BEHAVIOUR OF REINFORCED CONCRETE BEAMS STRENGTHENED IN SHEAR
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ABSTRACT
Non-engineered construction in rural areas of developing third world in recent years has gained attention of many agencies mainly due to the alarming damage to property and life caused by earthquakes. Ferrocement having excellent ductility may become one of the main structural materials for retrofitting and strengthening of modest span reinforced concrete beams in such construction, specially, in earthquake prone areas.

Shear mode of failure in beams is undesired mainly being a brittle failure. An attempt, therefore, has been made to explore the potentials of Ferrocement in transforming brittle mode to ductile mode, through an experimental study presented in this paper.

Test results of 4 beams in which shear spans were strengthened by providing a complete Ferrocement warp and equally spaced strips, with one and two layers of woven square mesh are presented and compared with reinforced beam having identical material and sectional properties. The beams were loaded up to service load, de-loaded and strengthened prior to test up to failure. The sections were designed for brittle shear-compression failure by keeping shear stirrups, which provided 3.5 to 4 times the shear capacity of concrete alone. The flexural reinforcement was kept as the minimum that is normally provided in expected non-engineered construction.

The strengthened beams showed a marked improvement in performances at service load, greatly improved ductility at ultimate with either a ductile shear failure or seemingly a transition from shear to flexure mode of failure.

Key words: ferrocement wrap; ferrocement strips; shear; strengthening; non-engineered construction.

INTRODUCTION
Reinforced concrete in one of the most abundantly used construction material not only in the developed world, but also in the remotest parts of the developing world. In the rural areas of the developing world, however, due to transference of expertise and technology know how, reinforced concrete poses threat due to its abuse rather than use, and majority of the houses are constructed in traditional manner using indigenously developed techniques preferably following simpler and economical procedures. Unfortunately such non-engineered construction is mostly prevalent in earthquake prone areas of the developing world e.g. Turkey, Pakistan, India and Iran. The rural population in the developing world have mostly to rely on local skill, material and technology. The transformation of non-engineered construction into an engineered one, therefore needs to be such that it could be sustained. The methodology should be simple in execution, offer better performance even when handled by less experienced workers, must involve materials, which are readily available, and yet durable, strong and economical. Ferrocement is one such

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material which could afford to offer answer to such a situation and hence the present study is part of a programme under taken at NED University where the potentials of Ferrocement are explored for its utilization in non-engineered construction, for improved performance in the event of an earthquake.

**LITERATURE REVIEW**

A 30 years record of major Turkish earthquake shows almost 0.2 million dwellings destroyed by earthquake [1], which is about 65% of the destruction caused by all other natural disasters. Dinar earthquake of 1995 and Kocoeli earthquake of 1999 have substantially increased the percentage.

Almost all post earthquake studies and damage assessment have led to the conclusion that a building should be designed and constructed such that in the event of the probable maximum earthquake intensity: the building should not suffer total or partial collapse; it should not suffer such irreparable damage which would require demolishing and rebuilding and in case it sustain such damage it could be repaired quickly and easily to bring it to its usual functioning [2].

Ferrocement over the years have gained respect in terms of its superior performance and versatility, and now is being used not only in housing industry but its potentials are being continuously explored for its use in retro-fitting and strengthening of damaged structural members [3,4]. Ductility requirements are the main feature of an efficient earthquake restraint design process, and Ferrocement being highly ductile material have led to its application in rehabilitation of houses damaged by earthquake and the effectiveness of its use has been reported by many researchers [5,6,7,8]. Taking the lead from its potential use in enhancing earthquake resisting abilities, 5 houses were built in Northern area of Pakistan, using indigenous materials and local skills utilizing Ferrocement bands to improve the earthquake resisting of such houses in 1990 [9]. The houses since then have performed remarkably well and have sustained low to moderate shocks effectively. The detail were simple to follow and execute by the local skilled workers, and materials were readily available from near by cities.

