EXPANDED WIRE FABRIC PERMENANT FORMWORK FOR IMPROVING FLEXURAL BEHAVIOR OF REINFORCED CONCRETE BEAMS

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ABSTRACT. A new technique for using expanded wire fabric (EWF) as additional reinforcement and permanent formwork for reinforced concrete beams is proposed. Five beam specimens were experimentally tested, namely, an under reinforced control beam containing only conventional reinforcement and other four beams additionally reinforced with EWF for shear and flexure. The studied parameters included the orientation of EWF, the amount of longitudinal and transverse EWF, and the method of application of EWF. The results showed that the use of EWF led to an improvement in deflection and ductility of test beams. In addition, beams reinforced with EWF showed better crack control in comparison with the control beam having only conventional reinforcement. The orientation and method of application of EWF have a great effect on flexural behavior of beams. The beam reinforced with U shape EWF jacket and additional layer of EWF flexural reinforcement showed better properties compared with the other beams. Its load capacity was increased by 20%, strain reached the maximum of (0.014) and the crack widths were reduced by approximately 35% compared to the control beam with conventional reinforcement. A proposed formula was developed for predicting the effect of EWF on crack control. The results obtained by this formula were in good agreement with the experimental results.

Keywords: Expanded wire fabric, Crack control, Deflection, Ductility, Reinforcement orientation, Flexural behavior, Ferrocement.

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INTRODUCTION

The rapid increase in the cost of construction has forced engineers to look for economical and better methods for building and/or repair of distressed structures. Among the materials used for construction and repair, ferrocement is comparatively a promising approach. Ferrocement is constructed of hydraulic cement mortar reinforced with closely spaced layers of small wire diameter mesh, or wire fabric, made of metallic or any other suitable material [1]. Ferrocement possesses a high degree of toughness, ductility, durability, strength and crack resistance within a relatively small thickness (approximately 25 mm), [2]. Combining these advantages with the fact that steel stresses of more than 550 MPa can be tolerated without excessive cracking, indicates a material which is ideally suitable for rehabilitation and/or new construction [2]. Hussin and Zakaria [3] and Nedwell and Swamy [4] reported that by proper choice of reinforcement and method of production, ferrocement pools, houses and boats were more economical than reinforced concrete ones. In Egypt, it is believed that the use of ferrocement in the construction can be a competitive modern building material because of its low cost in comparison with conventional concrete. Therefore, it can be considered one of the ideal solutions for the housing problem [5].

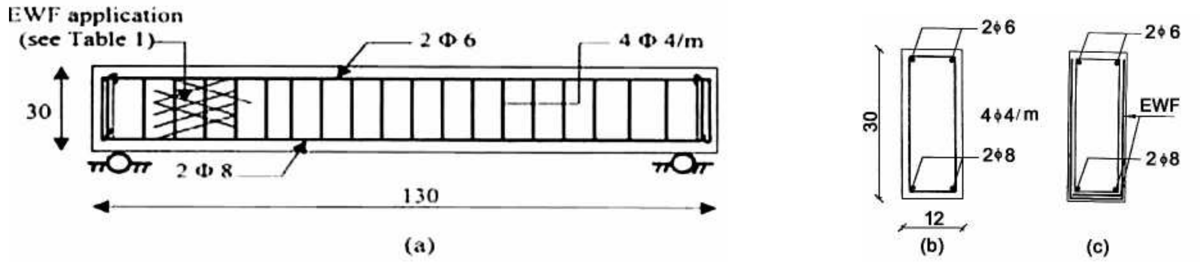
Recently, extensive research work has been carried out into ferrocement properties and applications [6 and 7]. Abdul Kadir et al [8] tested the flexural behavior of sixteen simply supported RC beams with ferrocement permanent formwork. The test results showed that such beams failed by flexure. The composite beam with shear connectors carried about 12% higher load and 10% reserved flexural strength and showed lower deflection when subjected to the same loads as compared to reinforced concrete beams without shear connectors. Lin and Perng [9] investigated the flexural behavior of beams with welded wire fabric (WWF) as shear reinforcement. The parameters studied in their research included concrete strength, shear span to depth ratio, amount of fly ash, amount of longitudinal reinforcement and amount of transverse reinforcement. It was found that beams with WWF shear reinforcement exhibit higher strength, better ductility and crack control than those with conventional shear reinforcement due to better confinement. In 1988, ACI Committee 549 [10] updated both of the guides for the design, construction and repair of ferrocement, and State-of-the-Art Report on Ferrocement. The main objective was to provide owners with a reference document to check the acceptability of a ferrocement alternative in a given application. However, since 1988 no update was issued to these documents [11].

