupture ($f_{rf}$).
7. Three 8 shape for direct tension ( $f_{tf}'$ ).

For reinforced concrete beams, two different concrete mixes were used to give high and normal strength of concrete, the first mix was 1:1.2:2.6 with w/c = 0.4 and the second mix was 1:1.5:3 with w/c = 0.6 and slump of 80 mm for the first mix and collapse for the second.

For the ferrocement, three different mortar mixes, 1:2 , 1:3 and 1:5, and w/c = 0.6 for the three mixes to give different strengths of mortar, were adopted.

**Reinforced Beam Mould and Mixing Procedure:**

The mixing of concrete and mortar was carried out in a rotary pan type mixer of 0. 2 $m^3$ capacity. In all the mixes of concrete the aggregates and cement were first mixed dry for about 60 seconds and for further 120 seconds after the addition of water.

Steel mould with inner dimensions (150mm width, 200mm height and 3000mm length) was prepared for casting all the 20 beams. After the steel moulds were cleaned and lightly oiled, the previously prepared reinforcement steel were placed inside the mould and justify the concrete cover by multi spacers. Then the concrete was poured and vibrated using table vibrator. The top surface was then smoothed and covered with polythene sheets. After 24 hours the mould and control specimens were demolded and cured for 28 days. With each beam the following specimens were cast to determine the properties for the hardened concrete; three 150mm cubes for compressive strength (*fcu*), three 150×300 mm cylinders for the compressive strength (*f'c*), and three 100×100×500 mm prisms for modulus of rupture (*fr*).

The same procedure was used for mixing the mortar. Each beam encasement included the following specimens of hardened mortar; three 75×150 mm cylinders for compressive strength ($f_{cf}$), three 50mm cube for compressive strength ($f'_{cuf}$), three 40×40×160 mm prisms for modulus of rupture ($f_{rf}$) and three 8 shape for direct tension ($f''_{tf}$). The standard slump test was carried out according to ASTM C143 – 78.

**Quality Assurance:**

In addition to testing control specimens, ultrasonic test was also used to check similarity of two groups of concrete, the first group (B1 to B18) with ($f''_c$) of about 43 MPa and the second group (B19 to B20) with ($f'_c$) of about 25 MPa. Measuring by direct method was used, similar pulse velocities were recorded for any status of test for each group.

**Encasement of Reinforced Concrete Beams:**

The contact surface was first cleaned from dust and oil. The mesh and skeletal reinforcement were cut off to an appropriate size. The mesh layers were stretched, strengthened and bounded to the skeletal steel using mild steel binding wires. The meshes were oriented in the effective direction. The mortar was forced into the mesh reinforcement cage with trowels. Steel angles were held in position on each side, so that the forced mortar could be confined with required thickness. Control specimens were also made from the same mixes. Figure (1) shows beam geometry with its reinforcement and ferrocement encasement and Table (6) gives all details of beams considered in the present work.

**Instrumentation:**

Deflection Meter: Digital display reader was contacted to a rod with spiral resistive metal, to measure the large deflection of the beams until the failure with an accuracy of 1mm at mid span and 1/4 span of the beams.

Impact Load Reader: Load cell of 50 kN capacity having an accuracy of 0.1 kN with digital storage reader was used to record the peak of impact strike force. It was placed in the left support by means of mechanical bond.

Impactor: A drop-weight impact machine was used in the tests. The machine is capable of dropping a 13248 gm mass from a constant height of 5300 mm. It has a tilting support to avoid bearing failure at any support. Load cell mounted in the left support records the contact load between the falling mass and beam, see Figure (2).

