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# THE EFFECTS OF INCLINED SHEAR REINFORCEMENT IN REINFORCED CONCRETE BEAM

Nor Fazlin Zamri, Roslli Noor Mohamed*, NurHafizah A. Khalid & Kang Yong Chiat

*Department of Structures and Materials, Faculty of Civil Engineering, 81310 Johor Bahru, Johor, Malaysia*

*Corresponding Author: *roslli@utm.my*

***Abstract:*** This paper presents the findings of an experimental data on the effects of inclined shear reinforcement in reinforced concrete (RC) beam. Two types of shear reinforcement of RC beam were investigated, conventional stirrups (vertical links) and inclined shear reinforcement (45 degrees of inclined shear reinforcement). The RC beam with conventional stirrups was designated as a control specimen. The RC beams with different types of shear reinforcement were tested for shear under four-point loading system. Comparisons were made between both types of RC beam on load-deflection, load-steel strain, load-concrete strain behaviour and mode of failure. The theoretical and experimental were calculated by using conventional formulation in accordance to EC 2 in order to verify the experimental results. From the results, it was observed that the RC beam with 45 degree inclined shear reinforcement improved structural performance in shear by approximately 20% and thus prolong the shear failure behaviour as compared to the RC beam with vertical links.

**Keywords:** *Inclined shear reinforcement, reinforced concrete beam, conventional stirrups, vertical links.*

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## 1.0 Introduction

Sudden failure of reinforced concrete structure due to low strength must be avoided. In the design requirement, the shear reinforcement must be provided when the value of actual shear stress exceeds the permissible shear stress of the concrete at design stage. The shear reinforcement is important to prevent shear failure by increasing the ductility of the beam. Conventional shear reinforcement has been used widely in the construction industry due to the simplicity in the fabrication and installation. Congestion near the support of the beams due to close spacing between links is unavoidable due to development of high shear region. Thus, other types of shear reinforcement such as bent-up bars (Qader *et al.*, 2013) and (Leondardt,1965), swimmer bars (Al-nasraand

Asha, 2013), the combination of inclined and horizontal bars (Abdul Hamid, 2005), horizontal shear reinforcement (Yang *et al*., 2007) and inclined shear reinforcement were investigated to solve congestion issue by applying less amount of steel whilst maintaining similar shear resistance as conventional shear reinforcement.

The use of inclined shear reinforcement has not been popular in the industry due to the difficulty of fabrication. However, diagonal cracking pattern of shear failure in RC beams support the fact that inclined position is more effective in resisting the shear (Saravanakumar and Govindaraj,2016), (Suhaimi,2015), (Colajanni *et al.*,2014)compared with the use of vertical position as recommended by Eurocode 2 (EC2,2004) and ACI 318-14(2014); the actual shear reinforcement configuration was in inclined position. This is stipulated in clause 6.2.3 EC2 (2004), in that "the concrete acts as the top compression and diagonal compression member inclined at the angle $\theta$ to the horizontal and EC2 (2004) limits the $\theta$ value to be between 22 to 45 degrees". It is also proved that structures failed due to shear forces transferred through diagonal compression struts as observed by Mohamed and Elliott (2008). Therefore, in this study, the use of inclined links in the high shear region was investigated to examine the efficiency the inclined links as compared with vertical links in RC beams.

Previous findings from Saravanakumar and Govindaraj (2016), Suhaimi (2015)and Colajanni *et al.,* (2014) supported the fact that inclined links provided the most effective solution for beam having high shear at disturbed region. This study is carried out to investigate the effects of using inclined shear reinforcement at 45 degrees for the whole span of the beams. The observations were made on the load-deflection behaviour, load-steel strain behaviour, load-concrete strain behaviour and mode of failure. Furthermore, theoretical shear capacity was calculated using conventional formulation and compared with vertical links to verify the experimental results.

