BEHAVIOR OF THIN PLATES REINFORCED WITH WIRE FABRIC

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ABSTRACT

Five plates made of multiple layers of wire fabric impregnated with cement mortar were tested. Such plates can be used for constructing structural elements or strengthening and repair of reinforced concrete structures. The studied parameters were the lamination process and the plate aspect ratio. The transverse deflection and strain distribution across the thickness of plates were measured on prototype models. It was found that increasing the number of cast layers in constructing the plates resulted in a reduction of mid-span deflection. The experimental results were found to be in good agreement with the theoretical findings. The latter were obtained using a developed non-linear finite element analysis based on the layered approach.

ملخص البحث:

تم اختبار عدد خمسة من الألواح المصنوعة من مونة الأسمنت المسلح بالشبك الممدد بغرض دراسة سلوك تلك النوعية من الألواح والتى يمكن استخدامها فى تنفيذ العناصر الأنشائية أو تدعيم واصلاح المنشآت الخرسانية المسلحة. والعوامل المأخوذة فى الدراسة هى طريقة صب الألواح (عدد طبقات الصب) ، ونسبة طول اللوح الى عرضه. ويتم تقييم سلوك الألواح عن طريق قياس الترخيم وكذلك توزيع الأنفعالات الأفقية على سمك اللوح. وقد وجد أن زيادة عدد طبقات الصب ينتج عنه انخفاض ملحوظ فى ترخيم الألواح. وبمقارنة النتائج العملية بأخرى نظرية تم الحصول عليها باستخدام برنامج تحليل لاخطى، تم تطويره سابقا وتطويعه للدراسة الحالية، ويعتمد على نظرية العناصر المحددة متعددة الطبقات ظهر أن هناك تقاربا ملحوظا بين النتائج مما يشير الى دقة البرنامج.

INTRODUCTION

Renovation of concrete elements after a certain time is sometimes inevitable. A number of rehabilitation methods have been developed, one of these involves the use of advanced composite materials for repair of reinforced concrete structures [1]. This technique is new and has many structural advantages but is expensive.

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The use of wire fabric to reinforce mortar layers (i.e. ferrocement) for strengthening structural elements [2] or constructing new structures [3] is increasing rapidly. Ferrocement construction competes favorably with advanced composites such as fiber glass laminates in special structures, e.g., domes, wind tunnels, shell roofs and pools [4]. Two feasibility studies have shown ferrocement costs to be less than steel or fiber glass laminates in the construction of wind tunnels [5] and hot water storage tanks [6].

In the conventional construction of ferrocement, several layers of wire mesh are tied to a framework of reinforcing bars and then mortar is impregnated into the steel matrix. The full details of conventional ferrocement construction techniques are reported else where [3]. Irons [7] defined the laminated ferrocement production as a system which has each layer of mesh separately embedded into mortar matrix. He argued that this laminating process eliminates voids, allows more reinforcement to be incorporated without mortar penetration problems and the technique has proven to be impact and corrosion resistant.

The objective of this research was to study the behavior of thin plates made of mortar layers reinforced with wire mesh. The studied parameters were the number of cast layers of mortar reinforced with welded square wire mesh and the aspect ratio of plates. In addition, the experimental results were compared with numerical ones obtained by a developed non linear finite element code for the analysis of 2-dimensional layered elements.

EXPERIMENTAL STUDY

Plates Design

The ferrocement plates were designed to meet specifications of EC 95 [8]. The flexural reinforcement consisted of steel bars 3 mm in diameter, welded to form a square 6 cm mesh and two layers of expanded wire fabric. In order to study the effect of method of casting, three plates of 90 cm length, 50 cm width and 7 cm thickness were cast in one, two and three layers respectively (see Figure 1). In order to study the effect of aspect ratio on the behavior of plates, two other plates of 50 and 70 cm length having the same width and thickness as the previous plates were cast. The latter plates were cast in three layers each.

Plates Fabrication

A total of 5 ferrocement plates were cast in wood forms (See Figure 2). The mortar mix proportions for ferrocement were sand-cement ratio = 2 by weight, the maximum size of sand particles was 5 mm and water cement ratio of 0.5 by weight. This meets the specifications of the ACI Committee 549-R88 [5]. Four batches of mortar were used to cast the plates and the standard test cubes. The casting process was described in the previous section and is shown in Figure 1.