**Table (6) Encasement detailing and compressive strength of concrete and ferrocement mortar**

| Beams | Encasement shape | Wire mesh layers | Ferrocement thickness (mm) | Skeletal steel (bars) | | | | MPa | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | top | bottom | left | right | $f_c'$ | $f_{cf}'$ |
| Beam "1" | - | - | - | - | - | - | - | 43.1 | - |
| Beam "2" | - | - | - | - | - | - | - | 42.9 | - |
| Beam "3" | - | 4 | 20 | - | - | - | - | 43.3 | 32.8 |
| Beam "4" | U | 2 | 20 | - | 2 | 2 | 2 | 42.8 | 31.7 |
| Beam "5" | U | 4 | 20 | - | 2 | 2 | 2 | 43.1 | 32.1 |
| Beam "6" | U | 6 | 20 | - | 2 | 2 | 2 | 43.1 | 33.6 |
| Beam "7" | O | 4 | 20 | 2 | 2 | 2 | 2 | 43.1 | 31.9 |
| Beam "8" | U | 2 | 30 | - | 2 | 2 | 2 | 42.6 | 34.1 |
| Beam "9" | U | 4 | 30 | - | 2 | 2 | 2 | 43.3 | 33.5 |
| Beam "10" | U | 6 | 30 | - | 2 | 2 | 2 | 43.1 | 32.7 |
| Beam "11" | O | 4 | 30 | 2 | 2 | 2 | 2 | 42.8 | 30.9 |
| Beam "12" | U | 4 | 20 | - | 3 | 2 | 2 | 43.3 | 33.2 |
| Beam "13" | U | 4 | 20 | - | 2 | 3 | 3 | 43.4 | 32.7 |
| Beam "14"* | U | 4 | 20 | - | 2 | 2 | 2 | 45 | 32.9 |
| Beam "15" | _ | 4 | 20 | - | 2 | - | - | 43.3 | 33.6 |
| Beam "16"** | U | 4 | 20 | - | 2 | 2 | 2 | 42.1 | 34.1 |
| Beam "17" | U | 4 | 20 | - | 2 | 2 | 2 | 47.3 | **45.3** |
| Beam "18" | U | 4 | 20 | - | 2 | 2 | 2 | 41.7 | **21.2** |
| Beam "19" | - | - | - | - | - | - | - | **25.6** | - |
| Beam "20" | U | 4 | 20 | - | 2 | 2 | 2 | **24.7** | 34.1 |

* Fastening the skeletal steel at each end by 20 mm steel plate.

** Roughing the contact surface between concrete and ferrocement by using rough cloth lining the steel mould with inner dimensions (150mm width, 200mm height and 3000mm length) before placing the concrete mix and remove it at remolding.


Beams (1, 2, 19) | Beam (3) | Beam (4) | Beams (5, 17, 18, 20)

Beam (6) | Beam (7) | Beam (8) | Beam (9)

Beam (10) | Beam (11) | Beam (12) | Beam (13)

Beam (14) | Beam (15) | Beam (16)