## 2.0 Materials and Methods

### *2.1 Concrete*

The concrete mix were prepared and designed according to Building Research Establishment, (BRE) (1997). The type of cement used in this concrete mix is Ordinary Portland Cement (OPC). 10mm diameter size aggregates and river sand were used as coarse and fine aggregates in this mixture. Admixture (superplasticizers) was added at the rate of 1.0 % by cement weight to increase the workability of the concrete. The concrete mix proportion is given in Table 1.

The slump test was carried out to detect the change in workability according to BS1881(1983). The slump test gave a result of 60 mm. Trial mix was carried out prior to the actual testing including the preparation of six concrete cubes with dimension of

100mm x 100mm x 100mm. The concrete specimens were left in water tank for curing process for a period of 28 days.

Table 1: Concrete mix proportions

| Concrete materials | Mix proportions (kg/m$^3$) |
|---|---|
| Cement | 379.6 |
| Fine aggregate | 849.9 |
| Coarse aggregate | 920.6 |
| Water | 205 |

### *2.2 Manufacturing of Beams*

Two reinforced concrete (RC) beams were designed according to EC2 (2004). Figure 1 shows the dimension of beam. High tensile steel with grade of 460 MPa and mild tensile steel with grade of 250 MPa were used for main reinforcement and shear links, respectively. In detail, the bar size for links, tension and compression reinforcement used were 6mm, 16mm and 10mm, respectively. The cross-section of control RC beam with vertical links, RCB-A, is shown in Figure 2. Meanwhile, the detailing and cross-section of the RC beam with inclined links of 45 degrees (RCB-B) are shown in Figures 3 and 4, respectively. Both samples were casted at the same time and covered with damp sponge and wet sacks for 28 days for curing process.

The steel strain gauge of TML (Tokyo Sokki Kenkyujo Co. Ltd. of Japan) type FLK-6-11 was used to measure the steel strain. Two steel strain gauges were attached at shear reinforcement at location of 309mm distance from the left and the right end from support of the beam. Additionally, the concrete strain gauge of TML type PL-60-11 also was applied to measure the surface concrete strain during the tests. Two concrete strain gauges were attached at the surface of concrete at the same location with steel strain gauges, as shown in Figure 1.

