CHAPTER (8)

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1 Summary

The present thesis is concerned with the behavior of epoxy-modified reinforced concrete (EMRC) beams. Comprehensive experimental programs were carried out in order to study the epoxy addition as a supplementary cementing material. To study the flexure behavior of the EMRC beams, ten simply supported beams were tested with shear span-to-depth (a/d) ratio of "7.0". According to the weight ratio of epoxy (w_e), these ten specimens were divided into three groups. The first group consisted of four beams with 0% epoxy ratio. The first beam of that group was reinforced by 1.1% tensile steel ratio while the second beam was 1.97% steel ratio, and the third and fourth beams were also with 1.1% steel ratio but with un-bonded lengths of bottom reinforcement as 200 mm and 400 mm at mid-span. The second group composed of two beams similar to the first and the second beams of the first group but with 5% epoxy. Finally, the third group was the same as the first group except the weight ratio of epoxy which was 10%. For the investigation of shear behavior of EMRC beams, eighteen simply supported beams were tested with shear span-to-depth (a/d) ratios as 2.5, 3.5, and 4.5. According to the weight ratio of epoxy (w_e), the eighteen specimens were divided into three equal groups. The first group consisted of six beams with 0% epoxy ratio. The first and the second beam of this group were with (a/d) of 2.5, but the first beam was with stirrups ratio (ρ_v) of 0.24% and the second beam was without stirrups. The third, the fourth, and the fifth beam of this group were with (a/d) of 3.5, but with ρ_v of 0.24%, 0%, 0.48% respectively. The sixth beam of this group was with (a/d) of 4.5 and without stirrups. The second and the third group were identical to the first group except the weight ratio of epoxy which was 5% and 10% respectively.

In the flexural and shear tests, the performance and failure mechanisms of EMRC beams under monotonic static loading were monitored, recorded, and compared with non-polymer RC beams. The effects of epoxy weight ratio, concrete strength, shear span-to-depth (a/d) ratio, longitudinal steel ratio, and transverse stirrups ratio were carefully studied. Also, the research investigates the response characteristics of EMRC beams such as load carrying capacity, resistance, stiffness, deflection, ductility, and cracking patterns at different levels. Additionally, comprehensive theoretical study was carried out in order to develop a mathematical model for nonlinear finite element analysis of EMRC beams with validation studies. Also, the theoretical study includes the development of design equation for EMRC beams and performing comprehensive parametric studies. From the validation studies, the predicted theoretical response and limiting values were nearly the same as the measured experimental results. Finally, comparison of the measured results with the estimated values of current design codes was done.

8.2 Conclusion Points for Flexure Behavior of EMRC Beams

Based on the results of experimental investigation, and analytical studies of the flexural behavior of EMRC beams, the following conclusion points are made:

1- Beams containing higher epoxy content tend to produce less propagated, less widened, and more spreaded cracks. The final crack patterns of the tested beams emphasize the fact that due to the ability of polymer-modified concrete in arresting the growth and widening or of cracks, epoxy-modified concrete beams exhibit less deformation and higher load-carrying capacity. In general, the crack initiation is slightly retarded for the beams with epoxy-modified concrete rather than the beams without epoxy.

2- The use of 5% and 10% epoxy weight ratio in beams with 1.1% steel ratio, results in 4.4% and 8% increase in the cracking load. The increase was 6% and 10% for beams with steel ratio 1.97%. Also, by using of 5% and 10% epoxy weight ratio results in 10% and 14.5% increase in the yielding load for beams with steel ratio 1.1%, while it was 2.25% and 3.5% for beams with steel ratio 1.97%. In addition, the ultimate load capacity was increased by 3.6% and 7.3% when using 5% and 10% epoxy weight ratio for beams with steel ratio 1.1% respectively, while it was 2.3% and 5.2% for steel beams with ratio of 1.97%.

3- For beams with un-bonded length of 200 mm or 400 mm, the cracking load was increased by 10% when using epoxy modified concrete with 10% epoxy weight ratio. The yielding load was increased by 9% for beams with 200 mm un-bonded length or for beams with 400 mm un-bonded length. For beams with un-bonded length 200mm and 400 mm, the failure load of the epoxy-modified concrete beams was increased by 7% of that of the 0% epoxy weight ratio beams. Similar enhancements were measured for the crack, yield, and ultimate moments.

4- The increase of epoxy weight ratio leads to a decrease in steel strain at yield level, and to an increase in steel strain at failure level. For beams with 1.1% steel ratio, the measured steel strains at yield level were 0.0025, 0.00224, and 0.00204 respectively for 0%, 5%, and 10% epoxy weight ratio. The measured steel strains at failure level for such beams were 0.017, 0.019, and 0.02. For the beams with higher steel ratio of 1.97%, the measured steel strains at yield level were 0.0035, 0.00275, and 0.00196 for epoxy weight ratio of 0%, 5%, and 10% respectively. Also, the measured steel strains for such beams at ultimate level were 0.015, 0.017, and 0.018.

5- The load-deflection curves predicted by the finite element analysis for all beams were in a good agreement to the experimental load-deflection curves. Similar to the experimental results, the finite element predictions of the load-deflection curves indicated that by increasing the used epoxy weight ratio leads to an improvement of the load carrying capacity, stiffness, and ductility of high strength epoxy-modified reinforced concrete beams tested for flexure.