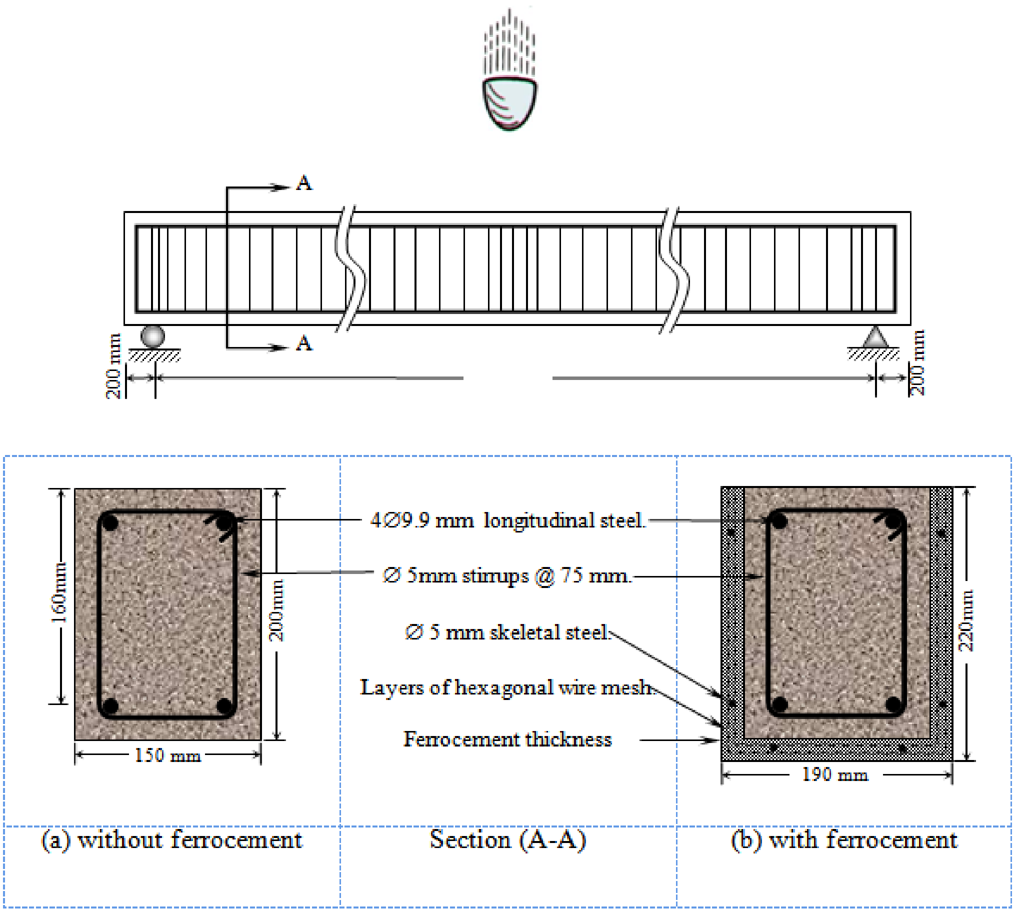


**Fig. (1) Beam geometry, and its reinforcement and ferrocement encasement.**

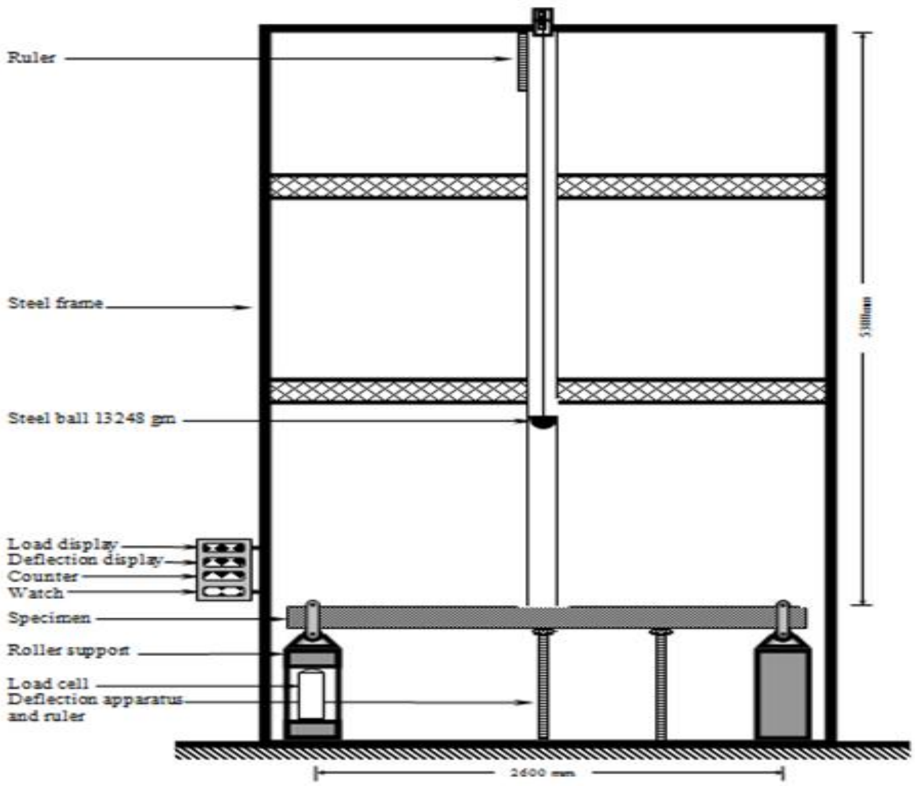


**Fig. (2) Impactor machine used in the present work**

## V Results:

As it was mentioned earlier that a sudden failure of reinforced concrete beams due to impact load has a great importance, a progressive collapse may occur by some abnormal loading, which causes local failure. This study shows the utility of ferrocement to increase the ability of reinforced concrete beams against impact load. The twenty beams that had been described were tested by the impact apparatus, after justification of the each beam at the supports of the impactor as a simply support beam, then the deflection meter, impact load indicator, counter of blows and timer were adjusted before testing. With a constant interval time of one minute the drop weight will fall from the constant head. The impact load was then recorded by the load display, permanent deflection by the deflection meter and the number of blows was recorded by the counter. The impact load was applied continuously every one minute with same last recording procedure until beams arrived collapsed. Table (7) gives the measured values of all beams.

It may be noted from the load/or deflection-number of blows that the utility of ferrocement encasement improves the impact load resistance of rectangular reinforced concrete beams and coating the reinforced concrete beams increases the impact resistance which is up to eight times that of the bare reinforced concrete beams, and the strength is almost dependent on the detailing of ferrocement composite. The test results of control specimens are given in Table (8).

**Effect of Number of Wire Mesh Layers**

Reinforced concrete beams encased by ferrocement elements behaved in a different manner from that of bare reinforced concrete beams. The wire mesh is an important factor in ferrocement element, it is usually expressed as a percentage of total composite material (volume fraction $V_f$) and may be noted that number of wire mesh layers has a significant effect on the impact resistance of reinforced concrete beams.

Reinforced concrete beam with 20 mm thickness of ferrocement and 2,4 and 6 layers has enhanced the resistance by 180, 380 and 270% respectively, under impact capacity of 10kN (which representative the capacity of the reference beam), but the total number of impact blows increases slowly according to the increment of the number of wire mesh layers at total collapse load of the beams.