Reinforced concrete elements are designed to fail in a ductile manner by emphasizing on the detailing requirements due to the brittle nature of concrete. Shear failure are also classified as brittle and shear zones are therefore reinforced by provision of stirrups for transformation to ductile failure, however, a limit is imposed on the provision to avoid brittle shear-compression failure. In the event of an earthquake, however, the shear loads can exceed shear capacities, and damage in shear zones may lead to catastrophic failure of such members.

Many experimental studies has been conducted in recent years to strengthen flexure members by using various materials [10,11,12,13,14,15].

Andrew and Sharma [10 ] in an experimental study compared the flexural performance of reinforced concrete beams repaired with conventional method and Ferrocement. They [10] concluded that beams repaired with Ferrocement showed superior performance both at service and ultimate load. The flexural strength and ductility of beams repaired by Ferrocement was reported to be greater than the corresponding original beams and the beams repaired by conventional method.

Al-Farabi et al [11] while investigating the effectiveness of Fiberglass bonded plates for capacity enhancement, reported increased strength and reduced ductility. Premature failure by plate separation was also identified as a potential problem at the plate curtailment place.

Steel plates bonded by epoxy were used to repair shear cracked beams utilizing various forms of plate bonding by Basunbul et al [12]. The experimental investigation clearly demonstrated that the effectiveness of the repair primarily depends on how effectively the diagonal tension cracks in the shear-damaged beams were trapped. Flexural mode of failure was observed surpassing shear capacity for only those specimens where full encasement of the shear zone was carried,
while for all other forms of bonding the failure either occurred due to separation or ripping of steel plates. Enhanced ductility was, however, reported for all methods.

In a similar study where fiberglass plates were bonded instead of steel plates, Al-Sulaimani et al [13] reported almost similar results. The shear capacities for beams where full encasement of shear zone was carried, was enhanced to such an extent that the failure occurred by flexure, with enhanced ductility.

An experimental study in strengthening of reinforced concrete beams using Ferrocement laminates was conducted by Ong et al [14], where eight beams were strengthened with a 20 mm thick laminate attached on the tension face. Three different series with different methods of attachments including Ramset nails, Hilti bolts and epoxy resin adhesive were used. The performance of the strengthened beams were compared to the control beams with respect to cracking, deflection and ultimate strength. All the strengthened beams exhibited higher ultimate flexural capacity and greater stiffness. Use of epoxy resin adhesive and Ramset nails at closer spacing of shear connectors were able to ensure composite action. A decrease in the volume fraction of reinforcement of Ferrocement laminates from 3.25% to 2.36% resulted in a reduction of strength. The presence of the Ferrocement laminates had an inhibiting effect on the tensile crack, and the crack spacing and crack width were reduced after strengthening.

Paramasivam et al [15] reported tests on six damaged RC beam repaired by Ferrocement laminates. Repair of cracks was done by epoxy resin injection and the beams were then strengthened by Ferrocement laminates attached to the soffit by means of L-shaped bar connectors, to ensure composite action between the Ferrocement laminates and the in-situ concrete. The results showed that substantial improvement in the ultimate capacity and stiffness may be obtained, provided the shear connectors are adequately spaced and the cracks are well grouted.

Paramasivam [16] reported that a total of six T-beams were tested inverted and simply supported under static and cyclic loads applied at mid-span by Aurellado [17]. Except for control beam all beams were strengthened with Ferrocement laminates as encasements onto the beam web and soffit. Three methods of attachment were examined with bar shear connectors installed through web or through flanges of beams. This was compared with conventional methods of strengthening where additional “U” shaped stirrups were inserted through predrilled holes in the flange before bending the ends in to form closed links. The results showed that the beams were substantially strengthened and stiffened due to the provision of the Ferrocement laminates.

**OBJECTIVES AND SCOPE**

The objective of the study is to provide the rural population especially in earthquake prone areas, with a simple and easily applied technology to upgrade and strengthen non-engineered structural members. It has been observed that most of the time the rural learned in an effort to provide sufficient shear strength and a flexure mode of failure, fails to recognize the danger of over-reinforcing shear zones and thereby paving way to catastrophic failure.

The scope of the study was thus confined to study the effect of confining shear spans of such beams with Ferrocement, where shear stirrups provides 3.5 to 4 times the shear capacity of concrete alone. The main parameters of the study were confined to one and two layers of woven square mesh and application of Ferrocement by way of providing wraps in full shear span and equally spaced strips in shear span.

