Shear Strength of Reinforced Concrete Beams Strengthened with Near Surface Mounted Steel Plates

R Thamrin¹,*, S Haris¹, and Zaidir¹

¹Civil Engineering Department, Engineering Faculty, Universitas Andalas, Padang, Indonesia

*Corresponding author: rendythamrin@eng.unand.ac.id

Abstract. Near surface mounted horizontal steel plates was applied to study the contribution of this strengthening method on the shear capacity of reinforced concrete beams. Specimens were nine reinforced concrete beams without stirrups consisting of three control beams and six beams strengthened with steel plates. The test variables were the ratio of the longitudinal reinforcement and the position of steel plates in the vertical direction of the web side of the beam. The specimens were loaded up to failure using a four-point bending test. The contribution of steel plates on the shear capacity was observed by monitoring the ultimate load and deflection of the beams. The test results show that the shear capacity of beams strengthened with steel plates 17% to 50% higher than the control beams depending on the position of steel plates and the ratio of longitudinal reinforcement. It was also observed that the ratio of longitudinal reinforcement influences the failure mode of the beams.

1. Introduction
It is widely known that one of the simplest methods to strengthen an existing reinforced concrete structure is to increase the quantity of reinforcement by gluing steel plates, steel bars, FRP plates, FRP bars or FRP sheets to the surface of the structural elements [1]. However, inadequate protection from environmental attacks may decrease the service life of the strengthened structure. In a decade, near surface mounted (NSM) reinforcement was introduced as a technique for strengthening existing reinforced concrete structures [2,3].

Some reports have been published related to the application of the NSM technique [4-10]. It is reported that structural elements strengthened with NSM reinforcement show higher load-bearing capacity [4]. It has also been proven that this method is an effective way to increase the shear capacity and ductility of reinforced concrete elements [5,6]. This method also provides better fire resistance than lamination with externally bonded reinforcement (EBR) [6]. In another report [7] the position of NSM steel plates significantly affects the stiffness and flexural capacity of the beam. Comparison between the NSM and EBR methods is presented in another report [9] where the report states that the adhesion of the NSM method is better than the EBR.

From the reports in the above literature, further studies on the contribution of steel plates to the shear strength of reinforced concrete beams are still needed. The objective of this study is to determine the effect of steel plate installation on the shear strength of reinforced concrete beams. In addition, the position of the plate was also investigated by installing steel plates in two different positions. Variations in shear capacity requirements are carried out using three types of longitudinal reinforcement ratios as test variables. Furthermore, the theoretical flexural capacity of each specimen needs to be known to determine the ultimate flexural capacity of the beam. In this study, the calculation of the complete response of the beam flexural capacity is carried out with a computer program that has been developed by the author.
2. Experimental study
The effect of steel plate installation on the shear strength of reinforced concrete beams was experimentally investigated by means of four point bending tests. Test set-up and loading arrangement for each beam are shown schematically in Figure 1. Applied load and resulting deflections at each beam were recorded continuously using a load cell and LVDT’s. Load cell and LVDT’s were connected to a data logger and the data was stored on data media.

Two different positions of steel plates and three different longitudinal reinforcement ratios were chosen as the test variables to observe the effect of steel plate installation on the shear strength as shown in Figure 2. The beam cross-section was 125x250mm and the diameter of longitudinal reinforcing bars was 13 mm with a yield strength of 394 MPa. The concrete compressive strength on the basis of 28 days cylinder crushing strength was 23.7 MPa.

![Figure 1. Beam dimension and four point bending tests mechanism.](image)

![Figure 2. Beam cross-section and positions of steel plates.](image)

For each of the specimens, the groove cuts were initially prepared on the vertical side of the formwork. The groove dimension was 50 mm wide and 5 mm deep. The formwork was released after 28 days of curing time. Then, the groove surfaces were cleaned to remove out fine particles and dust.
The epoxy adhesive paste (Sikadur 31) is filled halfway into the grooves using a palette knife. Then the steel plates (3 mm thick and 50 mm width and yield strength of 304 MPa) were placed on the top of the adhesive layer and pressed lightly along the plates. The grooves were finally filled with epoxy adhesive paste and the surface was levelled. Table 1 shows the beams data, details of the reinforcement and test results.