A considerable load capacity was observed before failure, this is an essential improvement of reinforced concrete-ferrocement composite beams. For deflection, four layers are more adequate. For 30 mm thickness, the same behavior for impact resistance, and deflection with four layers.

**Effect of Ferrocement Element Thickness**

Thickness of ferrocement has significant effect on the resistance of impact load. For 2 layers the increase change from 178 to 306% for 20 and 30 mm ferrocement thickness respectively with respect to reference beam, so 367 to 420% the increase of 4 layers to same varying of thickness, 6 layer has similar increases from 267 to 367%. O shape has increment of 711 to 778%.

**Effect of Encasement Shape**

It was observed that the improvement of the impact resistance and ductility of the tested beams were controlled by encasement shape. Bottom flange of the ferrocement encasement with a thickness of 20 mm increased the impact resistance by 145%, while ferrocement encasement with U shape increased the impact resistance by 380 and 440% for 20 and 30 mm thickness respectively. It may also be stated that the impact resistance of reinforced concrete beams was affected significantly by the ferrocement encasement having O shape, i.e., the increase in impact resistance by 700 and 778% for 20 and 30 mm thickness respectively.

**Effect of Skeletal Steel and its Distribution**

Construction of ferrocement elements can be divided into four phases summarized with fabrication of skeletal framing system, fixing the mesh, plastering and curing. This means that the skeletal steel has a multiple role in construction besides serving as a reinforcement. The skeletal steel acts as a forming surface during the construction stage and withstands the stresses incidental to the casting process. For example using skeletal reinforcement with beam (5) raises the impact strength by 380% in comparison with 200% for the beam (3) with no skeletal reinforcement and using an extra amount of skeletal steel at bottom will enhance the impact strength and ductility more than the other faces.

**Fastening skeletal steel bar**

Fastening skeletal steel bars enhances properties of the composite beam at the beginning of the test, i.e., increases the stiffness of the beam, hence, the failure at the final stage is delayed and the deflection is reduced.

**Roughness of Contact Surface**

Composite action between skin and core components was fully obtained until the reduction in beam load capacity. Beyond that stage and up to failure, partial separation occurred. Beams(5) and (16) having similar behavior, this means that the bond stress between skin and core is not critical, due to the great bond length, so that the very rough beam surface has no importance and no special surface treatment is generally required.

**Mortar Compressive Strength**

There is an optimum compressive strength for the ferrocement mortar to increase the impact resistance and ductility of the encased rectangular reinforced beams. Using very high or very low compressive strength of ferrocement mortar will yield lower impact resistance and ductility.

## VI Conclusions

The reinforced concrete beams encased by a ferrocement skin have shown a superior performance in resisting impact load as compared with ordinary reinforced concrete beams in the following respects:

Impact strengths of the composite beams were up to 778% higher than those of the reference beams due to the additional strength contributed by the skin elements.

Composite action between the skin and core components was fully obtained until loss of the load capacity. Beyond that stage and up to failure, a partial separation occurred, therefore, if mechanical bond projected on the contact surface were used or at least if clearly roughness was provided to the contact surface of the forms, full composite action up to failure be obtained. Because of the large contact surface between the precast and in-situ components, no special surface treatment is generally required.

The number of layers of wire mesh has a significant effect on the strength of impact load. The magnitude of impact blows increases or is reduced clearly according to the increase in the number of wire mesh layers. There is an optimum number of wire mesh layers for the ferrocement to increase the impact resistance and ductility of the encased rectangular reinforced beams

The thickness of skin has significant effect on the strength of impact load. The increase in thickness can increase resistance especially at the beginning of failure.

The shape of encasement has a great effect. The magnitude of variation will increase from slow for just bottom to high increment in strength of impact for overall encasement.

Skeletal bars have important effect; their distribution will enhance impact properties also. The production of ferrocement with fastening skeletal bar will enhance properties of the product and increase the strength of members that are subjected to impact load. There is optimum mortar compressive strength to be more favourable with respect to failure. Ferrocement has great influence on strengthening reinforced concrete with wide range of ultimate concrete strength.

