Experimental study: Shear behaviour of reinforced concrete beams using steel plate strips as shear reinforcement

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Abstract. Stirrups bars are widely used as shear reinforcement in reinforced concrete beams. It is quite attractive to explore the use of another type of material for stirrups. This study aims to investigate the shear behaviour of reinforced concrete beams using steel plate strips and conventional stirrups as shear reinforcement. Two full-scale reinforced concrete beams were tested to fail in shear in this experimental program, and the test parameter for this study was the types of shear reinforcement. The shear resisting behaviour of the beam specimens was discussed by evaluating the crack patterns, load-deflection response and the shear strengths of the beam specimens. The shear capacities determined experimentally were compared with the prediction values calculated based on the Modified Truss Theory. The ratio of the measured to estimated shear strength in the steel plate RC beams and reference beam showed a fairly good agreement as these ratios were only slightly different. Results of this study show that there is only a slight difference in the global behaviour of the steel plate RC beam and the reference beam using conventional stirrups.

1. Introduction
Over the last decade, researchers have been attempting to find new methods for shear reinforcement. Different types of shear reinforcements have been studied on reinforced concrete beams [1-5]. Apart from the widely adopted vertical stirrups, other methods of shear reinforcements recently studied are; bent-up bars, inclined stirrups and swimmer bars. The first study using steel plates for shear reinforcement was carried out in 2015, and this topic remains widely unexplored.

Researchers performed an experimental study on the effect of steel plate in shear reinforced wide beam concrete [6]. The authors presented that using steel plate in combination with stirrups increased the shear capacity, load capacity, as well as ductility in the RC wide beams. Also, the authors concluded that using independent steel plate in wide beams that require a large number of flexural reinforcements provides anchorage feasibility which is much easier than providing stirrup legs in the cross-sectional area of wide beams.

Ibrahim and Ameer conducted experimental research to investigate the effect of using internal steel plates for shear reinforcement on the flexural behaviour of self-compacting reinforced concrete beams [7]. The thickness and spacing of the steel plate were varied in their experiment. The authors concluded that the ductility in all beams using internal shear plates was lower than the control beam. Also, using thicker steel plates increased the ultimate carrying capacity of the reinforced concrete.
beams. The yield load in beams using steel plates as shear reinforcement was lower than the control beam using traditional stirrups. The lower yield load in the steel plate reinforced concrete beams led to a corresponding higher deflection than the control beam by an average of 13.72%.

Ammash [8] carried out an experimental and theoretical study on the behaviour of reinforced concrete beams using steel plate strips as shear reinforcements. The result of this study showed that using steel plate strips improved the shear capacity of RC beams. Also, the author reported that the steel plate can control the crack width and reduce the length and number of cracks compared with reinforced beams with regular stirrups.

2. Research significance
Based on the illustrated literature reviews, results from the previous research showed that using steel plate strip as a shear reinforcing material can help control crack width after the development of diagonal cracks. The advantages of using steel plate strips in RC beams are the relatively cheap cost of the material compared to traditional shear rebars, improvement of shear capacity, control of crack width and reduction in the length and number of cracks. Nevertheless, the use of closed-profile steel plate strips as shear reinforcements remains unexplored. In this study, the shear resisting behaviour of RC beam with steel plate strips type of shear reinforcement is compared to that of RC beam with traditional stirrups. The shear resisting behaviour of the beam specimens is discussed by evaluating the crack patterns, load-deflection response and the shear strengths of the beam specimens.

3. Experimental program

3.1. Materials
In this study, a relatively high tensile reinforcement ratio and low concrete compressive strength were used to ensure the beams fail in shear. The steel bars used in this study have a nominal diameter of 10 mm, 22 mm and 25 mm. The steel plate strips used in this study have a nominal cross-section of 3 x 26 mm (Figure 1). The concrete properties are presented in Table 1 and the reinforcing steel mechanical properties are presented in Table 2.

