Shear cracking behavior of RC beams with side face reinforcement

Irish Sultan TAMBIS
Candidate for the Degree of Master of Engineering
Supervisor: Professor Tamon Ueda
Division of Engineering and Policy for Sustainable Environment

Introduction

The on-going studies of the problem of cracking have been encouraged particularly on shear cracking in reinforced concrete structures because of the adverse effects it can cause with regards to the structural performance during serviceability conditions. Shear cracks with uncontrollable widths occurring in the structures can become the cause of reduction of structural performances because it can allow corrosion of reinforcements, reduce the water/air-tightness and even deteriorates its appearance. Structural codes give guidelines for checking the amount of reinforcement required for the structure to limit the cracking to a certain value. The use of side face bars to large and deep beams are provided by the codes for the control of cracking. However, several construction industries are now using side face reinforcement even to not so deep beams as their common practice. Still, not so much information is available for the shear cracking behavior considering additional parameter in the RC beam.

Experimental Program

In order to investigate the influence of various parameters, an experimental program was carried out. All beams in rectangular cross section have constant depth and width of 400 mm and 200 mm, respectively and with clear concrete cover of 25 mm. Cross sectional details and typical layouts are shown in Fig. 1. All beams were subjected under monotonic loading but before carrying out the test for shear crack investigation, contact chips designated as demec points arranged in rosette strain gauges were attached to the concrete surface with adhesive. The demec digital mechanical strain gauge with precision of 0.001 mm was used to measure the concrete deformations shear cracking by calibrating first to correct errors before using. Typical locations showing in rosette arrangement are shown in Fig. 2. The rosette demec points stations can be used to obtain the concrete strain in horizontal X, vertical Y and diagonal Z direction using 100 mm gauge length [1], as shown in Fig. 2. Only the demec point stations intersecting with single major shear crack was considered in the investigation.

The measurements of concrete strains combined with the record of shear crack angle was used to estimate shear crack displacements i.e. shear crack opening (width) that occurs in the direction perpendicular to shear crack and shear crack sliding in the direction of shear crack [1] (Fig. 2).

Fig. 1 Layout and cross-sectional details of the specimens

Fig. 2 Typical location and definition of of the demec points along surface of each beam
Table 1. Measured shear cracking behavior and loadings

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Measured diagonal crack spacing, mm</th>
<th>Measured vertical crack spacing, mm</th>
<th>Measured average crack angle, degree</th>
<th>Measured flexural crack load, Vfcr (kN)</th>
<th>Measured shear crack load, Vc (kN)</th>
<th>Predicted flexural crack strength (JSCE 2007) (kN)</th>
<th>Predicted shear crack strength (JSCE 2007) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1 left</td>
<td>117.59</td>
<td>119.73</td>
<td>87.00</td>
<td>59.50</td>
<td>&gt;172.50</td>
<td>46.60</td>
<td>150.80</td>
</tr>
<tr>
<td>B1 right</td>
<td>96.17</td>
<td>102.74</td>
<td>52.00</td>
<td>80.80</td>
<td>106.60</td>
<td>51.10</td>
<td>82.70</td>
</tr>
<tr>
<td>B2 left</td>
<td>91.36</td>
<td>102.19</td>
<td>49.00</td>
<td>79.50</td>
<td>121.30</td>
<td>64.70</td>
<td>88.00</td>
</tr>
<tr>
<td>B2 right</td>
<td>74.06</td>
<td>88.30</td>
<td>44.00</td>
<td>79.50</td>
<td>111.70</td>
<td>64.70</td>
<td>88.00</td>
</tr>
<tr>
<td>B3 left</td>
<td>85.97</td>
<td>89.56</td>
<td>67.67</td>
<td>41.10</td>
<td>191.70</td>
<td>48.80</td>
<td>124.90</td>
</tr>
<tr>
<td>B3 right</td>
<td>73.02</td>
<td>70.78</td>
<td>50.67</td>
<td>101.30</td>
<td>119.30</td>
<td>48.80</td>
<td>68.70</td>
</tr>
<tr>
<td>B4 left</td>
<td>93.45</td>
<td>92.06</td>
<td>47.50</td>
<td>80.00</td>
<td>120.50</td>
<td>67.60</td>
<td>102.40</td>
</tr>
<tr>
<td>B4 right</td>
<td>94.49</td>
<td>95.67</td>
<td>62.00</td>
<td>60.30</td>
<td>102.40</td>
<td>67.60</td>
<td>102.40</td>
</tr>
</tbody>
</table>

The shear crack angle corresponds to each shear crack intersecting with certain rosette station was measured as the average angle which are the values at each major crack and get the mean. This follows the measured crack width through concrete displacement is the average crack width in the particular station of demec point.