**Table(7) Deflection-Number of Blows for the beams considered in the present investigation**

| Blows | Beam "1" | | Beam "2" | | Beam "3" | | Beam "4" | |
|---|---|---|---|---|---|---|---|---|
| | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm |
| 1 | 11.2 | 1 | 11 | 1 | 11 | 0 | 11.2 | 0 |
| 5 | 11 | 2 | 11.2 | 2 | 11.2 | 2 | 11 | 1 |
| 10 | 11 | 5 | 11.6 | 4 | 11 | 4 | 11 | 1 |
| 15 | 11 | 12 | 11.2 | 11 | 10.6 | 5 | 11 | 1 |
| 20 | 7 | 33 | 7.2 | 34 | 10.8 | 6 | 10.4 | 2 |
| 25 | 4.2 | 60 | 4.4 | 57 | 10.8 | 7 | 10.2 | 3 |
| 30 | 2.4 | 246 | 2.8 | 242 | 10.6 | 8 | 10.2 | 4 |
| 35 | 1.4 | | 1.4 | | 10.4 | 11 | 9.6 | 6 |
| 40 | | | | | 7.2 | 41 | 8.6 | 7 |
| 45 | | | | | 6.4 | 80 | 8.4 | 9 |
| 50 | | | | | 5 | 168 | 8.2 | 21 |
| 55 | | | | | 4.8 | 254 | 8.2 | 33 |
| 60 | | | | | 2.8 | 474 | 8 | 55 |
| 65 | | | | | 1.4 | | 6.6 | 75 |
| 70 | | | | | | | 6.2 | 131 |
| 75 | | | | | | | 4 | 245 |
| 80 | | | | | | | 2.6 | 435 |
| 85 | | | | | | | 2.4 | 575 |
| 90 | | | | | | | | |
| 95 | | | | | | | | |
| 100 | | | | | | | | |
| 105 | | | | | | | | |
| 110 | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 115 | | | | | | | | |
| 120 | | | | | | | | |
| 125 | | | | | | | | |
| 130 | | | | | | | | |
| 135 | | | | | | | | |
| 140 | | | | | | | | |
| 145 | | | | | | | | |
| 150 | | | | | | | | |
| 155 | | | | | | | | |
| 160 | | | | | | | | |
| 165 | | | | | | | | |
| 170 | | | | | | | | |
| 175 | | | | | | | | |
| 180 | | | | | | | | |
| 185 | | | | | | | | |
| 190 | | | | | | | | |
| 195 | | | | | | | | |
| 200 | | | | | | | | |
| 205 | | | | | | | | |
| 210 | | | | | | | | |
| 215 | | | | | | | | |
| Failure | 35 | | 35 | | 64 | | 87 | |

**Table (7) Cont.**

| Blows | **Beam "5"** | | **Beam "6"** | | **Beam "7"** | | **Beam "8"** | |
|---|---|---|---|---|---|---|---|---|
| | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm |
| 1 | 11.8 | 0 | 12.4 | 0 | 12.2 | 0 | 12 | 0 |
| 5 | 11.8 | 1 | 12.2 | 1 | 11.8 | 0 | 11.6 | 0 |
| 10 | 11.6 | 1 | 11.2 | 1 | 11.6 | 1 | 10.8 | 0 |
| 15 | 11.4 | 2 | 10.4 | 2 | 11.4 | 1 | 10.8 | 0 |
| 20 | 11.4 | 3 | 10.6 | 2 | 11.4 | 1 | 10.8 | 1 |
| 25 | 11.4 | 5 | 10.8 | 2 | 11.4 | 1 | 10.8 | 2 |
| 30 | 11.6 | 5 | 11.2 | 3 | 10.6 | 1 | 10.8 | 3 |
| 35 | 11.4 | 6 | 10.8 | 6 | 10.6 | 1 | 10.6 | 6 |
| 40 | 11.2 | 6 | 10.6 | 8 | 10.6 | 1 | 10.4 | 8 |
| 45 | 11.2 | 7 | 10.4 | 9 | 11.2 | 1 | 10.4 | 11 |
| 50 | 11 | 7 | 9.8 | 10 | 11.2 | 1 | 10.4 | 18 |
| 55 | 11.2 | 12 | 8.4 | 16 | 10.8 | 1 | 9.6 | 29 |
| 60 | 11 | 15 | 7.6 | 36 | 10.8 | 1 | 9 | 39 |
| 65 | 10.2 | 19 | 7 | 73 | 11 | 1 | 7 | 74 |
| 70 | 9.6 | 31 | 6.4 | 132 | 10.8 | 1 | 6.8 | 124 |
| 75 | 7.6 | 52 | 5.6 | 174 | 10.4 | 1 | 4 | 214 |
| 80 | 4 | 143 | 4.4 | 269 | 10.4 | 1 | 3 | 364 |
| 85 | 2.6 | 300 | 3.4 | 412 | 10.6 | 1 | 2.8 | 534 |
| 90 | 2.2 | 695 | 3 | 520 | 10.2 | 1 | 2.2 | 694 |
| 95 | | | | | 10.4 | 1 | | |
| 100 | | | | | 10.6 | 1 | | |
| 105 | | | | | 10.2 | 1 | | |
| 110 | | | | | 10.4 | 1 | | |
| 115 | | | | | 10.8 | 1 | | |
| 120 | | | | | 10.2 | 2 | | |
| 125 | | | | | 10.6 | 2 | | |
| 130 | | | | | 9.4 | 3 | | |
| 135 | | | | | 9.4 | 5 | | |
| 140 | | | | | 8.4 | 15 | | |
| 145 | | | | | 7.8 | 25 | | |
| 150 | | | | | 6.6 | 43 | | |
| 155 | | | | | 6 | 70 | | |
| 160 | | | | | 4.6 | 115 | | |
| 165 | | | | | 4.6 | 189 | | |
| 170 | | | | | 4.4 | 297 | | |
| 175 | | | | | 4.2 | 355 | | |
| 180 | | | | | 4 | 395 | | |
| 185 | | | | | 3.8 | 495 | | |
| 190 | | | | | 3.6 | 585 | | |
| 195 | | | | | 2.8 | 682 | | |
| 200 | | | | | | | | |
| 205 | | | | | | | | |
| 210 | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 215 | | | | | | | | |
| Failure | 90 | | 93 | | 199 | | 94 | |