![Figure 1. Model of steel plate strip used as shear reinforcement.](image)

Table 1. Concrete properties.

| Property                        | Average Values |
|---------------------------------|----------------|
| Slump (mm)                      | 102.00         |
| Compressive Strength (MPa)      | 13.51          |
| Concrete Strain (µε)            | 1211.25        |
| Weight (Kg)                     | 11.85          |
| Unit Weight (Kg/m³)             | 2235.24        |
| Splitting Tensile Strength (MPa)| 1.80           |
Table 2. Properties of steel reinforcements.

| Reinforcing Steel | Yield Stress (MPa) | Ultimate Stress (MPa) | Elongation (%) |
|-------------------|--------------------|-----------------------|----------------|
| D10               | 265.06             | 428.41                | 11             |
| D22               | 397.72             | 560.08                | 24             |
| D25               | 365.70             | 556.25                | 34             |
| Plate 3 x 26      | 222.92             | 304.86                | 44             |

3.2. Details of test specimens

During the experimental program, two beam specimens were tested. One beam specimen used 3x26 mm steel plate strips as shear reinforcement, while the other served as the reference beam using 10 mm conventional stirrups. The beam specimens were named using alphabets and numbers. The beam specimen having the B-S initials (Figure 2(b)) represent the steel plate strips RC beam, while the beam specimen having the B-K initials (Figure 2(c)) represent the reference beam. The test region is located between two simple supports, and the remaining length of the beam is overhung on both ends. Shear span to depth ratio of 3.0 is used across all beams to investigate the behaviour of the RC slender beam with different types of stirrups. In all beams, the flexural reinforcement contained 3#22 bars and 2#25 bars corresponding to a tensile reinforcement ratio of 2.02%, and additional 2#10 longitudinal rebars in the compression zone which serve as hangers for the shear reinforcements (Figure 2(a)).

![Typical elevation view of beam specimens.](image1)

![Details of reinforcements and cross-sections (units in mm).](image2)

3.3. Test facilities and instrumentation

The loading test was carried out at the Structural Laboratory of the Department of Civil Engineering, Universitas Sebelas Maret. The loading frame was equipped with a 500 kN capacity hydraulic jack for the load application (Figure 3). The load cell which was attached to the hydraulic jack was used to measure the applied load. For a uniform distribution of the two-point load, a steel beam was utilized.
A linear vertical displacement transducer installed at the midspan of the beam specimens was used to measure the specimens’ deflection during the loading test. The specimens’ deflection was monitored until the beams failed in shear. Cracks that formed on the surface of the beams were marked at a loading interval of 10 kN.

Figure 3. Test program set-up.

4. Behaviour of test specimens

4.1. Failure mode
The failure mode of all beam specimens was typical diagonal tension. As expected, all of the beam specimens failed in shear. After the formation of the first inclined crack, the specimens showed a ductile response by resisting more shear force accompanied by the further development of shear cracks. The diagonal crack penetrating the compression zone near the loading points caused the shear failure.

4.2. Crack pattern
Generally, the flexural cracks occurred early in the specimens midspan. The first flexural cracks occurred at load around 40 – 60 kN in all beam specimens. When the applied loads increased, new vertical flexural cracks spread horizontally from the midspan into the shear span. At load around 100 – 120 kN, inclined flexure-shear cracks started developing. Increasing the load, diagonal cracks appeared. As the load increased further, more flexural cracks appeared, and the diagonal crack penetrating the compression zone caused the shear failure.

Figure 4 displays the crack patterns exhibited in the beam specimens. At the ultimate stage of the beams, the steel plate strips RC beam developed more cracks and flatter angle of diagonal cracks compared to the reference beam using conventional stirrups. The angle of the critical diagonal crack in steel plate strips RC beam range between 25° to 35° at different loading intervals. In the reference beam, these values range between 38° to 42°.