The objective of this research is to study the use of expanded wire fabric (EWF) as a multipurpose material, as a formwork instead of the traditional wood formwork and as an additional reinforcement for reinforced concrete (RC) beams to improve flexural and shear behaviors of such beams. The results reported in this investigation are part of a wider research program study the potential application of EWF in RC beams. The studied parameters were the orientation of EWF, amount of longitudinal and transverse EWF, and the method of application of EWF. The behavior of the test beams was monitored by measuring deflections, crack widths, horizontal and shear strains for different load stages.

EXPERIMENTAL PROGRAM

Five beam specimens were cast in this study. The control beam was designed according to EC 2000 [12]. The reinforcement was chosen to approach the lower limit of an under-reinforced beam. This allowed the Expanded Wire Fabric (EWF) to be added to the other test beams without over-reinforcing such beams, which would lead to premature brittle failure of concrete in compression. The dimensions, reinforcement of the control beam and the combination of conventional and EWF reinforcement used in the other test beams are shown in Figures 1 and 2. The control beam was cast in the usual manner. A formwork of EWF of diameter 1 mm and diamond shape was used as additional shear and flexural reinforcement for the other four test specimens as shown in Table 1 and Figure 2. Then the fresh concrete was poured in the middle of the beams until mortar started to pass through the EWF openings. After that the external surfaces of the EWF were plastered using semi-dry mortar until the EWF was fully coated with mortar. The parameters investigated were amount of EWF for flexure and shear, EWF orientation and method of application.

All the specimens were tested under monotonic loading. A 50 ton Shimadzu universal testing machine with a computer controlled hydraulic servo system was adopted to apply loads. The load was spread into two point loads on the beams at a 1 mm/min rate of loading. Demec studs were glued to the sides of the test beams. Three groups were fixed on one side of each beam for the measurement of concrete surface strains and principal strains at various locations on the top compression and bottom tension surfaces of the beams. The measurements were carried out using a 100 mm demountable digital demec gauge. The deflections were measured using dial gauges (0.01 mm divisions) fixed on the bottom surfaces of the test beams. Crack widths were also observed and measured before yield. The load-deflection curve was plotted during test. Figure 3 shows a schematic diagram for a simply supported typical test beam with load position and demecs fixed at its side. It can be seen from Figure 3 that shear span/depth ratio of studied beams was kept constant (0.4/0.3).



+Figure 1 A typical studied beam specimen; (a) Sectional elevation for reinforcement details; (b) Cross section of control beam; (c) Cross section of Beams reinforced with EWF.
+(Dimensions are in cm, 1cm = 10 mm)