All plates and cubes were cured in a water bath for at least 28 days prior to testing. The cubes were tested on the same day when the plates were tested. Batches 1 through 4 had an average compressive strength of 270 kg/cm^2. Compressive strength of the batches differed by less than 10% from this average.

Instrumentation and Test Setup

The plates were tested according to the following procedure. The specimens were instrumented to obtain information related to the structural behavior of each plate, in terms of concrete strains and transverse deflections of plates, at various stages of loading. The locations of demec points (for measuring concrete strains) and dial gauges (for measuring deflections) are shown in Figure 3. The plates were tested under uniform increasing loads obtained by the pyramid shape of wooden pieces (as shown in Figure 4) on a 50 ton Shimadzu universal testing machine with a computer controlled hydraulic servo system. The plates were simply supported at the two short edges and free at the other two ones (see Figure 3). All plates were statically tested to failure in a single load cycle. The rate of loading was 1mm/min since the machine operated a displacement control loading scheme. The test arrangements are shown in Figures 3 and 4.

Concrete strain measurements

Demec studs were glued to each of the two free sides of plates using rapid-hardening Araldite epoxy resin. Five pairs were fixed on one side and 2 pairs on the other side for the measurement of concrete surface strains at various locations on the top compression and bottom tension surfaces of the plates. All demecs were symmetrically located on both sides of the mid-span as shown in Figures 3 and 4. The measurements were carried out using a 100 mm demountable digital demec gauge (See Figure 5).

Transverse deflection measurements

The deflections were measured using dial gauges (0.01 mm divisions) fixed on the bottom surfaces of the test plates. The dial gauge positions for the test specimens are shown in Figure 3.

EXPERIMENTAL RESULTS

All the tested plates failed in flexure at different load levels depending on the number of cast layers and the aspect ratio of plates. The behavior of plates with regard to the measurements of the mid-span deflections, concrete strains and crack patterns shall be discussed in the following sections. Results from the tests are shown in Figures 6 through 11. The notation of each plate starts with three letters and a value referring to the plate length to width ratio, followed by a hyphen and then a letter and a number which refer to the number of cast layers.

For example, the notations Plw1.8-L_1 and Plw1.4-L_3, represent plates having length / width ratio of 1.8 and 1.4 which were cast in one layer and 3 layers respectively.

Mid-span Deflection

The mid-span load-deflection relationship for all the test specimens is shown in Figure 6. In general, mid-span deflection increased as the plate length/width ratio increased. It can be seen from the figure that the plate Plw1.8-L_2 failed before Plw1.8-L_1 while plate Plw1.8-L_3 sustained large deflections prior to failure. Figure 6 shows that changing the method of casting by increasing the number of cast layers to 3 layers lead to an increase of the load capacity of the plate. For example, the ultimate load of plates Plw1.8-L_3 and plate Plw1.8-L_2 was 2542 and 1751 respectively. It goes without saying that decreasing the aspect ratio for the same plate thickness and the same number of cast layers resulted in a reduction of deflection for the same applied load and lead to an increase of the ultimate load. Plates Plw1.4-L_3 and Plw1.0-L_3 had mid-span deflections of 5.8 and 4.1 mm at ultimate loads of 2800 and 3300 kg respectively.

Deflection Distribution Across The Plate

Figure 7 shows the deflection measurements at the three dial gauges located at position 1,2 and 3 in Figure 3. It is clear from the deflection distribution diagrams that the deflection values are almost symmetrical around the dial gauge number 2 at the center line of the test plates. This was expected since the load was uniformly distributed over the plate surface. The behavior of plates was dependent on the load value. For example, at load levels up to 1000 kg, the deflection values were found to increase in order of Plw1.8-L_3, L_2 and L_1. For higher levels of loads, the trend is changed and the deflection values were observed to increase in order of Plw1.8-L_3, L_1, L_2 at load level of 1500 kg (see Figure 7). Plate Plw1.8-L_2 failed at higher load level and the plate Plw1.8-L_3 showed less deflection than Plw1.8-L_1 at load level = 2000 kg. Plw1.8-L_1 failed at load of 2200 kg while Plw1.8-L_3 sustained large deflection prior to failure at load level higher than 2500 kg.