**EXPERIMENTAL PROGRAM**

In all, five beams were cast where beam A was the control specimen while B1, B2 and C1, C2 were the beams to be strengthened by way of providing Ferrocement strips and wraps with one or two layers of wire mesh respectively.
All beams having 100 mm width, 200 mm over all depth and 170 mm effective depth, were cast with same mix having proportion of 1:2:4 with a w/c ratio of 0.55. The overall length of all beams were kept as 915 mm whereas the simply supported span was 762 mm. The beams were reinforced with 2-12.7 mm dia. bars having yield strength of 445 N/mm$^2$ as main flexural reinforcement, and 2-6 mm dia. bars were used as hanger bars, shear stirrups consisted of 6 mm dia. bars spaced at 50 mm c/c. The yield strength of 6 mm dia. bars was 240 N/mm$^2$. Material strengths were obtained by testing control specimens in Material Testing Laboratory, NED University of Engineering and Technology, Karachi.

18 gauge woven square mesh with wire diameter of 0.9 mm and mesh opening of 4.6 mm was used for Ferrocement, where 1:2 cement-fine sand mortar with a w/c ratio of 0.45 was used for all strengthened beams. The yield strength of the single wire was found to be 229 N/mm$^2$. The average cylindrical crushing strength of concrete was found to be 22 N/mm$^2$. The average cube crushing strength of mortar using 50 mm x 50 mm x 50 mm cubes was found to be 25 N/mm$^2$, while the tensile strength was evaluated through briquette test and was found to be 3.5 N/mm$^2$.

**Testing of Specimen**

All specimens were loaded under third point loading using Forney Universal Loading Machine having a resolution of 0.025kN and capacity of 300 kN, at Material Testing Laboratory, NED University of Engineering and Technology, Karachi. One end of specimen rested on a roller arrangement allowing horizontal movement and the other on a simple support. All the beam specimen were tested under load control with monotonically prescribed incremental loads. At each incremental load of 10kN, deflections, crack pattern, crack width and surface strains were recorded.

Each specimen was loaded up to 70kN and de-loaded to represent a beam in service and than the prescribed strengthening method was applied, and reloaded to failure. The description of load sequence and method of strengthening is presented in Table 1. Plate 1 and Plate 2 shows the specimens of B and C series before application of 1:2 cement-sand mortar.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Load Applied</th>
<th>Method of Strengthening</th>
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<tbody>
<tr>
<td>A-i</td>
<td>Control specimen loaded from un-cracked state to P$_{70}$ and de-loaded.</td>
<td>N.A</td>
</tr>
<tr>
<td>A-ii</td>
<td>Loaded from cracked state up to failure</td>
<td>N.A</td>
</tr>
<tr>
<td>B1-i</td>
<td>Loaded from un-cracked, unstrengthened beam to P$_{70}$ and de-loaded</td>
<td>N.A</td>
</tr>
<tr>
<td>Specimen</td>
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| B1-ii    | Loaded from strengthened state up to failure | • After de-loading from $P_{70}$ i.e. as B1-i, 3-50 mm equally spaced strips in the shear span were chiseled from all around the beam up to outside of stirrups  
  • One layer of mesh strips cut to size, wrapped and impregnated with mortar  
  • Left for 14 days curing before testing to failure |
| B2-i     | Loaded from un-cracked un-strengthened beam to $P_{70}$ and de-loaded | N.A |
| B2-ii    | Loaded from strengthened state up to failure | • After de-loading from $P_{70}$ i.e. as B2-i, 3-50 mm equally spaced strips in the shear span were chiseled from all around the beam up to outside of stirrups.  
  • Two layers of mesh strips cut to size, wrapped and impregnated with mortar.  
  • Left for 14 days curing before testing to failure. |
| C1-i     | Loaded from un-cracked, un-strengthened beam to $P_{70}$ and de-loaded | N.A |
| C1-ii    | Loaded from strengthened state up to failure | • After de-loading from $P_{70}$ i.e. as C1-i beam, full shear span on both sides were chiseled from all around the beam up to outside of stirrups.  
  • One layer of mesh strip cut to size and wrapped all around and impregnated with mortar  
  • Left for 14 days causing be for testing to failure |
| C2-i     | Loaded from un-cracked un-strengthened beam to $P_{70}$ and de-loaded. | N.A |
### Table-1 Cont’d