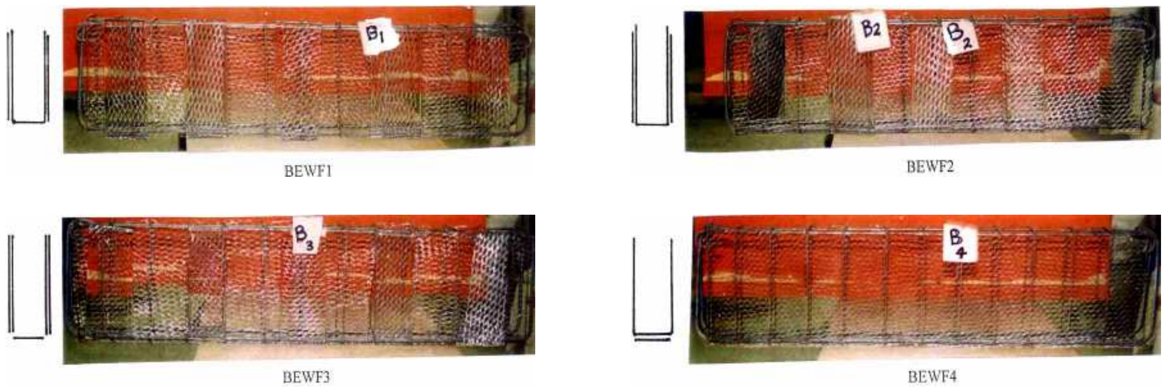


Figure 2 Photographs for using EWF as reinforcement and formwork for different beams.

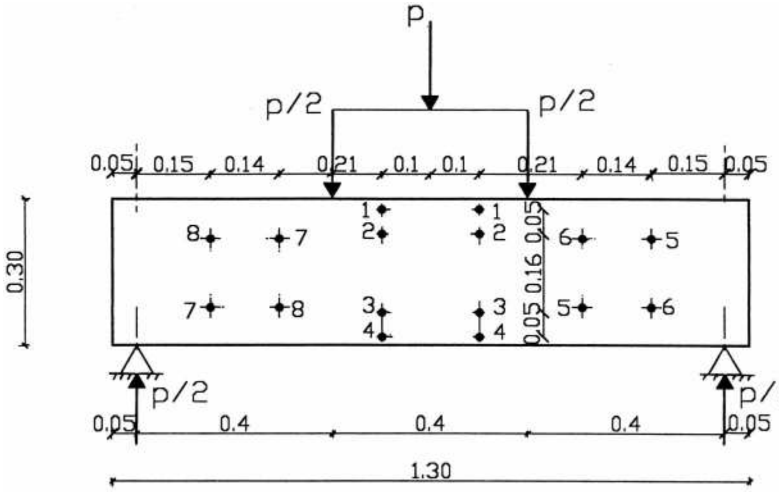
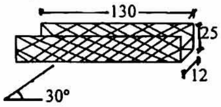
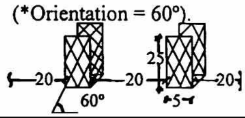
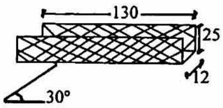
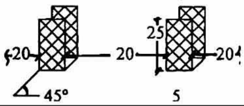
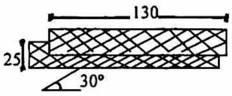
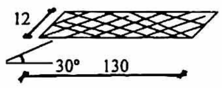
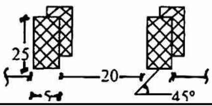
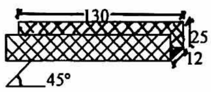
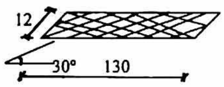


Figure 3 Loading arrangement and demec points for a typical test beam.

Table 1[+] Details of beams reinforced with Expanded Wire Fabric (EWF)

Specimen	TYPE AND ORIENTATION OF EWF REINFOREEMENT (SEE FIGURES 1 ADN 2)		
BEWF1	One Jacket of EWF (U shape, *Orientation = 30°). 	Wings of EWF (U shape) each of width equals 5 cm and spaced at 20 cm (*Orientation = 60°). 	----------
BEWF2	One Jacket of EWF (U shape, *Orientation = 30°). 	Wings of EWF (U shape) each of width equals 5 cm and spaced at 20 cm (*Orientation = 45°). 	----------
BEWF3	Two side strips of EWF for shear reinforcement, 25 x 130 cm each, *Orientation = 30°. 	One horizontal strip of EWF for flexure reinforcement at bottom of the beam, 12 x 130 cm, *Orientation = 30°. 	Vertical strips of EWF for shear reinforcement each of width equals 5 cm, 25 cm height and spaced at 20 cm (*Orientation = 45°). 
BEWF4	One Jacket of EWF (U shape, *Orientation = 45°). 	One horizontal strip of EWF for flexure reinforcement at bottom of the beam, 12 x 130 cm, *Orientation = 30°. 	---------