In general, it was found that plate Plw1.8-L_3 showed a more ductile type of failure after sustaining large deformations prior to failure. This is clear from Figure 8, that the ratio between first crack load and ultimate load for plates Plw1.8-L_1, L_2 and L_3 is 0.68, 0.77 and 0.50 respectively. This shows that the difference between the first crack load and ultimate load for plate Plw1.8-L_2 is the highest and this supports the observation of the ductile type failure mentioned earlier. This is consistent with the findings of Irons [7] that the number of cast layers (the lamination process) affects the behavior of structural elements and in turn this leads to a better behavior of plates by decreasing the deflection.

Crack Patterns

The first crack to form was a result of flexural stresses in all plates but it was initiated at each plate at different load value. For plate Plw1.8-L_1, the first crack was initiated at a distance of 39 cm from the left side of the plate as shown in Figure 9 (a) at load value of 1490 kg, the second crack was formed at load value of 1678 kg and then a sudden reduction of the machine load to a value of 1446 kg was recorded since the machine operated on a displacement control basis.

For plate Plw1.8-L_2, which was cast in two layers, the first vertical crack was developed at load = 1340 kg as shown in Figure 9(b) along a line parallel to the width of the plate at its center line. The crack progressed in length and width to the interface between the cast layers and then a horizontal crack developed at this surface. On further increase in load, the existing cracks progressed in length and width till load value of 1678 kg. A sudden reduction of the machine load from 1340 kg to 1213 kg was recorded when the first crack occurred.

Figure 9 (c) shows the cracks formed in plate Plw1.8-L_3. It can be seen that this plate generally showed similar behavior to Plw1.8-L_2. The first crack was developed at load 1283 kg and extended in length till the second cast layer and then a horizontal crack was observed. As a result of this crack, the machine recorded a sudden reduction of load to 1216 kg. Another crack was formed at load 1481 kg (Figure 9 (c)) at a distance of 34 cm from the left support of the plate. The progress of this crack was similar to the first one.

It can be noticed from the previous discussion and from Figure 9 that plates Plw1.8-L_2 and Plw 1.8-L_3 sustained horizontal cracks at interface surface between layers, and these were generated at the tip of the vertical cracks. This might be attributed to the fact that these plates were cast in more than one layer; two and three layers respectively. However, plate Plw1.8-L_2 failed earlier than Plw1.8-L_3 because it has only two layers and the horizontal crack developed at the surface between the two cast layers lead to a further slip between the two layers (see Figure 9 b). Figures 9 (a) and (c) show that the first crack formed in Plw1.8-L_1 and L_3 were not at the center of these plates and new cracks were developed after progressing of the first crack till failure. It can be argued that the use of wooden pieces to distribute the load may have created some stress concentration under the wooden pieces at the location of cracks. It is worth mentioning that the flexural cracks for different plates originated from the bottom (tension zone) surface along a line parallel to the width of the plate (see Figure 10).

Concrete Strains

The horizontal strain results measured at the demec points on the sides of plates were highly affected by the formation of cracks. The effect was found to be more pronounced when such cracks formed through or at the vicinity of the demec points. The strains developed across the plate thickness under load were studied in order to assess the effect of the number of cast layers and plate aspect ratio.

Figure 11(a) shows the load strain relationship at demec point (1) which is located at the top compression zone for different plates (see Figure 3). It can be seen from Figure 11(a) that the strain in compression (shortening) increased in the following order for different specimens; Plw1.0-L_3, Plw1.4-L_3, Plw1.8-L_3, L_1 and L_2. The recorded ultimate load of Plw1.8-L_2 was 1751 kg. After failure of plate Plw 1.8-L_2, the strains at plates Plw1.8-L_3 and Plw1.8-L_1 were in close agreement till the ultimate load of Plw1.8-L_1 of 2195 kg. This might be attributed to the fact that the crack formed at Plw1.8-L_2 was at its center line, where the strains were measured while the cracks at Plw1.8-L_1 and Plw1.8-L_3 were at other locations as mentioned earlier in Section 3.3.

