Ultimate shear force of R/C beam failed in bond splitting

H. Takagi  
Meiji University, Japan  
H. Matsubara  
Fujita Corporation, Japan

ABSTRACT: The authors discuss the effect of high-strength web reinforcement on resistance to splitting bond failure in beam that precedes flexural yielding of the member subjected to bending and shear under a monotonic loading test. This paper describes the following manner, splitting bond failure in the member of the beam, splitting bond strength along bars, shear capacity of the member accompany by splitting bond failure.

1 INTRODUCTION

When a bending shear force is applied, splitting bond failure may occur in such a way that the covering concrete around deformed bars is split by the wedge action of the reinforcing steel node, and bearing strength deteriorate accordingly. This phenomenon, termed splitting bond failure, is attracting attention in many associated fields. In this failure, the bonding force between reinforcing steel and the surrounding concrete is lost by the splitting action. The main reinforcement's stress is thus not transmitted to the concrete, and as a result the truss mechanism, which is an essential component of any reinforced concrete structure, is no longer maintained. Much research on the use of high-strength reinforcing steel is in current progress. The application of high-strength reinforcing steel as stirrups to utilize its high tension capacity, however, decreases the ratio of the stirrup, which in turn increases the likelihood of a splitting bond failure. In this paper, we collectively discuss the features of splitting bond failure and the effect of stirrups on bearing strength and on splitting bond failure.

2 EXPERIMENTAL RESULTS

2.1 Experimental parameters

Table 1 shows the parameters the authors used in the experiments on high-strength stirrups. The table indicates that the experiment consists of three series (A, F, B) in which the cross section, concrete strength, and the amount of main reinforcements are varied. The A-series has a cross section of 20x30 cm, three super high-strength main reinforcements that are subjected to tensile force (deformed PC bar of 23 mm diameter and 93755 N/cm² of σₚ), and a concrete strength of 2746 N/cm². The F-series, like the A-series, has three super high-strength main reinforcements that are subjected to tensile force sufficient to cause a splitting bond failure. The B-series, which is different from the F-series, has five super high-strength main reinforcements that are subjected to tensile force such that a splitting bond failure is prevented. In each series, the amount of stirrups and the strength were made variables and their effects were evaluated. Throughout the whole series, the shear span ratio was determined to be a/D = 2.0.

2.2 Test specimens

Table 2 shows 16 test specimens for this discussion. In the A-series, the stirrups' yield strength σₚ and diameter were selected as variable factors and the intervals between stirrups were made constant. In the F and B-series, high-tension steel of 98100 N/cm² or more was used as stirrups, and the stirrup diameter and the intervals were changed to provide three different web-reinforcement ratios (pₚ).

In the A-series, concrete was vertically placed from the upper end of the beam, but in the F and B-series, concrete was horizontally placed from the side face to avoid a difference between the bonding forces in the reinforcements at the upper and lower ends.

2.3 Load application and measurement method

Load was applied in one direction loading of the bending and shear in the antisymmetric moment mode method (Ohno-system). All test specimens were loaded in the same pattern in such a way that a uni directional force less than or equal to 2/3 of the ultimate bearing strength was applied twice, then the load was increased until the specimen failed. In the measurement, the vertical displacement of the beam's center point with respect to the stabs at both side was measured. Also, the strains of the main reinforcements and stirrups were measured.
3 EXPERIMENTAL RESULTS

Table 2 lists the experimental results. Figure 1 shows a typical example of the comparison of the load-deformation curve and cracks at the maximum bearing strength for the F-series and B-series.

3.1 Maximum bearing strength

In every series, if the yield strength ($\sigma_y$) of the stirrups is the same, the greater the web reinforcement ratio ($\rho_w$), the greater the maximum bearing capacity: if the web reinforcement ratio ($\rho_w$) is the same, the greater the yield strength ($\sigma_y$), the greater the maximum bearing strength. When the F-series and B-series with different numbers of main reinforcements are compared for the same $\rho_w$, the B-series with five main reinforcements subjected to tensile force shows that the maximum bearing strength and the amount of deformation are greater than those of the F-series.

3.2 Failure conditions

The main reinforcements were not yielded in any test specimens. In the A and F-series, the maximum bearing strength was reached with splitting bond failure. In the B series, splitting bond failure rarely occurred and the maximum bearing strength was reached with bearing failure.