*Orientation angle is measured from the horizontal direction

[+](Dimensions are in cm, 1cm = 10 mm)

RESULTS AND DISCUSSION

General Behavior and Crack Pattern

The observed crack patterns till brittle shear failure for a typical test beam reinforced with EWF (BEWF1) are shown in Figure 4. The crack patterns developed similarly for all the beams reinforced with EWF. First cracking usually occurred at a higher load than in the control beam (see Figure 5). Initially, the cracks were vertical, as would be expected for flexural cracks, but later they would bend over in the shear regions. Crack widths of the beam specimens reinforced by EWF were generally smaller than that of beams reinforced by conventional reinforcement. After the control beam specimen reached its peak load, the concrete cover started to spall. Concrete cores of the beam specimens with EWF reinforcement remained more intact than those of specimens with conventional reinforcement after spalling of concrete cover due to the fact that the spaces of EWF were smaller and they provided better confinement.

Load-Deflection Relations

The load deflection relationships for the control beam B0 and the other beams reinforced with EWF are shown in Figure 5. Before yielding of the flexural reinforcement, the load-deflection curves were quite linear. It can be seen from the figure that the use of EWF as a formwork and additional reinforcement led to an increase in beam’s capacity by approximately 5-20% without the use of wooden formwork. It is worth mentioning that the increase in beam’s capacity to 20% was achieved by using one layer only of EWF for reinforcement.

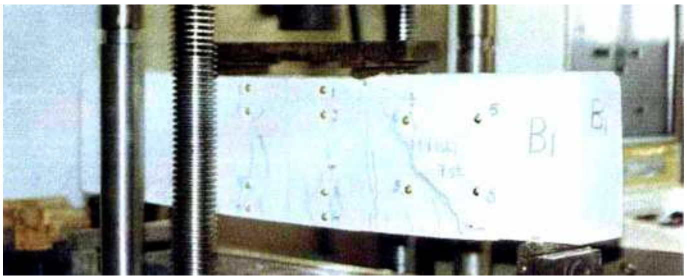


Figure 4 A typical test beam reinforced with EWF during testing.

Such enhancement may be attributed to the better confining effect from transverse (vertical) reinforcement as compared to ACI nominal strengths. Although, the amount of EWF used for Specimen BEWF3 was higher than that used for Specimen BEWF4, as mentioned earlier in Table 1 and shown in Figure 2, the capacity of the latter was higher than that for the former (see Figure 5). It can be argued that the horizontal strip used in BEWF4 improved its flexural strength and the U shape jacket used in the same beam contributed to both the shear strength and confinement. Moreover, the orientation of EWF for Specimen BEWF4, shown in Figure 2 and reported in Table 1, had a more pronounced effect on its behavior compared to the orientation applied to the other specimens. This can be attributed to the use of an orientation angle for vertical wings of the U shape jacket of 45°, which is ideal for shear resistance, and that for horizontal part of the U shape jacket, used for flexure, was 30° giving maximum contribution for flexural reinforcement.