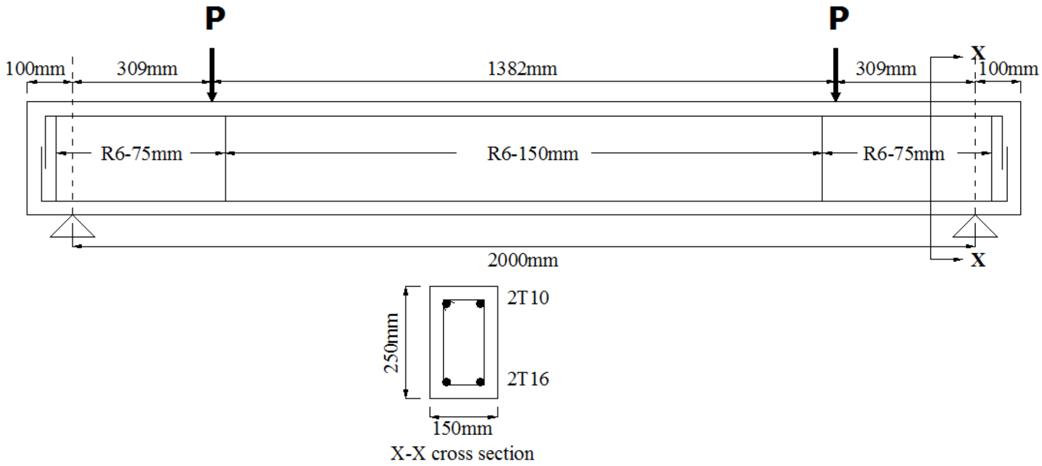


Figure 1: Beam dimension

Figure 2:Cross-section of RCB-A

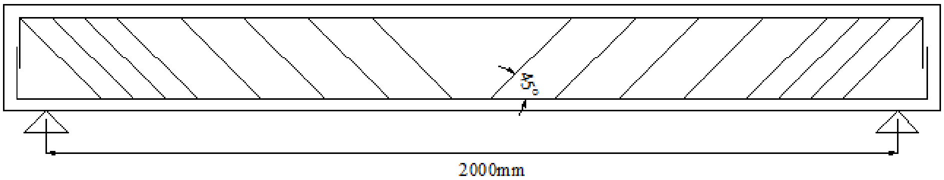


Figure 3: Detailing of RCB-B

Figure 4:Cross-section of RCB-B

## *2.3 Test on beams*

The beams were tested under four-point loading test arrangement as shown in Figure 5. The loading was positioned at 309mm from support, resulting in a ratio of shear span to effective depth ($a_v/d$) of 1.5. The beams were tested when the concrete reached the age of 28 days. The beams were tested by using universal testing machine with 200 kN load cell. A linear variable displacement transducer (LVDT) was vertically attached at the concrete soffit at the centre of beam's span in order to measure the deflection of tested beam. The load was applied manually using hydraulic jack, at interval of 10 kN. During the load interval, strain at reinforcement and concrete surface were recorded and checked for any crack propagation.

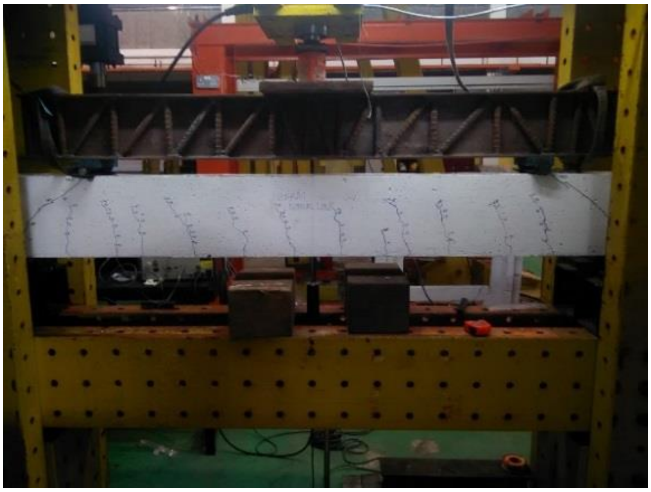

Figure 5: The testing arrangement

## 3.0 Results and Discussion

The compression test was carried out at 7 and 28 days in accordance to BS EN 12390-3(2009). The average compressive strength of concrete cube specimens is 46 MPa.

### *3.1 Load-Deflection Behaviour of Beam*

Figure 6 shows the comparison between RCB-A and RCB-B in terms of load-deflection relationship. From the figure, the deflection of RCB-A and RCB-B at applied load of 200 kN were 14.78 mm and 3.72 mm, respectively. RCB-B shows approximately about 75% reduction of deflection compared with RCB-A at applied load of 200 kN. The difference in deflection values for both beams may be due to the stiffness of beam. Generally, stiffness is an initial slope of load-deflection curve. The behaviour of RC beam with inclined links was found more ductile than RC beam with vertical links.Thus, RC beam with inclined links, RCB-B had experienced smaller deflection compared with the RC beams with vertical shear reinforcement. Moreover, the RCB-B showed higher performance in load resistance as compared to RCB-A of about 20%. Lower load resistance shows brittleness behaviour of such beam specimens.