**Table (7) Cont.**

| Blows | Beam "9" | | Beam "10" | | Beam "11" | | Beam "12" | |
|---|---|---|---|---|---|---|---|---|
| | Load kN | Def. mm | Load KN | Def. mm | Load kN | Def. mm | Load kN | Def. mm |
| 1 | 12 | 0 | 12.2 | 0 | 12.2 | 0 | 12.2 | 0 |
| 5 | 11.2 | 0 | 12 | 0 | 12.2 | 0 | 12.2 | 0 |
| 10 | 11.4 | 0 | 11.6 | 0 | 11.6 | 1 | 11.6 | 0 |
| 15 | 11.2 | 0 | 11.6 | 0 | 11.4 | 1 | 11.6 | 1 |
| 20 | 11.2 | 0 | 11.4 | 1 | 11.4 | 1 | 10.8 | 1 |
| 25 | 11.2 | 1 | 11.4 | 1 | 11.4 | 1 | 11.2 | 1 |
| 30 | 11.2 | 1 | 11.2 | 2 | 10.6 | 1 | 11.4 | 3 |
| 35 | 11.2 | 1 | 11.2 | 4 | 10.6 | 1 | 11.4 | 5 |
| 40 | 11 | 1 | 11.2 | 6 | 10.6 | 1 | 11.2 | 7 |
| 45 | 11 | 1 | 11.2 | 9 | 11.2 | 1 | 11.2 | 7 |
| 50 | 10.6 | 2 | 10.8 | 20 | 11.2 | 1 | 10.8 | 10 |
| 55 | 10.4 | 4 | 10.6 | 30 | 10.8 | 1 | 10.8 | 11 |
| 60 | 10.4 | 14 | 10.6 | 56 | 10.8 | 1 | 10.4 | 13 |
| 65 | 10.2 | 14 | 10 | 99 | 11 | 1 | 11 | 15 |
| 70 | 10.2 | 23 | 9.6 | 162 | 10.8 | 1 | 8.4 | 26 |
| 75 | 10 | 50 | 6.6 | 254 | 10.4 | 1 | 8.2 | 46 |
| 80 | 4.6 | 179 | 6 | 350 | 10.4 | 1 | 7.6 | 73 |
| 85 | 3.2 | 281 | 5.2 | 447 | 10.6 | 1 | 5.8 | 120 |
| 90 | 2.4 | 387 | 3.6 | 522 | 10.6 | 1 | 4.4 | 230 |
| 95 | 2.2 | 552 | 2.8 | 652 | 10.4 | 1 | 3.4 | 338 |
| 100 | | | 2.2 | 672 | 10.6 | 1 | 3 | 530 |
| 105 | | | | | 10.4 | 1 | 1.2 | 731 |
| 110 | | | | | 10.4 | 1 | | |
| 115 | | | | | 10.4 | 1 | | |
| 120 | | | | | 10.2 | 1 | | |
| 125 | | | | | 10.4 | 2 | | |
| 130 | | | | | 10.4 | 2 | | |
| 135 | | | | | 10.2 | 2 | | |
| 140 | | | | | 10 | 2 | | |
| 145 | | | | | 9.4 | 3 | | |
| 150 | | | | | 9 | 5 | | |
| 155 | | | | | 8.4 | 10 | | |
| 160 | | | | | 7.8 | 15 | | |
| 165 | | | | | 6.6 | 33 | | |
| 170 | | | | | 6 | 64 | | |
| 175 | | | | | 5 | 114 | | |
| 180 | | | | | 4.6 | 190 | | |
| 185 | | | | | 4.6 | 295 | | |
| 190 | | | | | 4.2 | 356 | | |
| 195 | | | | | 4 | 395 | | |
| 200 | | | | | 3.2 | 492 | | |
| 205 | | | | | 3 | 575 | | |
| 210 | | | | | 2.2 | 672 | | |
| 215 | | | | | | | | |
| Failure | 97 | | 101 | | 214 | | 106 | |