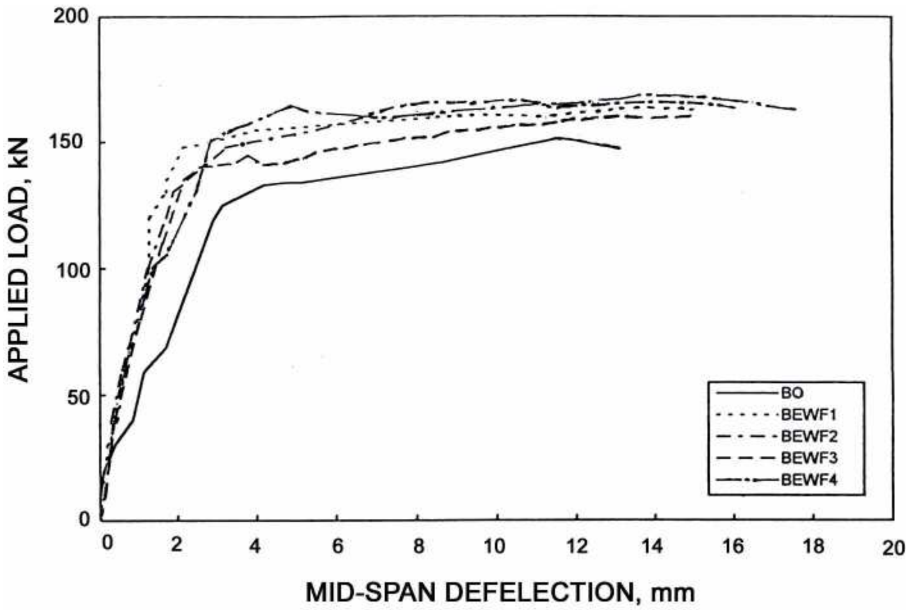


Figure 5 Load deflection relationships for different studied beams.

Crack Width

Widths of flexural cracks were measured during the tests and crack widths of the different beam specimens were compared. Typical load versus crack width curves is shown in Figure 6. It can be seen that beams with EWF reinforcement showed better crack control over the control beam B0. The loads at allowable crack width proposed by ACI code, which is about 0.3mm, can be also used for comparison [9]. Loads on the beams reinforced with EWF were generally higher than those on the control beam B0. It can be seen from Figure 6 that the beam BEWF4 had the minimum crack widths compared with the other beams reinforced with EWF. This may be attributed to the fact that this beam has a combination of good confinement, as a result of using U shape EWF jacket, and closely spaced wires, as a result of using two layers of EWF in flexural reinforcement.

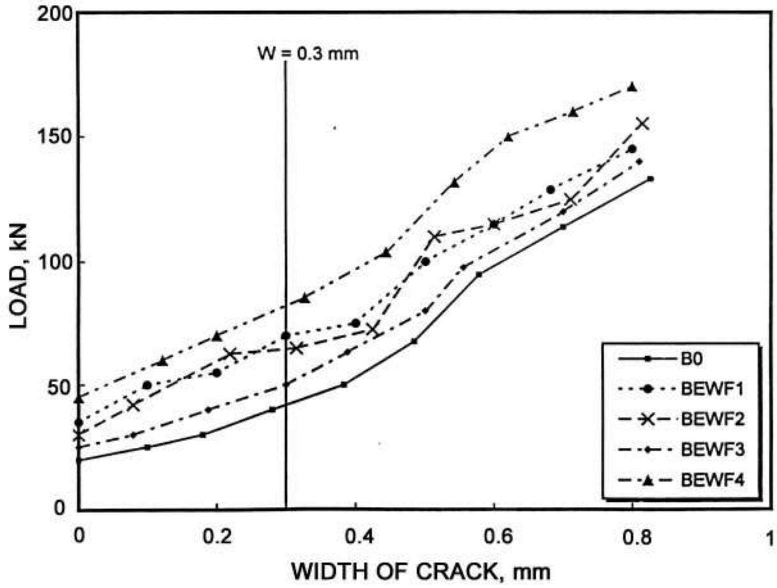


Figure 6 Crack width for different studied beam specimens.

Strains

(a) Horizontal strains

The measurement of the horizontal strain distribution across the depth of the test beams for different load steps were recorded and plotted in Figure 7. It can be seen from the figure that the tensile strains were much higher than the compressive strains and the strain distribution was almost linear across the beam depth except for beam BEWF1. This finding reflected the ductile behavior of the beams as the tensile reinforcement reached its yield strength. The horizontal strain results measured at the demec points (1-4) on the sides of beams (see Figure 3) were highly affected by the formation of cracks. It can be seen from Figure 7 that the strains in the tension zone increased slowly for different beams to different load levels before the formation of cracks. After the formation of cracks, the contribution of reinforcement led to a rapid and significant increase in strains until failure occurred. The contribution of EWF enhanced the ultimate capacity of the studied beams to different degrees. Figure 7 shows also that the horizontal strains at maximum ultimate loads of the studied beams ranged between 0.006 to 0.014. The beam BEWF4 had the maximum strain (0.014) at a maximum ultimate load (160 kN) which indicates the high ductility of this beam compared with the control beam and the other beams reinforced with EWF. This is in good agreement with the findings observed earlier for the load-deflection relationships and crack widths.

