Flexural behavior of reinforced concrete beams with high strength material layer in compression zone

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Abstract. The flexural behavior of reinforced concrete beams with high strength material layers in the compression zone was observed. The compression zone of the beams was filled with high strength material to increase the ductility of the beams. Three control beams and three beams with high strength compression layer were tested until failure. The tested beams were simply supported and loaded with a four-point bending mechanism. The test variable in this study was the ratio of longitudinal reinforcement (1%, 1.5%, and 2.5%). The test results show that the ductility of beams with high strength material in the compression zone is significantly higher than the control beams. However, the flexural capacity of beams with high strength materials is almost the same as the control beam. Theoretical prediction using finite element analysis also confirms that beams with high strength material in the compression zone show higher ductility.

1. Introduction

The method commonly used for seismic rehabilitation is to locally increase the capacity of structural elements. This strategy is carried out by increasing the capacity of structural components for deformation, ductility, strength, and stiffness [1]. The strength and stiffness of structural elements are usually increased by increasing the cross-sectional area of the structural elements. This method can also increase the capacity and reduce the deformation of the structure [2]. One of the processes for increasing the capacity of structural elements can be done by wrapping the existing structural elements with cement grout, as shown in Figure 1.

In this study, cement grout material, which is easily found in the market, was used to simulate the strengthening process, and the performance of the material in resisting compressive forces is investigated. The effect of cement grout installation in the compressive area of the beam on the flexural capacity and ductility of the beam was investigated by examining the increase in beam capacity against deformation. In this study, only the compression zone between the two concentrated loads was filled with cement grout.

In this work, an analytical study using the finite element method is carried out to obtain the deformation behavior and crack patterns of the beam. The analysis was performed using two-dimensional, ATENA commercial software [3]. Furthermore, the results obtained from the test are then compared with the results obtained from analytical work.
2. Experimental study
In the experimental work, six reinforced concrete beams with simple support consisting of three control beams and three beams with cement grout installed on the beam compression zone were tested. The beams were loaded until failure with a two-point load using a hydraulic jack with a capacity of 500 kN. All beams have a cross-section dimension of 125 mm wide and 250 mm high. Whereas the clear span length was 2000 mm, the shear span was 800 mm long. The anchorage length beyond the support was set as 150 mm to avoid premature bond failure [4]. All beams have a shear span-effective depth ratio (a/d) of 3.7. A schematic presentation of beam dimension, experimental set-up, and equipment used is shown in Figure 2.

The load from the hydraulic jacks was spread out into a two-point load using a steel spreader beam. The load from the load cell was measured by the load cell, which is placed on the top of the spreader beam. Meanwhile, the deflections of the beam were measured by the LVDT’s which were placed in the middle of the beam span and at the loading point. This two equipment were connected to a data logger to record data during the test.

Concrete with a design compressive strength of 30 MPa was ordered from a ready-mix concrete company. The maximum aggregate size for concrete was 10 mm. Five concrete cylinders with a size
of 150 x 300mm were prepared for testing the compressive strength of concrete at the age of 28 days. The average compressive strength of concrete obtained from the test was 29 MPa. The stirrups used were the closed type stirrup with a diameter of 10 mm and a yield strength of 529 MPa. The diameter of the longitudinal tensile reinforcement was 13 mm with a yield strength of 400 MPa, and the diameter of the longitudinal reinforcement was 10 mm, with a yield stress of 529 mm. Reinforced concrete beam specimens were cast in wooden formwork. Cement grout was poured after the wooden formwork was removed on the day 28th after the concrete was cast. The compressive strength of cement grout is 60 MPa based on the value obtained from the catalog.

3. Analytical study
The analytical model of the beam can be seen in Figure 3(a). The process of dividing the elements in the finite element model is done automatically by the ATENA software. The finite element model of the beam with element mesh can be seen in Figure 3(b). The model uses only half of the beam for reasons of symmetry. Steel plates with a thickness of 40 mm were positioned on the support and point load to avoid stress concentrations due to the applied loading. Restraints are placed on two important locations of the beam, namely the support and the middle of the span. Restrain rollers are used in the support as well as in the middle of the span to accommodate vertical restrain and vertical deformation of the beam, respectively.

Figure 3. Finite element model of the beam.

Figure 4. The material model used in the analysis.
Reinforcement was modeled with bar elements that extend along half of the beam span. The cement grout and the part of the beam use different macro elements to separate the type of material used in the analytical model. The stress-strain models of concrete, reinforcing steel, steel plate, and cement grout use material models available in the ATENA software, as shown in Figure 4 [3]. Steel plate material located at the support and point loads was modeled using a linear stress-strain model of elastic material. The load is given by adding a small displacement of 0.0001 m for each analysis step. During the analysis process, the load and displacement values are monitored using the monitoring point command included in the software. Nonlinear solutions are carried out using the standard Newton-Raphson method available in the software.

4. Results and discussion

![Figure 5. Crack patterns of the tested beams and obtained from finite element analysis.](image-url)

Figure 5. Crack patterns of the tested beams and obtained from finite element analysis.
Figure 5 shows the beam crack pattern at maximum load obtained from the test results and the crack pattern obtained from the analytical results. The first crack in all beams occurs in the pure bending zone, namely in the area between the two-point loads. The first crack occurs at an average load level of 7 kN. The analytical results show that the average first crack load is almost the same as the test results. The beam crack pattern in the tension region and the shear span area shows a pattern that is not much different between the test and analytical results.

![Figure 6. Load-deflection curves of tested beams.](image1)

![Figure 7. Comparison between test (dashed line) and analytical results (solid line).](image2)

The difference in the crack pattern can be seen in the compressive zone of the beam, which is in the zone between two concentrated loads. It can be seen from Figure 5 that there is concrete crushed between two concentrated loads on the control beams. However, in beams with cement grout, the
concrete crushed occurred beside the zone filled with cement grout. This shows that cement grout with higher compressive strength can avoid concrete destruction in the compressive zone.

Figure 6 shows the load-deflection curve obtained from the test results. These results indicate that the capacity of the control beams is not much different from the capacity of beams with cement grout. However, the deformation of beams with cement grout is much greater than that of control beams. This causes the ductility value of beams with cement grout greater than control beams. Figure 6 also shows the effect of the tensile reinforcement ratio on the capacity and ductility of the beam. Beams with a higher tensile reinforcement ratio show a higher capacity value but less ductility. Figure 7 shows a comparison between the analytical results and the test results. It can be seen from the figure that there is no significant difference between the analytical results and the test results. This proves that the finite element model can predict the flexural behavior of the tested beams with reasonable accuracy.

5. Conclusions
Six reinforced concrete beams consisting of three control beams and three beams with high strength material layers in the compression zone were tested to study the flexural behavior of the beams. The results of this study provide the following conclusions:
- The crack pattern of the beam in the compressed zone is influenced by the presence of cement grout.
- For all specimens, as the ratio of tensile reinforcement increases, the capacity of the beams increases, but the ductility decreases.
- The compression zone filled with cement grout can significantly increase the ductility of the beam.
- Analytical prediction using ATENA software can predict test results with reasonable accuracy.

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