<table>
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<tr>
<th>Specimen</th>
<th>Load Applied</th>
<th>Method of Strengthening</th>
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| C2-ii    | Loaded from un-cracked un-strengthened beam to $P_{70}$ and de-loaded. | • After de-loading from $P_{70}$ i.e. as C2-i, 3-50 mm equally spaced strips in the shear span were chiseled from all around the beam up to outside of stirrups.  
• Two layers of mesh strips cut to size, wrapped and impregnated with mortar.  
• Left for 14 days curing before testing to failure. |

$P_{70}$ = Estimated service load of 70 kN

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*Plate 1* - Detail of beam strengthened by ferrocement strips in shear span.

*Plate 2* - Detail of beam strengthened by ferrocement wraps in shear span.
TEST RESULTS

The load-deflection curves of second cycle of loading for control specimen and strengthened beams are presented in - Fig. 1.

Fig. 1- Measured load-deflection curves for control and strengthened specimen.

The state of strengthened specimens is presented in Plate 3 through Plate 6. Plate 3 shows the control specimens loaded to failure in a cracked state where failure occurred due to shear-compression failure. Specimen B2-ii representing beam strengthened with Ferrocement having two layers of wire mesh applied in equally spaced strips in the shear span is presented in Plate 4. Specimen C1-ii represent beam strengthened with complete wrap of one layer of wire mesh along full shear span, Plate 5, while C2-ii represents beam strengthened with complete wrap of two layers of wire mesh along full shear span as shown in Plate 6 receptively.

Plate 3 - Typical brittle shear-compression failure of controlled specimen A-ii.
The failure loads of the test specimen and their deflections at cracking load, service load and ultimate load along with the failure mode are presented in Table 2.
DISCUSSION OF RESULTS

At service stage the strengthened beams showed improved performance, as is evident from - Fig. 1 and column (3), column (4) of Table 2, where increased stiffness due to Ferrocement strips and wraps and relatively decreased deflection in comparison with control specimen is evident. Increased number of cracks with decrease in crack width was observed for strengthened specimen, however, no significant difference in pattern was noticed between the two methods of Ferrocement application.

The mode of failure as described in Table 2 is also evident from Plate 3 to Plate 6. The load that the test specimen could sustain theoretically in shear was calculated to be 119.5 kN, using ACI Code model without using capacity reduction and load factors.

The increase in shear capacity varied between 1.5% to 5.8% , the maximum being for C2-ii, where the specimen was wrapped with 2 layer of wire mesh. The increase in shear capacity, therefore, is not substantial, however, an evidence of transformation of brittle, shear-compression failure to ductile shear failure is evident from - Fig. 1 and Plate 6. Almost all the failures were shear failures, however, the presence of Ferrocement strips and wraps delayed the failure giving ample warning before failure, which is considered as the desired mode of failure by almost all codes. Greater number of cracks and sufficient ductility is apparent from - Fig. 1 and Plate 3 through Plate 6 of the strengthened beams. This is a significant result, which may allow beams that are over-reinforced in shear to fail in a ductile mode. In earthquake zones where larger moments had to be resisted by beam on small openings, the use of Ferrocement wrap may allow use of shear stirrups of capacity more than 4 times the capacity of the beam.

CONCLUSIONS

The following conclusions may be drawn from the present experimental study.
1. Confining concrete in the shear zone by Ferrocement have the potential of transforming brittle shear-compression failure to ductile shear failure.
2. Ferrocement wraps are more effective than Ferrocement strips.
3. The enhancement in load carrying capacity is not substantial, however, is present. In service range increased stiffness of strengthened beams reduces the crack width and deflections in comparison with the un-strengthened beam.
4. The method is simple to understand and apply, and, therefore, may be utilized in non-engineered rural construction and could achieve maximum results.

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