(b) Principal tensile strains

The relationship between applied loads and principal tensile strains is shown in Figure 8. It can be seen from the figure that reinforcing beams with EWF improves both of the beams' capacity and ductility. As observed earlier for the horizontal strains, all the beams show slow increase in principal tensile strains before cracking. After cracking, only the EWF and steel reinforcement provide tensile resistance, and hence, principal tensile strains increases much more rapidly. Figure 8 shows that the beam BEWF4 sustained a higher load at low strain compared to that of the other studied beams. The other beams sustained almost equal loads at low strains till cracking, after cracking the beams reinforced by EWF showed higher resistance compared to the control beam B0. It is interesting to note that the order of improvement in the behavior of beams reinforced with EWF in principal tensile strains was not the same as that in horizontal strains. For example, despite that Specimen BEWF4 showed excellent ductility till failure, at a maximum load for horizontal strains compared with the other beams (see Figure 7), Specimen BEWF3 sustained ultimate principal tensile strains higher than that of BEWF4 by 65% (0.068 mm/mm) at almost equal loads (see Figure 8). This may be attributed to the fact that the amount of EWF for shear reinforcement of Beam BEWF3 was higher than those for Beam BEWF4 (see Table 1 and Figure 2).

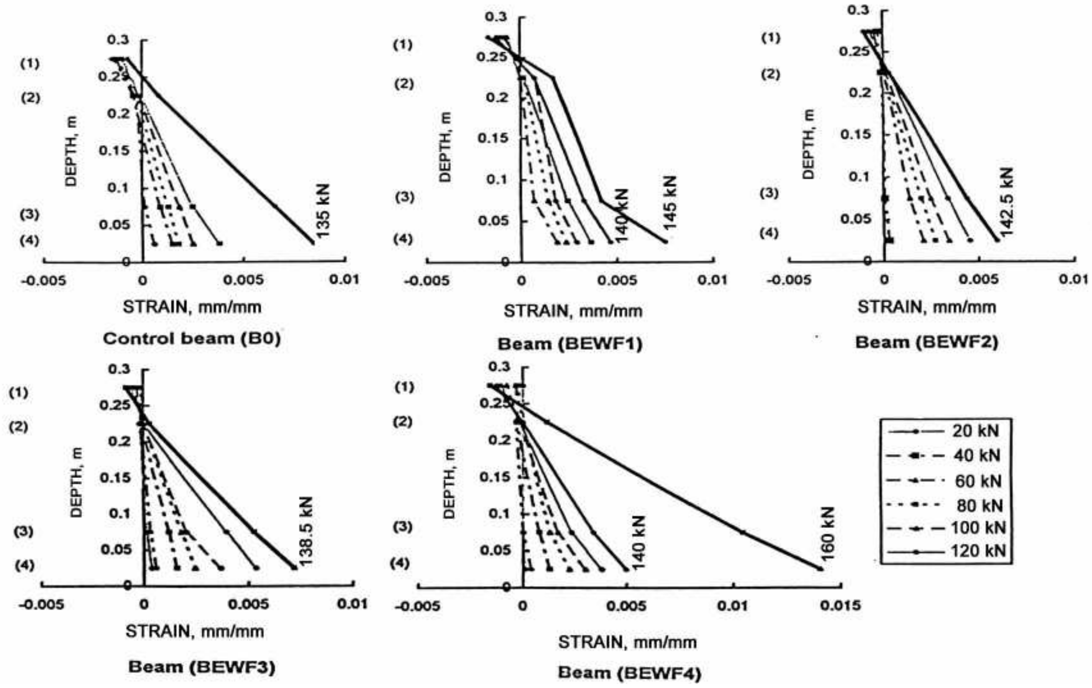


Figure 7 Strain distribution for studied beams.