**Table (7) Cont.**

| Blows | Beam "13" | | Beam "14" | | Beam "15" | | Beam "16" | |
|---|---|---|---|---|---|---|---|---|
| | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm |
| 1 | 12 | 0 | 12.6 | 0 | 11.2 | 1 | 12.2 | 0 |
| 5 | 10.8 | 1 | 12.4 | 0 | 11 | 2 | 12 | 0 |
| 10 | 10.6 | 1 | 12.4 | 0 | 10.8 | 3 | 11.8 | 0 |
| 15 | 10.6 | 3 | 12 | 1 | 10.8 | 3 | 11.8 | 0 |
| 20 | 10.6 | 3 | 11.6 | 1 | 10.6 | 5 | 11.8 | 0 |
| 25 | 10.8 | 4 | 11.8 | 2 | 10 | 9 | 11.8 | 1 |
| 30 | 11 | 4 | 11.8 | 3 | 0.4 | 25 | 11.8 | 1 |
| 35 | 11 | 5 | 11.6 | 4 | 2.6 | 186 | 11.6 | 2 |
| 40 | 11.2 | 6 | 11.8 | 4 | 2.2 | 489 | 11.6 | 2 |
| 45 | 11.2 | 8 | 11.8 | 4 | 0.8 | 659 | 11.4 | 3 |
| 50 | 11.4 | 10 | 11.6 | 7 | | | 11.4 | 6 |
| 55 | 11.2 | 11 | 11 | 7 | | | 11.2 | 8 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 60 | 10.2 | 15 | 10.2 | 10 | | | 11.4 | 10 |
| 65 | 10.2 | 20 | 9.5 | 17 | | | 11.2 | 15 |
| 70 | 9.6 | 26 | 9 | 24 | | | 10.6 | 25 |
| 75 | 8.4 | 49 | 7.6 | 32 | | | 8.4 | 75 |
| 80 | 5.6 | 101 | 6.6 | 49 | | | 6.4 | 150 |
| 85 | 3.6 | 251 | 6.4 | 64 | | | 4.6 | 275 |
| 90 | 1.8 | 472 | 5.6 | 86 | | | 2.4 | 604 |
| 95 | 1.4 | 671 | 4.2 | 118 | | | | |
| 100 | | | 3.2 | 201 | | | | |
| 105 | | | 2.6 | 358 | | | | |
| 110 | | | 0.8 | 459 | | | | |
| 115 | | | 0.6 | 671 | | | | |
| 120 | | | | | | | | |
| 125 | | | | | | | | |
| 130 | | | | | | | | |
| 135 | | | | | | | | |
| 140 | | | | | | | | |
| 145 | | | | | | | | |
| 150 | | | | | | | | |
| 155 | | | | | | | | |
| 160 | | | | | | | | |
| 165 | | | | | | | | |
| 170 | | | | | | | | |
| 175 | | | | | | | | |
| 180 | | | | | | | | |
| 185 | | | | | | | | |
| 190 | | | | | | | | |
| 195 | | | | | | | | |
| 200 | | | | | | | | |
| 205 | | | | | | | | |
| 210 | | | | | | | | |
| 215 | | | | | | | | |
| Failure | 97 | | 118 | | 48 | | 90 | |