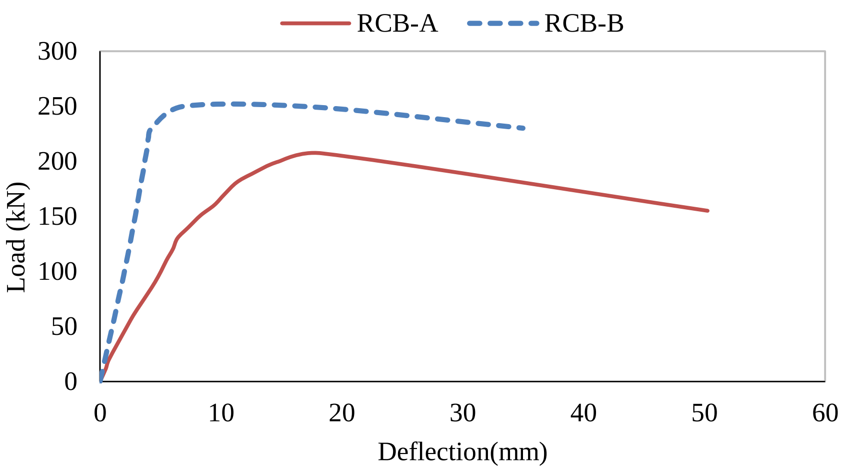


Figure 6: Load-deflection behaviour of RC beams

### *3.2 Load-Steel Strain Behaviour of Beam*

Figure 7 shows the comparison of RCB-A and RCB-B in terms of load-steel strain relationship. From the figure, the steel strain value of RCB-A registered lower strain value as compared to RCB-B at applied load of 200 kN. This is due to the fact that the inclined steel in RCB-B effectively take the strain as compared to RCB-A. This clearly indicates that the RCB-A failed at 207 kN. This phenomenon indicates the vertical links are less significant to resist the shear as compared to the inclined links in RCB-B. In this case, the shear reinforcement with 45 degrees of inclination had improved the performance of beam at shear condition. This is because the inclined position of shear reinforcement is perpendicular to the diagonal cracking pattern of the RC beam as reflected in Clause 6.2.3 (EC2, 2004). Hence, it clearly shows that the RCB-B could delay the shear failure as well.

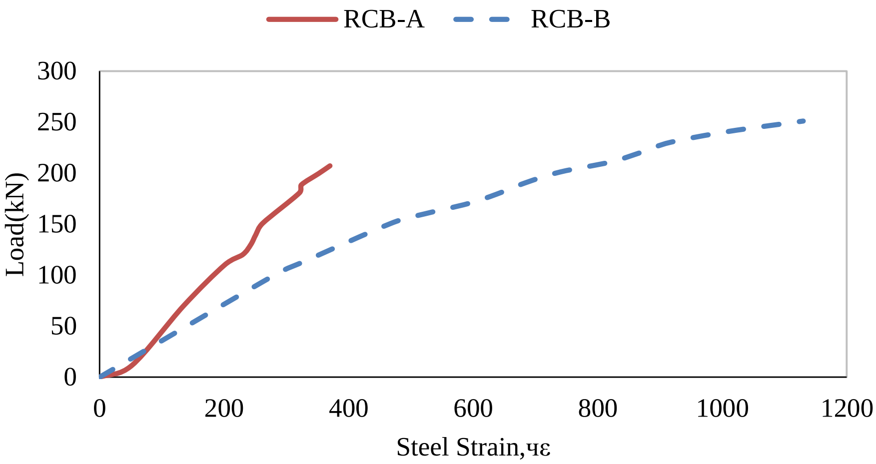


Figure 7: Load steel strain behaviour of RC beams

### *3.3 Load-Concrete Strain Behaviour of Beam*

Figure 8 show the comparison of RCB-A and RCB-B in terms of load-concrete strain relationship. The figure shows the concrete strain value of RCB-A at applied load of 200 kN is 3000 $\mu\varepsilon$ as compared to RCB-B, in which the concrete strain of that beam had approximately about 2000 $\mu\varepsilon$. In this case, the concrete of RCB-A failed in compression before the steel yielded. The beam failed dramatically without any sign of warning. For RCB-A, it was concluded that concrete was working to resist load. The vertical links in RCB-A work lessthan the inclined links in the RCB-B. In contrast, the concrete was crushed due to excessive shear stresses. Thus, the concrete itself needs to work more in resisting the load.