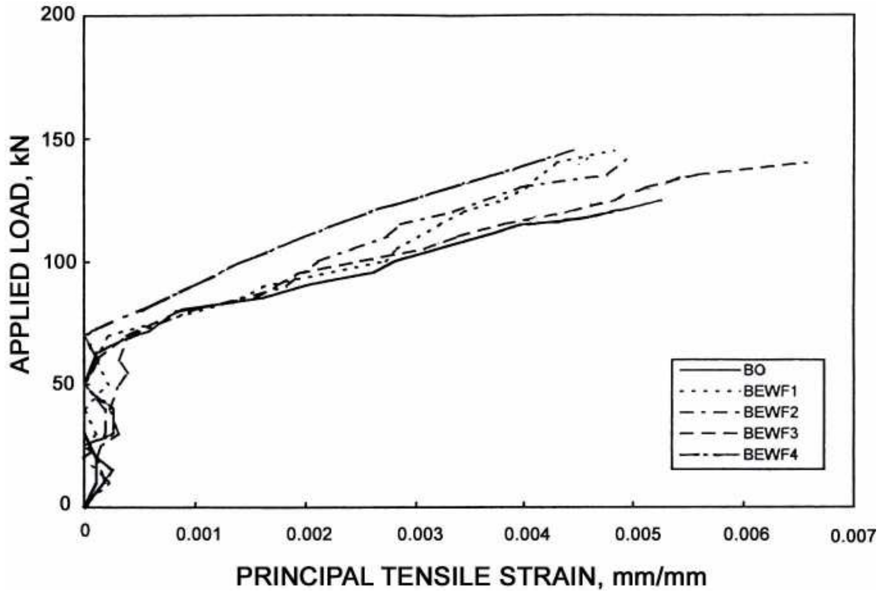


Figure 8 Load-principal tensile strain relationship for different studied beams.

THEORETICAL PREDICTION OF CRACK WIDTHS

The maximum crack width for square mesh reinforcement in flexural members was predicted earlier [1] as follows:

$$W_{max} = \frac{f_s}{E_r} S\beta \qquad (1)$$

Where

f_s = stress in the outermost layer of steel.
S = spacing of transverse wires.
β = ratio of distances to the neutral axis from the extreme tensile fiber and from the outer most layer of steel.
Er = effective modulus of the reinforcing system.

Equation (1) is based on the observation that the average crack spacing in flexure is approximately equal to the spacing of transverse wires and was found to represent an upper bound in observed data on average crack width. An overall linear regression equation for predicting the maximum crack width in flexure was developed [1] based on experimental data on cracking of ferrocement specimens reinforced with different amounts of square meshes with wire spacing of 12 mm and 6 mm.

$$W_{max} = (1.194\ f_s - 111)\frac{15.85}{E_r} \qquad (2)$$

Where W_{max} is in mm, f_s and E_r are in MPa (N/mm^2).

The following conservative procedure [12] can be followed, assuming the stress in the steel is less than the yield strength and in any case less than 414 MPa, to predict maximum crack width in tensile ferrocement members:

For $f_s \leq 345\ S_{r\ell}$

$$W_{max} = \frac{35000}{E_r} \qquad (3)$$

Where

fs is in MPa, W_{max} in mm and E_r in (N/mm^2).

$S_{r\ell}$ is the specific surface of reinforcement in loaded direction is cm^{-1} and is defined as the total bonded area of reinforcement (interface area or area of the steel that comes in contact with the mortar) divided by the volume of composite.

For a ferrocement section of width b and depth h, the specific surface of reinforcement can be computed from

$$S_r = \frac{\sum_0}{bh} \qquad (4)$$

In which $\sum_0$ is the total surface area of bonded reinforcement per unit length (the perimeter of flexural reinforcement bars and EWF are considered in full contact with concrete).