**Table (7) Cont.**

| Blows | Beam "17" | | Beam "18" | | Beam "19" | | Beam "20" | |
|---|---|---|---|---|---|---|---|---|
| | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm | Load kN | Def. mm |
| 1 | 11.8 | 0 | 10.8 | 1 | 10.4 | 1 | 11.2 | 0 |
| 5 | 11 | 2 | 11 | 2 | 10.4 | 1 | 11.2 | 1 |
| 10 | 10.6 | 4 | 10.4 | 2 | 10.2 | 11 | 10.6 | 1 |
| 15 | 10.6 | 4 | 10.4 | 8 | 9.6 | 13 | 10.6 | 1 |
| 20 | 10.8 | 5 | 10.4 | 8 | 9.2 | 31 | 11 | 2 |
| 25 | 10.8 | 5 | 11 | 8 | 6.6 | 86 | 10.8 | 2 |
| 30 | 10.6 | 6 | 11 | 10 | 3 | 236 | 10.6 | 3 |
| 35 | 10.4 | 8 | 11.2 | 10 | 1.2 | 636 | 10.4 | 3 |
| 40 | 10 | 10 | 11 | 11 | | | 9.8 | 4 |
| 45 | 9.4 | 16 | 10.4 | 21 | | | 9.8 | 5 |
| 50 | 8.6 | 30 | 8.8 | 28 | | | 9.4 | 5 |
| 55 | 6.6 | 60 | 7.4 | 45 | | | 9.4 | 7 |
| 60 | 4.2 | 157 | 6.2 | 70 | | | 9 | 16 |
| 65 | 2.8 | 310 | 5.6 | 96 | | | 8.2 | 29 |
| 70 | 2.2 | 547 | 5.6 | 138 | | | 5.4 | 83 |
| 75 | | | 5 | 226 | | | 3.4 | 187 |
| 80 | | | 4 | 296 | | | 2.2 | 417 |
| 85 | | | 3.4 | 396 | | | 1.6 | 517 |
| 90 | | | 3.4 | 476 | | | | |
| 95 | | | | | | | | |
| 100 | | | | | | | | |
| 105 | | | | | | | | |
| 110 | | | | | | | | |
| 115 | | | | | | | | |
| 120 | | | | | | | | |
| 125 | | | | | | | | |
| 130 | | | | | | | | |
| 135 | | | | | | | | |
| 140 | | | | | | | | |
| 145 | | | | | | | | |
| 150 | | | | | | | | |
| 155 | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 160 | | | | | | | | |
| 165 | | | | | | | | |
| 170 | | | | | | | | |
| 175 | | | | | | | | |
| 180 | | | | | | | | |
| 185 | | | | | | | | |
| 190 | | | | | | | | |
| 195 | | | | | | | | |
| 200 | | | | | | | | |
| 205 | | | | | | | | |
| 210 | | | | | | | | |
| 215 | | | | | | | | |
| Failure | 73 | | 94 | | 36 | | 90 | |

**Table (8) Results of control specimens N/mm$^2$**

| Beams | Concrete | | | Mortar | | | |
|---|---|---|---|---|---|---|---|
| | Cylinder 152×305 mm | Cube 152×152×152 mm | Prism 100×100×500 mm | Cylinder 75×150 mm | Cube 50×50×50 mm | Prism 40×160×160 mm | 8 shape |
| Beam "1" | 43.1 | 53.5 | 4.32 | NO ENCASMENT | | | |
| Beam "2" | 42.9 | 52.9 | 4.31 | | | | |
| Beam "3" | 43.3 | 53.7 | 4.31 | 32.8 | 40.0 | 4.17 | 2.44 |
| Beam "4" | 42.8 | 52.1 | 4.32 | 31.7 | 38.7 | 4.03 | 2.43 |
| Beam "5" | 43.1 | 53.2 | 4.21 | 32.1 | 39.2 | 3.99 | 2.23 |
| Beam "6" | 43.1 | 52.6 | 4.27 | 33.6 | 40.1 | 3.98 | 2.75 |
| Beam "7" | 43.1 | 53.3 | 4.18 | 31.9 | 39.7 | 4.33 | 2.36 |
| Beam "8" | 42.6 | 52.0 | 4.07 | 34.1 | 40.6 | 3.87 | 2.41 |
| Beam "9" | 43.3 | 52.8 | 4.41 | 33.5 | 40.9 | 3.77 | 2.32 |
| Beam "10" | 43.1 | 53.2 | 4.23 | 32.7 | 39.6 | 4.12 | 2.69 |
| Beam "11" | 42.8 | 52.1 | 4.01 | 30.9 | 38.7 | 4.23 | 2.41 |
| Beam "12" | 43.3 | 50.2 | 4.22 | 33.2 | 40.2 | 3.99 | 2.71 |
| Beam "13" | 43.4 | 52.9 | 4.38 | 32.7 | 39.2 | 3.89 | 2.62 |
| Beam "14" | 45 | 54.7 | 4.57 | 32.9 | 40.2 | 3.98 | 2.46 |
| Beam "15" | 43.3 | 53.3 | 4.33 | 33.6 | 40.5 | 4.31 | 2.4 |
| Beam "16" | 42.1 | 51.8 | 4.22 | 34.1 | 41.5 | 3.98 | 3.4 |
| Beam "17" | 47.3 | 56.8 | 4.32 | 45.3 | 60.1 | 5.44 | 2.74 |
| Beam "18" | 41.7 | 50.9 | 4.19 | 21.2 | 26.3 | 2.36 | 1.81 |
| Beam "19" | 25.6 | 31.2 | 2.61 | NO ENCASMENT | | | |
| Beam "20" | 24.7 | 29.2 | 2.58 | 34.1 | 39.7 | 4.22 | 2.46 |

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