Experimental Investigation and Discussion

Crack patterns of all the tested specimens were recorded with shear crack angles. The first batch of cracks were flexural cracks occurring in the mid-span zone, and as the load was increased, a series of flexural cracks was formed in the shear span region then rotated to form flexural-shear cracks connecting the loading and supporting points. Additional shear cracks also appeared during the subsequent loading stages.

The series of relationship are represented giving the effect of each parameter on the shear crack width and shear crack spacing. All characteristics conditions are the same except for the indicated parameter (shear span to depth ratio $a/d_e$, longitudinal reinforcement ratio $\rho_L$, stirrup spacing and number and diameter of side reinforcement). The different variation of parameters has significant effect on the cracking behavior of beam. The shorter span created smaller diagonal crack spacing. Possible reason for the slightly smaller crack spacing in shorter span is due to higher local bond stress along flexural reinforcement due to small length span, which is induced by greater moment change per unit length. Because of limited cases, additional investigation is considered to be necessary to disclose the effect of shear span to depth ratio on the spacing between cracks. Shear crack opening increases proportionally with strains of both shear reinforcements and side face reinforcements. Indicating that the stirrup and side reinforcement has something to do with shear crack width.

It can be inferred that the higher longitudinal reinforcement ratio and higher side face reinforcement (bigger diameter) ratio promotes controlled cracking by reduced shear crack width and diagonal crack spacing. This is because of the increased bond between the shear reinforcement or side reinforcement and the surrounding concrete. The number of layer of side reinforcement also showed effects on the shear crack spacing and shear crack width. Providing more layers reduced the shear crack widths and shear crack spacing as well.

It was also observed that the larger stirrup spacing and larger side bar spacing yields greater crack width and spacing between shear cracks at the same stirrup strain and side bar strain. The reason for this behavior is the larger diagonal crack spacing created with larger spacing of reinforcements. The smaller stirrup spacing can significantly reduce the spacing between shear cracks due to decreasing the effective concrete area, in which shear crack is controlled by stirrup or side face reinforcement. Hence, increasing the bond effect between the reinforcement and the surrounding concrete results in reducing the transfer length (or crack spacing) because forces are transferred into the concrete between cracks. All influential parameters are in agreement with the previous studies (Zakaria et.al [1]; Adebar and Leeuwen [2]).

Development of the proposed model

Shear crack spacing

The development of the model for diagonal crack spacing is from the harmonized model of Zakaria et.al [3] and previous models and from the CEB-FIP [4-5] model codes. Zakaria et.al [1] successfully predicted shear cracking behavior using the harmonized model from Collins and Mitchell [6], CEB-FIP [4-5] model code and from the model provided by CSA-S474-04 (Canadian Standard Assoc.) [7] and NS-3473 E (Norwegian code) [8] for the crack spacing normal to the shear and
longitudinal reinforcement. The proposed model becomes:

\[
S_{mx} = 2c_x + 0.2S_{eqx} + k_1k_2 \frac{\phi(1-\rho_x)}{3.6\rho_x} \\
S_{my} = 2c_y + 0.2S_{eqy} + k_1k_2 \frac{\phi(1-\rho_y)}{3.6\rho_y}
\]

(1) (2)

where \(c_x\) and \(c_y\) are concrete covers; \(S_{eq} = \frac{(n_1-1)s_1^2+n_2s_2^2}{(n_1-1)s_1+n_2s_2}\) is the equivalent spacing of the main reinforcement and side reinforcement with \(n\) and \(S\) are number of bars and bar spacing, respectively. The \(\phi = \frac{n_1\phi_1+n_2\phi_2}{n_1+n_2}\) is the equivalent diameter of the main reinforcement and side reinforcement for different diameters from fib Model Code [9]; \(k_1\) the coefficient for bond characteristics of the bars as 0.4 for deformed bars and 0.8 for plain bar and \(k_2 = \frac{0.25(\varepsilon_1+\varepsilon_2)}{2\varepsilon_y}\) is the coefficient for strain gradient both from Canadian Standards Association (CSA-S474)[7] (\(\varepsilon_1\) and \(\varepsilon_2\) are the largest and smallest tensile strains respectively in the embedment effective zone) which is 0.25 for pure tension.