4 SPLITTING BOND STRENGTH ALONG BARS

The primary research studies conducted in Japan on splitting bond strength of the deformed bars have been those of Morita and Fujii (Ref. 1) and of Shibata and Sakurai (Ref. 2). According to Morita’s research, the splitting bond strength is related to the web reinforcement ratio but is unrelated to the strength while according to Shibata, it relates to the strength of web reinforcement. Figure 2 shows a typical example of the relation between the bond stress ($\tau_w$) in each region of a test beam and the shear force applied to it as observed by our tests. The value of $\tau_w$ gradually increases along with increases in shear force. When bond cracks form in a region, the region experiences a decrease in $\tau_w$. The decrease starts from the region near the point of maximum tensile force in each longitudinal bar, but the maximum bond stress in each region does not occur simultaneously. The average value $\tau_{wav}$ of bond stresses through regions (3)~(7), shown in Figure 3, continues to increase even after bond cracks form in a specific region and the value of $\tau_{wav}$ in the region turns to decrease. It does not tend to decrease until the ultimate strength of the beam is reached. The maximum value of the bond stress $\tau_{wmax}$ in each region was almost the same irrespective of the value of $\sigma_y$ and $\rho_w$. The value was estimated to be 0.97 $\tau_{wmax}$ (unit: kgf/cm²) corresponding to the value proposed by Morita as the maximum bond resistance of a bar which is fully restrained by web reinforcement. The web reinforcement decreases the bond stress gradually after bond crack forms in the region. Hence, a maximum value for the average bond stress $\tau_{wmax}$ throughout the bond failure regions increases as a function of the increase in $\rho_w$ but independent of the strength of the web reinforcement, as shown in Figure 4. The maximum average bond stress can be calculated based on the formula proposed by Morita and Fujii shown later. Muguruma and Watanabe ran tests to study the relationship between the maximum average bond stress for splitting bond failure in columns and values of $\rho_w \sigma_y$ and/or $\rho_w$. They concluded that a better correlation was obtained between the maximum average bond stress and the value of $\rho_{wmax}$ than between the bond strength and the value of $\rho_w \sigma_y$ (Ref. 3). These two research studies indicate that the splitting bond strength along a bar is a function of the web reinforcement ratio $\rho_w$ and does not depend on the strength of web reinforcement, as stated by Morita. Also, the bond stress does not decrease rapidly after the maximum value is reached, if a larger amount of web reinforcement is applied.

5 SHEAR CAPACITY OF THE BEAM MEMBER CAUSED THE SPLITTING BOND FAILURE

The committee on reinforced concrete structures at the Architectural Institute of Japan (hereafter referred to as AIJ) proposed in 1988 the following new formula to predict the ultimate shear strength of reinforced concrete beams and columns (Ref. 4).

\[
Q_o = b_1 \rho_{wmax} \sigma_y \cot \phi + \cot \theta \left( 1 - \beta \right) b \cdot D \cdot \nu f' \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \nu \n
of reinforced concrete members and the limit for effective reinforcement are predicted very well by modifying new A11 for shear.

NOTATIONS

\( b \): width of diagonal concrete struts for arch mechanism (cm)
\( b \): width of diagonal concrete struts for truss mechanism (cm)
\( b \): width of web of a member (cm)
\( c_t \): thickness of cover concrete to horizontal direction (cm)
\( c_v \): thickness of cover concrete to vertical direction (cm)
\( d_s \): diameter of longitudinal reinforcement (cm)
\( D \): total depth (cm)
\( j_c \): distance between top and bottom of longitudinal bars (cm)
\( L \): clear span length of the member (cm)
\( s \): intervals of shear reinforcement (cm)
\( A_{se} \): cross section area of shear reinforcement in one set (cm\(^2\))
\( \Sigma \phi \): total of circumferential length in longitudinal reinforcements (cm)
\( \theta \): angle of compressive strut of concrete in arch mechanism to longitudinal axis
\( \nu \): effective factor of compressive strength of cracked concrete
\( n \): number of longitudinal tensile reinforcement

REFERENCES

Fig. 1 - Comparison of bond splitting failure and shear failure

Fig. 2 - Relationships between bond stress ($\tau_a$) and shearing force in each region of a beam

Table I Outline of test

<table>
<thead>
<tr>
<th>Series</th>
<th>Section h x D (cm)</th>
<th>Clear span length (cm)</th>
<th>Effect depth of beam, d (cm)</th>
<th>Strength of concrete, f' (kgf/cm²)</th>
<th>Main relia. ratio; p₁, (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-series</td>
<td>20 x 30</td>
<td>120</td>
<td>21.0</td>
<td>280</td>
<td>2.99 (3-021)</td>
</tr>
<tr>
<td>F-series</td>
<td>20 x 40</td>
<td>160</td>
<td>21.5</td>
<td>280</td>
<td>1.72 (4-021)</td>
</tr>
<tr>
<td>B-series</td>
<td>20 x 40</td>
<td>160</td>
<td>31.4</td>
<td>280</td>
<td>2.06 (5-021)</td>
</tr>
</tbody>
</table>