The strains in concrete at demec point (5) in the tension zone (see Figure 3) have been affected by the formation of cracks in the gauge length. Figure 11(b) shows that the strains in tension zone increased slowly for different plates to different load levels before the formation of cracks. The order of slow increase of strains was L_3, L_1, L_2 for plate Plw1.8 with the maximum at L_2 as shown in Figure 11 (b). After the formation of cracks, the contribution of reinforcement lead to a rapid and significant increase in strains until failure occurred. From Figure 11 (b), it can be seen that the maximum horizontal strains of plates Plw1.8-L_1, Plw1.8-L_2 and Plw1.8-L_3 ranged between 7.3 /1000 to 7.8/1000. This small variation in strains, compared to the variation of strains in compression zone, may be attributed to the contribution of steel reinforcement to tension failure (see Figure 11 (a)). It can be noticed that the strain of plate Plw1.8-L_3 showed a steady increase with load prior to failure. The range between the maximum load at slow rate of strain and the ultimate load was maximum for Plw1.8-L_3 and then for plates Plw1.8-L_1 and L_2 respectively. This supports the findings in Section 3.2 and shown in Figure 8 that the range between the first crack load and ultimate load was in the order of Plw1.8-L_3, L_1 and L_2 respectively.

It is worth mentioning that the strains increased with the increase of plate aspect ratio for the same number of plate cast layers. This is clear from Figure 11 (a) & (b) for compression and tension zones that the order of increase of strains was Plw1.0-L_3, Plw1.4-L_3 and Plw1.8-L_3.

THEORETICAL FINDINGS

The finite element model developed earlier [9] for the non linear analysis of reinforced concrete elements strengthened by fiber reinforced plastics (FRP) sheets was based on the layered approach. The model is a quadrilateral isoparametric 4-nodes element with five degrees of freedom per node. The factors included in the program were; the elastoplastic behavior of concrete in compression, the elastic brittle fracture behavior in tension, as well as compression softening, crack tension stiffening, and rotating crack concept. The steel was modeled by an idealized bilinear curve identical in both tension and compression.

In order to improve the capability of the program, the author increased the previous factors by adding one more of the cracking effects namely aggregate interlock. Output results obtained by the program were then used for comparison with the experimental observations.

Mathematical Modeling

The ferrocement plates (steel wire fabric embedded in mortar matrix) were treated analytically by dividing them into a number of mortar layers through the thickness, while the steel wire fabric were smeared into equivalent steel layers, and each layer was assumed to be in a state of plane stress. Since the full details of this modeling is stated in [9], the formulation will be limited here to the new factor mentioned previously, aggregate interlock.

Aggregate Interlock

The simplified formulation proposed earlier [10] is adopted herein to account for aggregate interlock;

$$[\sigma_{nt}] = - f_c /30 + [1.8\ \delta_{nn}^{-0.8} + (0.234\ \delta_{nn}^{-0.707} - 0.20)\ f_c]\ [\delta_{nt}] \qquad (1a)$$

$$[\sigma_{nn}] = - f_c/20 + [1.35\ \delta_{nn}^{-0.63} + (0.191\ \delta_{nn}^{-0.552} - 0.15)\ f_c]\ [\delta_{nt}] \qquad (1b)$$

where σ_{nt} and σ_{nn} = the shear and normal stresses transferred across the rough crack surfaces (Mpa).

δ_{nt} and δ_{nn} = the shear displacement and the crack opening (mm).

f_c = the simple compression strength of concrete (Mpa).

The signs of the stresses are obtained by considering that the normal stress is always compressive (negative) and shear stress follows the sign of shear displacement. The crack opening is always positive. Figure 12 shows the sign correction of the relation in Equation (1) to obey these requirements.

After adding the effect of aggregate interlock to the constituent matrices of concrete layers [9], the material stiffness matrix for the whole section composed of mortar matrix reinforced with wire fabric is linked to the program and the element stiffness matrix is obtained directly. All the steps of the nonlinear analysis are listed else where [9].