### Table 1. Details of test beams and test results.

| Specimens   | Beams data | Longitudinal reinforcement (Tensile) | Calculated Flexural Capacity |
|-------------|------------|-------------------------------------|-----------------------------|
|             | $f_c$ (MPa) | $b$ (mm) | $H$ (mm) | $d$ (mm) | $a$ (mm) | $\phi_0$ (mm) | $N$ (mm) | $\rho$ (%) | $V_f$ (kN) | $V_m$ (kN) |
| Control beams | 220 | 2 | 1.0 | 26.2 | 4.5 | 17.8 |
| G2C-2 | 220 | 3 | 1.4 | 38.4 | 8.4 | 19.0 |
| G2C-3 | 205 | 5 | 2.6 | 57.5 | 5.0 | 26.8 |
| Type I | G2P1-1 | 220 | 2 | 1.0 | 37.0 | 5.3 | 35.2 |
| G2P1-2 | 23.7 | 125 | 250 | 220 | 800 | 13 | 3 | 1.4 | 48.3 | 6.1 | 40.3 |
| G2P1-3 | 205 | 5 | 2.6 | 61.5 | 5.2 | 34.3 |
| Type II | G2P2-1 | 220 | 2 | 1.0 | 42.7 | 7.5 | 29.4 |
| G2P2-2 | 220 | 3 | 1.5 | 54.0 | 6.2 | 25.0 |
| G2P2-3 | 205 | 5 | 2.5 | 68.9 | 5.9 | 34.5 |

3. Analytical study

The moment-curvature analysis was carried out in order to obtain the theoretical flexural capacity of the beam. This calculation requires the formulation of reinforced concrete sectional response [11]. It is assumed that the stress-strain relationship of concrete and steel are known. The stress-strain model of concrete adopted from the literature [12] was applied while the bilinear stress-strain model for steel reinforcement and steel plates was used in this study. The procedure is started by dividing the beam cross-section into several thin layers. The next step is assuming the value of curvature and axial strain. Then the stresses and internal forces are calculated by using assumed stress-strain laws of concrete and steel. The equilibrium of internal forces is achieved by the iteration process. Once the equilibrium is satisfied the moment at corresponding curvature can be calculated. Then the calculation process can be continued to the next value of curvature. The maximum concrete compression strain was taken as 0.003. Figure 3 shows an analytical model for the strengthened beam cross-section and schematic algorithm of an analytical procedure is shown in Figure 4.

![Figure 3. Analytical model for the strengthened beam cross-section [8].](image)

![Figure 4. Schematic algorithm of the analytical procedure [8,9].](image)

4. Test results and discussion

At the early steps of loading, the flexural crack was first developed in the constant moment zone at an average load level of 6 kN. As the load increased, the flexural crack developed to the shear span zone which then propagated to become diagonal shear cracks.
In all tested beams diagonal shear crack were observed in the shear span zone as shown in Figure 5 to Figure 7. Soon after the occurrence of diagonal shear cracks, the beams failed in shear except for beam G2P1-1. Beam G2P1-1 was failed in the flexural type of failure indicated by crushing of compression zone between two point loads. Typical crack patterns of the tested beams at failure are shown in Figure 5, Figure 6 and Figure 7.
Figure 8 shows the load-deflection curve of the tested beams. It is shown that the curves suddenly drop due to shear failure except for beam G2P1-1. Analytical predictions of flexural capacity for both beams with and without steel plates are shown in Figure 9 and Figure 10. It can be seen that only the G2P1-1 beam reaches an ultimate bending capacity which is also confirmed by the analytical results.

Figure 8. Test results based on beams categories.

Figure 9. Comparison between control beams, strengthened beams type 1 and analytical results.

Figure 10. Comparison between control beams, strengthened beams type 2 and analytical results.
Figure 11. Comparison between strengthened beams type 1 and strengthened beams type 2.

Even though majority of the beams failed in shear but the shear capacity of the strengthened beams higher than control beams for about 17% to 50% as shown in Figure 9, Figure 10 and Figure 11. These results also prove that steel plates contribute significantly to the shear capacity of the beam. It was found from the test results that the plate in the centre of the beam height contributed to the greater shear strength although analytical results show the opposite results. It was also observed that the contribution of steel plates to resist shear forces decreases with increasing ratio of longitudinal reinforcement.

5. Conclusions
Nine reinforced concrete beams were tested. The comparison between two positions of steel plates are discussed and based on the test results the following conclusions are drawn:
1. Shear capacity of the strengthened beams higher than control beams for about 17% to 50%.
2. The plate position in the centre of the beam height contributed to the greater shear strength.
3. The contribution of steel plates to resist shear forces decreases with increasing ratio of longitudinal reinforcement.

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