The shear crack spacing is embraced from the fib Model Code [9] \(S_{eq}\), in which the shear crack spacing is related to the crack control characteristics of both the longitudinal and transverse reinforcement, represented by \(S_{mx}\) and \(S_{my}\):

\[
S_{m\theta} = \frac{1}{S_{mx}^{0.125} + S_{my}^{0.125}}
\]

(3)

**Evaluation of the Proposed Model with the Experiment Result**

**Evaluation of shear crack spacing using existing models and proposed model**

From Fig. 5, most of the existing models overestimated the experimental result of crack spacings. The reason for this overestimation is that the existing models does not take into account the effects of crack control characteristics of the side reinforcement. The proposed model shows closer values that are near the average line and with lesser coefficient of variance compared with existing models.

![Fig. 5 Prediction result using proposed and existing models](image)

**Evaluation of the model for shear crack spacing using available literature**

The use of proposed model to the available experimental result of shear crack spacing shows that the model predicts with 0.99 average predicted-to-experiment ratio and 31.67% coefficient of variation (COV) which means the proposed model is applicable to beams without side reinforcement.

![Fig. 6 Accuracy of the proposed model for average shear crack spacing for the conventional RC beam](image)

**Shear crack width**

The formulation of shear crack width equation, considers the combination of the physical model in the change of strain in flexure and the contribution of shear reinforcement at particular location of crack to be analyzed.

\[
w_x = S_{m\theta}(\varepsilon_y\beta\sin\theta + \varepsilon_{cry}\cos\theta)
\]

(4)

where, \(\beta = \frac{(\gamma_y-\gamma_{na})}{\gamma_{na}}\), the strain gradient at a particular location of crack; \(\varepsilon_y\) is the primary reinforcement strain at \(d_e\) (effective depth); and \(\varepsilon_{cry}\) is the crack strain at distance from the shear reinforcements and \(\theta\) is the cracking angle.

**Shear crack width evaluation**

The shear crack width prediction model is evaluated along with existing models as shown in Fig. 7. The accuracy of the models is examined by comparing the experimental shear crack widths with the shear crack

- **Fig. 7 Comparison of shear crack width results**

<table>
<thead>
<tr>
<th>Model</th>
<th>Ave</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>COV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed Model</td>
<td>0.99</td>
<td>0.01</td>
<td>0.95</td>
<td>0.99</td>
<td>0.04</td>
<td>31.67%</td>
</tr>
</tbody>
</table>
widths predicted by the different models from codes and previous studies (CEB-FIP model [4], CEB-FIP model [5], De Silva et al [10], Shinomiya and Watanabe [11] and Zakaria et al [3]). The shear reinforcement (stirrup) and side reinforcement strain measured at the location nearest to the shear crack width considered location is used for the determination of shear crack width. And it can be seen in Fig. 7 that the proposed model has the better prediction than the existing models. The result in the shear crack spacing reflects to shear crack width calculation as crack width is in direct relationship with crack spacing.

![Images](Images)

**Conclusions**

The following conclusions can be drawn from the study:

- The factors to be considered for the prediction of shear crack width in RC beams are strains of the nearest shear reinforcement and side reinforcement from the considered crack and the spacing between shear cracks. The relative location of the shear reinforcement and side reinforcement affects shear crack widths.
- The existing models for shear crack spacing and shear crack width do not consider the additional reinforcement along sides. Thus most of the result using existing prediction model overestimated the result of the experiment for shear crack spacing and shear crack width observing the average ratio of prediction-to-experiment ratio and coefficient of variance (COV) with having the greater percentage.
- Considering the above investigated parameters, a generalized shear crack spacing model and shear crack width model in reinforced concrete members was proposed.
- Still, further experiment with more series of specimens for more parameters, including beam height, is needed for better understanding of the shear cracking behavior of RC members and to check further the reliability of the model.

**References**