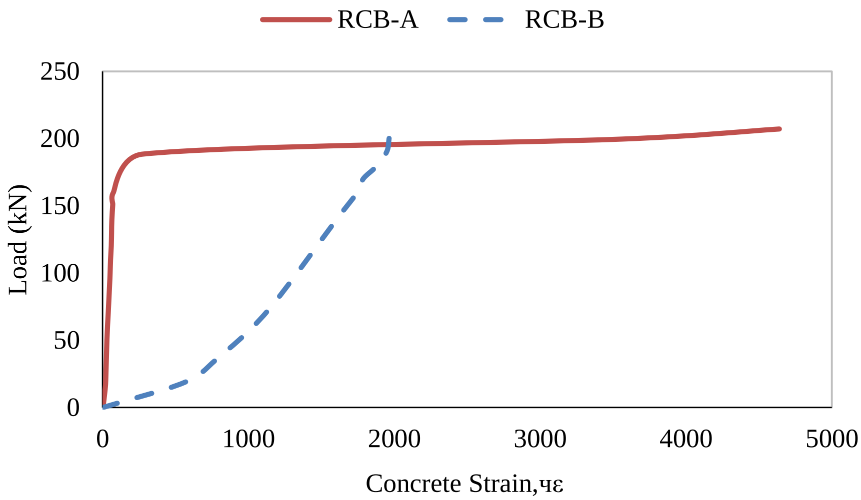


Figure 8: Load concrete strain behaviour of RC beams

### *3.4 Mode of Failure*

Figure 9 show the mode failure of both types of RC beams. The first flexural crack in RCB-A occurred at an applied load of 40 kN. The cracks initiated from the tension face of the beam in vertical direction propagated to the mid depth of the beam. As the load increased, more flexural cracks were visible at moment region. Shear crack started to become visible at an applied load of 90 kN and continued to propagate diagonally towards the loading point. At ultimate, the concrete crushed at applied load of approximately 207kN. As for RCB-B, the first flexural crack occurred with an applied load of 50kN.The cracks initiated from the tension face of the beam vertically propagated to the mid depth of the beam. Shear crack started to become visible at an applied load of 135 kN and continued to propagate toward the loading point. It can be concluded that the RCB-A showed better performance in flexure action but not in shear. On the other hand, the RCB-B specimens indicated better resistance in shear loading.

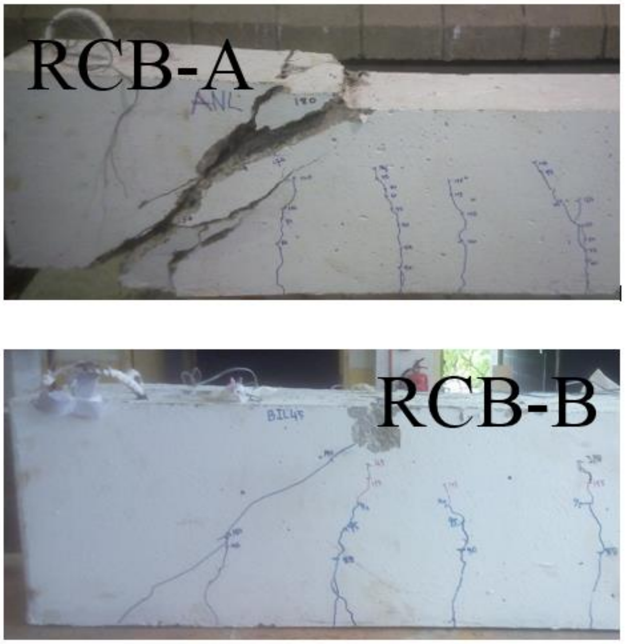


Figure 9: Mode failure of RC beams

### *3.5 The Comparison of Experimental and Theoretical Value of Shear Capacity*

In order to calculate the shear resistance of the beams used in the experiment work, EC 2 was referred in this study. The calculation of theoretical shear capacity is given by Eq. 1, Eq. 2 and Eq. 3 as adopted from EC2 as follows;

$$V = V_{Rd,c} + V_{Rd,s} \qquad \text{(Eq.1)}$$

$$V_{Rd,c} = \frac{0.36 f_{ck} b_w d (1 - \frac{f_{ck}}{250})}{(\cot\theta + \tan\theta)} \qquad \text{(Eq.2)}$$

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} (\cot\theta + \cot\alpha)\sin\alpha \qquad \text{(Eq.3)}$$

where:

$V_{Rd,c}$ = The design shear resistance of the member without shear reinforcement.
$V_{Rd,s}$ = The design value of the shear force which can be sustained by the yielding shear reinforcement
$f_{ck}$ = The compressive strength of concrete.
$b_w$ = The minimum width between tension and compression chords.

d = Effective depth.
$A_{sw}$ = The cross sectional area of the shear reinforcement.
s = The spacing of the stirrups.
z = The inner lever arm.
$f_{ywd}$ = The design yield strength of the shear reinforcememt.
θ = The angle between the concrete compression strut and the beam axis perpendicular to the shear force.
α = The angle between shear reinforcement and the beam axis perpendicular to the shear force.

Table 2 showed the summary of shear value calculated from Eq. 1 to 3, while Table 3 presented the comparison of shear capacity between theoretical value and experimental value.

Table 2: The calculation of shear capacity

| | $V_{Rd,s}$(kN) | $V_{Rd,c}$(kN) | V (kN) |
|---|---|---|---|
| RCB-A | 37.47 | 171.41 | 208.8 |
| RCB-B | 49.5 | 170.10 | 219.6 |

Table 3: The comparison of shear capacity between theoretical value ($V_{calc}$) and experimental value ($V_{exp}$).

| | $V_{exp}$ (kN) | $V_{calc}$(kN) | $\frac{V_{calc}-V_{exp}}{V_{calc}}$ (%) |
|---|---|---|---|
| RCB-A | 207 | 208.8 | 0.7 |
| RCB-B | 250 | 219.6 | 12.2 |

As mentioned in the relationship of load-steel strain, inclined shear reinforcement works effectively until it yielded as compared with vertical shear reinforcement. The graph of relationship as shown in Figure 7 proved the calculation of shear resistance of steel,$V_{Rd,s}$. According to the calculation from EC2, the value of $V_{Rd,s}$ for inclined shear reinforcement (49.5kN) is higher than the value of $V_{Rd,s}$ for vertical shear reinforcement (37.5kN). The strength of 45 degrees of inclined shear reinforcement in RCB-B was about 30% higher than the vertical shear reinforcement in RCB-A. The calculation of concrete shear resistance, $V_{Rd,c}$ does not show much difference. The graph of relationship of load-concrete strain as shown in Figure 8 had supported the calculation of $V_{Rd,c}$. According to the calculation, the concrete in RCB-A worked effectively, more than the vertical links in resisting the applied load. This is one of the reasons the RCB-A failed immediately after reaching the ultimate load. In addition, the comparison of shear capacity between theoretical and experimental are shown in Table 3. In the case of RCB-A, the experimental value is only 0.7% lower than the calculation value. This beam was expected to fail at an applied load of 208.8 kN. However, the beam failed slightly lower than the expected result.

On the other hand, in a comparison of the theoretical value and experimental value of the RCB-B, the difference is only about 12.2% as the experiment was terminated due to the lack of equipment and it needs further investigation However, according to the observation, this beam may have bigger shear capacity than the calculation.

## 4.0 Conclusion

From the experimental study, the following conclusions can be drawn:

(a) The inclined links significantly enhance the ductility of beams. The increase in the shear capacity is about 20% compared with the control beam. Therefore, the use of inclined links is an effective technique to enhance the shear capacity of reinforced concrete beam.

(b) Concrete in RCB-A works more than the vertical links in resisting the load. The concrete of RCB-A was failed in compression before steel yield. The steel strain value $\varepsilon_{st} < 2000\ \mu\varepsilon$ while the concrete strain, $\varepsilon_{cc} > 3000\mu\varepsilon$. The failure of this beam is sudden and without any sign of warning.

(c) The EC2 design codes was used to predict the shear strength of reinforced concrete beams with vertical links and inclined links. RCB-B achieved the highest value of shear resistance (219.6 kN) while RCB-A did not show much difference with the calculation of shear capacity at 208.8 kN. The percentage difference between the experiment reading of RCB-A shear capacity and the calculation value is less than 1%, while the experiment reading of RCB-B only shows a difference of about 12.2%.

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