CHAPTER 6

CONCLUSIONS

6.1 SUMMARY

In the present work, experimental and analytical investigations have been carried out to study the structural behaviour of reinforced concrete beams with openings of different sizes in the shear zone strengthened using rectangular stirrups, diagonal bars, steel fibres and steel plates around the openings.

Totally thirty beam specimens with the same cross section (150mm x 300mm), length (2000 mm) and reinforcement were tested. These specimens were tested under two point loading. The entire study was divided into 4 distinct phases.

In the first phase of study, 18 reinforced concrete beams were tested which included two RC beams without openings (one strengthened with steel fibres and another without steel fibres), four beams with openings of different sizes(NS) (150mm x 150mm, 200mm x 150mm, 250mm x 150mm and 300mm x 150mm) in the shear zone, four beams with openings of different sizes strengthened using rectangular stirrups around the openings (NRS), four beams with openings of different size strengthened using diagonal bars (NDS) and four steel fibre reinforced concrete beams with openings of different sizes in the shear zone (FS). A solid beam without openings was considered as the control beam. Steel

fibres were used to strengthen the reinforced concrete beam as it prevents the formation of local cracks around the openings.

In the second phase of study, four reinforced concrete beams with openings of size 200mm x 150mm strengthened with steel plates of various thicknesses (2mm, 4mm, 6mm and 8mm) were tested. The results showed that strengthening the duct openings with steel plates of 4mm thickness increased the load carrying capacity, the shear strength and the ductility characteristics of the beam. Therefore, steel plates of 4mm thickness were used for strengthening the opening region for further study.

The third phase of study involved the testing of 8 reinforced concrete beams, four beams with openings of different sizes in the shear zone strengthened using steel plates of 4mm thickness (CS) and four steel fibre reinforced concrete beams with openings of different sizes in the shear zone strengthened with steel plates of 4mm thickness (CFS).

In the fourth phase of study, the finite element analysis software ABAQUS was used to develop finite element models which where validated with the experimental results of reinforced concrete beams with openings of different sizes in the shear zone strengthened using steel plates of various thicknesses.

Based on the experimental and analytical investigation done on the reinforced concrete beams with duct openings of different sizes, the following conclusions were drawn.

6.2 CONCLUSIONS

6.2.1 Beams with Duct Openings

- The presence of openings of different sizes located within the shear zone reduced the ultimate load capacity of the beam from 45% to 70% and the deflecting capacity drastically.

- The first cracks were observed at the opening corners due to the stress concentration at the corners of the openings. Finally, the beam failed in a shear mode at the opening along the two diagonal cracks.

- When the opening size increased, there was reduction in the ultimate load capacity of the beam and the deflection of the beam at mid span due to immediate formation of cracks around the opening region.

6.2.2 Beams with Duct Openings Strengthened using Rectangular Stirrups/ Diagonal Bars

- When internal strengthening was done using rectangular stirrups around the opening in addition to the normal stirrups, the enhancement in the ultimate load capacity of the beam was in the range 6% to 50% in comparison to that for the un-strengthened beam with opening due to the contribution of the internal rectangular stirrups to the shear strength.

- The load carrying capacity was more effective in larger opening compared to smaller opening when rectangular stirrups were used.

- When internal strengthening was done using diagonal bars around the openings in addition to the normal stirrups, the enhancement in the ultimate load capacity of the beam was in the range of 12% to 50% when compared to un-strengthened beams with openings.

- The diagonal bars used in the beams with openings increased the ductile characteristics of the beams considerably.

6.2.3 Beams with Duct Openings Strengthened using Steel Fibres

- Using steel fibres in the beams with openings increased the load carrying capacity in the range 6% to 37%.

- Steel fibres used in beams with openings increased the ductile characteristics of the beams considerably when the openings were of larger size. In reinforced concrete beams with openings (NS), a large single crack was formed but the steel fibre reinforced concrete beams showed better crack distribution and smaller crack width when compared to the reinforced concrete beam with openings (NS).

6.2.4 Beams with Duct Openings of Size 200mm x 150mm Strengthened by Various Thicknesses of Steel Plates

- The beam strengthened with 8mm thick steel plates around the openings (CS200-8) experienced more flexural cracks at the bottom of the mid span than the other beams and the failure occurred due to flexural mode as the shear region was strengthened by steel plates of higher thickness. The ultimate load carrying capacity was less when compared to CS200-4 and CS200-6.

- The strengthening of the beam with opening using 4mm and 6mm steel plates resulted in a remarkable increase in the stiffness of the specimen. Taking into account the cost, 4mm thick steel plates were used for further strengthening the various sizes of the duct openings in the next phase of study to find out the detailed behaviour of beams with openings strengthened using steel plates.

6.2.5 Beams with Duct Openings Strengthened by 4mm Steel Plate

- Stiffening the duct openings with steel plates of 4mm thickness increased the load carrying capacity in the range of 50 to 70% when compared to the unstrengthened beam with openings.

- Crack formation was delayed in the case of beams strengthened using 4mm thick steel plates due to the steel plates around the openings which increased the shear strength of the opening section and resisted the stress concentration at the side of the openings leading to delay in crack propagation. Failure occurred in a flexural mode since the strengthening of the beam with steel plates confined the inner edge of the opening.

6.2.6 Beams with Duct Openings of Various Sizes Strengthened by 4mm Steel Plates and Steel Fibres

- Steel fibres used in reinforced concrete beams with duct openings strengthened by steel plates of 4mm thickness(CFS) considerably increased the load carrying capacity in the range of 0.5 to 1.12 times and the deflection by 0.8 to 1.7 times when compared to reinforced concrete beams without steel plates (NS).

- Crack formation was delayed in the case of steel fibre reinforced concrete beam strengthened using 4mm steel plates.

6.2.7 Analytical results of Reinforced Concrete Beams with Openings of Various Sizes Strengthened by 4mm Steel Plates

The experimental results agreed well with the analytical results. The usage of steel fibres in reinforced concrete beams with openings strengthened by 4mm thick steel plates increased the load carrying capacity. However, in practical situations, it is not possible to use steel fibres always. Thus it was concluded that steel plates can be used to strengthen the smaller openings as well as the larger openings in reinforced concrete beams as it was found to increase the load carrying capacity and the ductile behaviour and reduced the crack formation, delaying the failure of the beam.

6.3 CONTRIBUTIONS

The present investigation contributes to arrive at an optimum method to strengthen the duct openings.

- The presence of openings of different sizes located within the shear zone reduces the ultimate load capacity of the beam (45% to 70%) and reduces the deflecting capacity drastically. The provision of steel plates to strengthen the duct openings considerably increases the load carrying capacity (50 to 70%) and ductility of the beams.

- Beams strengthened using steel plates around the openings resist the stress concentration at the sides of the openings and delay the crack propagation.

- Steel fibres used in reinforced concrete beams with duct openings strengthened by steel plates considerably increase the load carrying capacity when compared to reinforced concrete beams without steel plates.

6.4 SCOPE FOR FUTURE WORK

- In the present study, for all the beams, openings were located in in the shear zone and strengthened using steel plates. The study may be extended to beams with openings in the flexural zone strengthened using steel plates.

- In the present study, all the beams had square and rectangular openings strengthened using steel plates. The study may be extended to beams with circular openings strengthened using steel plates.

- In the present study, openings of all the beams were strengthened by steel plates placed at the inner face of the openings. The study may be extended to beams with openings strengthened at the inner face as well as the exterior surface of the openings.

- In the present study, two openings were present in each beam in the shear zone and strengthened using steel plates. The study may be extended to the beams with multiple openings strengthened using steel plates.