PREDICTION OF THE RESULTS

The finite element code developed earlier [9] and modified herein was used for modeling and analyzing the ferrocement plates which were experimentally tested in this investigation in order to compare the numerical results with the experimental ones. Since the program treats each of the wire fabric mesh and mortar as individual layers, the numerical results will be compared with L_2 and L_3 series of experimental results which were based on casting the plate into 2 and 3 layers respectively. (i.e. Plw1.0-L_2, Plw1.4-L_2, Plw1.8-L_2 and Plw1.0-L_3, Plw1.4-L_3, Plw1.8-L_3).

The finite element mesh, boundary conditions, loading and reinforcement idealization adopted for the analysis are given in Figure 13. The material parameters used are those reported in [11] and given in Figure 13 (b).

Deflection For Different Aspect Ratios

Figures 14 and 15 show a comparison between theoretical and experimental load-deflection results for different aspect ratios and the same number of layers (Plw1, 1.4, 1.8-L_3). The global behavior is very well simulated up to about 1000 kg, but it deviates considerably beyond this value for different aspect ratios with different degrees. For example, Figure 15 shows that the difference between the experimental and predicted deflection is about 5% for aspect ratio = 1 at load level 2000 kg whilst that difference equals about 17% for aspect ratio =1.8 and the same load level. However, the shapes of both the experimental and theoretical results are very similar.

It is observed that the model under estimates the deflections compared to the experiment. It can be argued that the material properties reported in Figure 13 (b) and used as data for the computer program were obtained from the literature [11] and are not based on experimental testing of the materials used in this investigation. This is expected to have a significant effect on the results after cracking and especially for aspect ratios higher than one. It was mentioned earlier in Section 3.3 that the first crack for any of the plates occurred at loads higher than 1000 kg and that explains the good agreement between the experimental and theoretical results up to this load level.

Strain Distribution

Figure 16 shows the theoretical and experimental strain distribution results across the thickness of plates Plw1.0, 1.4, 1.8-L_3 at the demec points shown in

Figures 3 and 4 and for machine load of 2000 kg. This level of load is higher than the first crack load and less than the ultimate load for any of the test plates. It can be seen from the figure that the both experimental and theoretical strain distribution shapes were directly proportional to the distance from the neutral axis in the tension zone and in the compression zone till demec point (2) whilst the strain distributions were inversly proportional to the distance from the neutral axis between demec points (2) and (1). The strain distribution shapes are consistent with the assumptions of EC 95 [8] and ACI Committee 549, 1R-88 [11] for the tension zone and compression zone up to demec point (2). It can be argued that the layered approach and the formation of cracks may have affected the reversal of trend between demec points (2) and (1). It can be seen that, at load level of 2000 kg, the agreement between theoretical and experimental results decreased with the increase of aspect ratio as was noticed for the deflection results in Section 5.1.

Crack Patterns

Figure 17 shows the predicted and experimentally observed crack patterns for plates Plw1.8-L_2 and L_3 at initial crack load and second crack load for each of them. It can be seen from the figure that a very good agreement is observed for both of the directions and the locations of cracks for Plw1.8-L_2. The location of cracks was predicted for Plw1.8-L_3 at the center of plate as shown in Figure 17 while the experimentally observed ones were located at two different positions. This was explained earlier at Section 3.3 by the effect of stress concentration due to placing the wooden pieces at these two locations. In turn, cracks were generated at the locations shown in Figures 9 and 17 and not at the center of the plate as predicted by the theoretical modeling which were based on considering the load uniformly distributed on the plate.

CONCLUSIONS

The following conclusions can be drawn from the study of the experimental results and theoretical findings for the test cases:

The method of casting (number of cast layers) and aspect ratio of plates influenced the magnitude of the mid-span deflection of the tested plates.

Strains are affected by the same previously stated factors but are also dependent on the developed cracking pattern.

A realistic numerical simulation of the structural behavior of plates made of mortar layers reinforced with wire fabric (ferrocement) is verified. The load - deflection curves observed in the experiments, the crack patterns, and also the strain distribution are quite well predicted.

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