6- A proposed design equation to predict the ultimate moment capacity of EMRC beams has been formulated. The predicted ultimate moments of several reinforced concrete beams were compared with the experimental results in the present work and in other eleven sources of literature. Despite the difference in test specimens, the proposed approach predicts their ultimate moment capacity reasonably well. For the prediction of the ultimate moment capacity, the mean value of the ratio between the measured and calculated moment capacities is 1.13 and the standard deviation is 0.23.

8.3 Conclusion Points for Shear Behavior of EMRC Beams

Based on the results of experimental investigation, and analytical studies of the shear behavior of EMRC beams, the following conclusion points are made:

1- The increase of epoxy weight ratio has led to a decrease in the number of cracks, an increase in the spacing between cracks, and a decrease the crack width. These results are more noticeable in specimens with no stirrups. Increasing of (a/d) ratio led to increased number of cracks all over the beam length and especially in the central region of the beam. The mode of failure for specimens having (a/d) of 2.5 was shear compression failure, while the mode of failure for specimens having (a/d) of 3.5 and 4.5 was diagonal tension failure mode.

2- The increase of epoxy weight ratio from 0% to 5%, and 10% results in increasing the cracking load by 14% and 20%, and increasing the ultimate load by 3.1% and 10.2% respectively for specimens having (a/d) of 2.5 and without stirrups. While, for specimens having (a/d) of 3.5 and without stirrups, the increase was 13.3% and 15% in the cracking load, and 7% and 13.6% in the ultimate load capacity. For the specimens having (a/d) of 4.5 and without stirrups, the increase was 4.2% and 7% in the cracking load, and 6.7% and 11.1% in the ultimate load.

3- For specimens having constant stirrups ratio as 0.24% and constant (a/d) as 2.5, the increase of epoxy ratio from 0% to 5%, and to 10% results in increasing the cracking load by 12.6% and 21.2 % and increasing in the ultimate load by 8.6% and 23.8% respectively. Furthermore, the measured vertical deflection at mid-span for epoxy beams at the ultimate level decreases with the increase of epoxy weight ratio. Compared to beam with 0% epoxy, the ultimate deflection of beams with 5% and 10% epoxy are less by 31% and 45% respectively.

4- For specimens having (a/d) of 2.5 and without stirrups, the increase of epoxy weight ratio from 0% to 5%, and 10% results in decreasing the steel strain at failure by 12% and 28%, and the concrete strains at failure by 15% and 21% respectively. Also, for specimens having (a/d) of 3.5, the decrease of steel strains was 17% and 23%, and concrete strains was 20% and 25% respectively. Furthermore, for specimens having (a/d) as 4.5, the decrease in concrete strains was 13.5% and 20%, and the decrease in steel strain was 11% and 20% respectively.

5- For beams having (a/d) of 2.5 and with stirrups ratio 0.24%, increasing the epoxy weight ratio from 0% to 5%, and to 10% caused a decease in the stirrups strain by about 20% and 25.5% respectively at the same load level. Similarly, the reduction in stirrups strain when increasing the epoxy weight ratio from 0% to 5%, and to 10% at the same load level was 23% and 41% for specimens having (a/d) of 3.5, and was 15.5% and 29% for specimens having (a/d) of 4.5.

6- The increase of epoxy weight ratio from 0% to 5%, and to 10%, results in increasing of cracking shear strength by 14% and 20% for beams having (a/d) of 2.5, and by 13% and 15.4% for beams having (a/d) of 3.5, and by 5% and 11% for beams having (a/d) of 4.5. Also, the increasing of epoxy weight ratio from 0% to 5%, and to 10%, enhances the ultimate shear strength by 3% and 10% for beams having (a/d) of 2.5, and by 7% and 13.6% for beams having (a/d) of 3.5, and by 6.7% and 11.11% for beams having (a/d) of 4.5.

7- The load-deflection curves predicted by the finite element analysis for all beams tested for shear were nearly similar to the experimental load-deflection curves. The finite element predictions of the load-deflection curves indicated that the increase of the epoxy-weight ratio leads to an improvement of the shear carrying capacity, stiffness, and ductility of high strength epoxy-modified reinforced concrete beams tested for shear.

8- To predict the ultimate shear strength of EMRC beams, a design equation was formulated. The proposed equation was used to predict the shear strength of 218 test specimens in the current work and in other thirteen sources of literature. Despite the difference in test specimens, the proposed equation predicts their shear strengths reasonably well. The strength ratios that are defined as the ratio of the measured to the calculated strength indicate an acceptable precision of the proposed equation, where the average strength ratio is 1.31 and the standard deviation is 0.36.

8.3 Recommendations for Future Studies

For best understanding of the behavior of epoxy-modified reinforced concrete (EMCR) beams, the present experimental and theoretical research works can be extended to study the following parameters:

1- The effect of using higher epoxy weight ratio (more than 10%).

2- Different epoxy and polymer types with or without steel fibers.
3- The size effect and strain localization problems in high-strength concrete beams.
4- The effect of cyclic, repeated, and high strain rate loadings.
5- Different section configurations such as T-section and L-section.
6- Different structural members such as columns and beam-column connections.
7- The deep beam action in deep and short beams.
8- The structural continuity effect in overhanging and continuous beams.
9- The combined effect of flexure and axial forces or shear and torsion on EMRC beams sections.
10- The time-dependant effects due to creep and shrinkage for EMRC beams subjected to normal or aggressive conditions.