For $f_s > 345\ S_{r\ell}$ (applicable for the studied beams in this investigation)

$$W_{max} = \frac{20}{E_r}\ [175 + 3.69\ (f_s - 345\ S_{r\ell})] \qquad (5)$$

The above equation is modified herein for the application to RC beams reinforced with EWF used in this study, as follows:

$$W_{max} = \frac{20}{E_r}\ [175 + 3.69\ (f_s - 345\ \{\sum_{1}^{\ell}\ \alpha\ S_{r\ell}\cos\theta + S_{rb}\})] \qquad (6)$$

Where

S_r is divided into two terms, the contribution of longitudinal reinforcement bars (traditional reinforcement) "S_{rb}" and summation of specific surface of reinforcement for EWF layers, ℓ "$S_{r\ell}$" which includes strips, jackets, and wings. Since the predicted crack widths are the flexural ones, the calculated S_r is for flexural reinforcement only.

θ is the orientation angle of EWF with the horizontal direction.

α is a confinement factor and is estimated as 16 for EWF wings or jackets, 8 if jackets and wings are acting together and 1 for EWF strips.

f_s = 140 MPa (N/mm^2).

E_r in the longitudinal and transverse directions for EWF were reported in [10] as follows:
$E_{r\,(long)} = 138 \times 10^3\ (N/mm^2)$. & $E_{r\,(trans)} = 69 \times 10^3\ (N/mm^2)$.

The prediction of crack widths is normally carried out during service loads. However, the predicted crack widths obtained by the above equations are not functions in applied loads. Therefore, experimental values of crack widths, which are related to applied loads as shown in Figure 6, can not be compared with those predicted by Equation (6). It is more practical to compare the effect of EWF reinforcement on the crack widths obtained experimentally with that predicted theoretically. This effect can be estimated by;

$$\frac{\text{Crack width of a beam reinforced with EWF, } W_{EWF}}{\text{Crack width of the control beam, } W_o} \qquad (7)$$

The experimental effect of EWF is obtained on two steps. Firstly, by extracting crack widths for studied beams from Figure 6 at a load level less than the service loads, which are assumed to be half of the maximum test loads. Secondly, by applying Equation (7) to the experimental results. Predicted values of crack widths can be obtained by applying Equation (6) to each studied beam while the effect of EWF on predicted crack width is obtained by applying Equation (7). Table 2 shows a comparison between the experimental and predicted effect of reinforcing beams with EWF. The good agreement between the experimental and theoretical results shown in Table 2 indicates the sensitivity of Equation (6) to the studied parameters such as orientation of EWF, quantity of EWF reinforcement (number of reinforcement layers) and type of reinforcement (strips, jackets, wings and traditional reinforcement).

Table 2 Experimental and theoretical evaluation of EWF effect on crack width

Beam Specimen	**Crack Width Ratio, W_{EWF}/W_o**	
	Experimental Ratio	**Predicted Ratio**
BEWF1	0.5	0.52
BEWF2	0.48	0.5
BEWF3	0.9	0.9
BEWF4	0.3	0.28

CONCLUSIONS

Based on the experimental results reported herein and theoretical prediction presented in this investigation regarding the effectiveness of using permanent EWF formwork as additional reinforcement, the following conclusions can be drawn:

- Using EWF as additional reinforcement results in a reduction of deflection, increasing loads at first cracking, and enhancing section ductility. In addition the close spacing between wires in the EWF can reduce crack widths.

- The beams reinforced with a U-shaped EWF layer around the beam cross-section and additional layer at the tension face showed excellent response compared with other beams reinforced with EWF. Its load capacity was increased by 20%, strain reached the maximum of (0.014) and the crack widths were reduced by approximately 35% compared to the control beam with conventional reinforcement.

- Using EWF as a permanent formwork is a promising technique since it can achieve two goals, firstly it can replace the traditional temporary timber formwork which, in turn, lead to a reduction of the overall cost and avoid problems of placing concrete. Secondly, it can be used as additional reinforcement for improving shear and flexure behavior. However, further research is needed to study the potential application of this technique widely for beams of large spans.

- A proposed formula was developed for predicting the effect of EWF on crack widths. The prediction was in a good agreement with the experimental results.

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