4.3. Load-deflection response
The test program involved identifying the relationship between the applied load and midspan deflection for each beam (Figure 5). The midspan deflection at different loading intervals was obtained using a linear displacement vertical transducer (LVDT). Under the load control system's employment, the applied load-midspan deflection curves can only be recorded up to the peak load, after which further load increase is no longer possible. Before the formation of the first flexural crack, the steel plate strips RC beam showed a linear elastic response. As the load increased, flexure-shear cracks eventually developed causing the load-midspan deflection curves to be roughly linear. At ultimate shear, the curve becomes almost horizontal. However, the load-deflection curve for the
reference beam shows a quite different response. It can be observed that in the load-deflection curve for the reference beam, there is no reduction in stiffness after the first flexural cracking. The reason for this behaviour cannot be properly explained because it counters the existing theories. However, the author assumes that the reason for this response difference could be due to imperfection in the testing procedures. The deflection at maximum load in the reference beam is lower than the steel plate strips RC beams by an average of 19.31%.

![Crack patterns of the beams at ultimate stage.](image)

**Figure 4.** Crack patterns of the beams at ultimate stage.
5. Measured and estimated shear strengths

The shear strength of the B-S300 and B-K300 are not directly comparable due to slight unintended differences in stirrup’s cross-sectional area and yield strength. Hence, the stirrups type influence is determined indirectly by normalizing the measured strengths of the beams with the prediction ones. The estimated shear strength of reinforced concrete with shear reinforcement $V_{cal}$ is taken as the addition of the concrete contribution $V_{c,cal}$ and the shear resisted by the stirrups $V_{s,cal}$, as expressed in Equations (1), (2), and (3). In this study, Niwa’s equation [9] was used to estimate the concrete shear contribution $V_{c,cal}$, and the Modified Truss Theory with the 45° angle of diagonal compression [10] was employed to predict $V_{s,cal}$.

$$V_{cal} = V_{c,cal} + V_{s,cal}$$

$$V_{c,cal} = 0.20(f'_c \rho_n)^{1/3} \left( \frac{d}{1000} \right)^{-1/4} \left( 0.75 + \frac{1.4}{a/d} \right) bd$$

$$V_{s,cal} = \frac{A_v f_y d}{s}$$

where, $f'_c$: concrete compressive strength (N/mm²); $d$: effective depth (mm); $\rho_n$: ratio of tensile reinforcement (%); $a$: shear span length (mm); $b$: beam width (mm); $A_v$: area of 1 set of shear reinforcements (mm²); $f_y$: yield strength of shear reinforcement (N/mm²); $s$: stirrups spacing (mm).

Table 3 shows the normalized shear strength of the RC beams with different types of stirrups. Based on the $V_{test}/V_{cal}$ ratios, it seems that the prediction values underestimate the actual shear capacity. This might also be due to the high ratio of flexural reinforcements used in the beam specimens. The ratio of B-S300 is relatively lower compared to that of the B-K300 by 6.7%. A slightly different tendency was reported in the experiment conducted by Ammash [8]. He used relatively higher shear reinforcement ratios and smaller beams (with a beam height of one-third of that taken in this research).
In his study, the shear strength of the steel plate strips RC beam tended to have almost the same or higher value than the conventional beams.

**Table 3.** Shear strength of beam specimens.

| Specimen | $V_{\text{test}}$ (kN) | $V_{\text{c,cal}}$ (kN) | $V_{\text{cal}}$ (kN) | $V_{\text{cal'}}$ (kN) | $V_{\text{test}} / V_{\text{cal}}$ |
|----------|------------------------|------------------------|----------------------|-----------------------|-------------------------|
| B-S300   | 172.50                 | 95.58                  | 48.70                | 144.28                | 1.20                    |
| B-K300   | 197.50                 | 95.58                  | 58.20                | 153.85                | 1.28                    |

6. Conclusions

The present study evaluates the shear behaviour of RC slender beam with different types of web reinforcements. Two kinds of web reinforcements which were adopted in this study are the steel plate strips and conventional stirrups. The ratio of the measured to estimated shear strength in the steel plate strips RC beam is slightly lower than that of the reference beam. Regarding the crack development in the RC beams, the steel plate strips RC beam tend to develop more and flatter cracks in the shear span. The deflection at maximum load in the reference beam is lower than in the steel plate strips RC beams by 19.31%.

7. References

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