3110
Fig. 3-Relationships between average bond stress ($\overline{\tau_b, av}$) and shearing force

$$\tau_a (\text{kgf/cm}^2)$$

$$Q (\text{m})$$

Morita's formula

Top reinforcement

Bottom reinforcement

Fig. 4-Relationships between maximum average bond stress ($\overline{\tau_b, av}$) and $P_w$

$$\overline{\tau_b, av} (\text{kgf/cm}^2)$$

$P_w (%)$

- ■ Bond stress of bottom reinforcement
- ▲ Bond stress of top reinforcement

Fig. 5-Comparison between test values of ultimate shear force at splitting bond failure and calculated values by modified AJ new formula

$Q_{\text{test}} (\text{m})$

$Q_{\text{calc}} (\text{m})$

Table 2: Specimens and results of test

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Stirrup</th>
<th>$\tau_b, av$ (kgf/cm²)</th>
<th>$P_w$ (%)</th>
<th>$\phi$ (°)</th>
<th>Strength of concrete: $T_s$ (kgf/cm²)</th>
<th>Max. load: $Q_s$ (tonf)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-30-043</td>
<td>3600</td>
<td>0.43</td>
<td>6.0</td>
<td>205</td>
<td>18.06</td>
<td>15.38</td>
<td>B</td>
</tr>
<tr>
<td>A-30-077</td>
<td>3880</td>
<td>0.77</td>
<td>8.0</td>
<td>205</td>
<td>19.04</td>
<td>15.38</td>
<td>B</td>
</tr>
<tr>
<td>A-30-121</td>
<td>2140</td>
<td>1.11</td>
<td>10.0</td>
<td>205</td>
<td>22.38</td>
<td>22.38</td>
<td>B</td>
</tr>
<tr>
<td>A-30-015</td>
<td>1610</td>
<td>0.15</td>
<td>5.0</td>
<td>282</td>
<td>12.62</td>
<td>12.62</td>
<td>B</td>
</tr>
<tr>
<td>A-30-016</td>
<td>1990</td>
<td>0.50</td>
<td>5.0</td>
<td>287</td>
<td>16.33</td>
<td>16.33</td>
<td>B</td>
</tr>
<tr>
<td>A-30-059</td>
<td>2230</td>
<td>0.19</td>
<td>7.0</td>
<td>273</td>
<td>18.42</td>
<td>18.42</td>
<td>B</td>
</tr>
<tr>
<td>A-120-033</td>
<td>11710</td>
<td>0.30</td>
<td>5.0</td>
<td>286</td>
<td>19.67</td>
<td>19.67</td>
<td>B</td>
</tr>
<tr>
<td>A-120-058</td>
<td>11850</td>
<td>0.39</td>
<td>7.0</td>
<td>276</td>
<td>19.72</td>
<td>19.72</td>
<td>B</td>
</tr>
<tr>
<td>A-120-017</td>
<td>11940</td>
<td>0.77</td>
<td>8.0</td>
<td>286</td>
<td>20.40</td>
<td>20.40</td>
<td>B</td>
</tr>
<tr>
<td>A-120-121</td>
<td>13360</td>
<td>1.11</td>
<td>10.0</td>
<td>280</td>
<td>22.80</td>
<td>22.80</td>
<td>B</td>
</tr>
<tr>
<td>F-120-019</td>
<td>10030</td>
<td>0.19</td>
<td>6.0</td>
<td>351</td>
<td>22.38</td>
<td>22.38</td>
<td>B</td>
</tr>
<tr>
<td>F-120-059</td>
<td>10820</td>
<td>0.39</td>
<td>8.0</td>
<td>353</td>
<td>29.09</td>
<td>29.09</td>
<td>B</td>
</tr>
<tr>
<td>F-120-121</td>
<td>10870</td>
<td>1.11</td>
<td>10.0</td>
<td>353</td>
<td>43.30</td>
<td>43.30</td>
<td>B</td>
</tr>
<tr>
<td>B-120-018</td>
<td>10530</td>
<td>0.19</td>
<td>6.0</td>
<td>352</td>
<td>23.05</td>
<td>23.05</td>
<td>S</td>
</tr>
<tr>
<td>B-120-059</td>
<td>10820</td>
<td>0.39</td>
<td>8.0</td>
<td>354</td>
<td>48.42</td>
<td>48.42</td>
<td>S</td>
</tr>
<tr>
<td>B-120-121</td>
<td>10870</td>
<td>1.11</td>
<td>10.0</td>
<td>355</td>
<td>55.10</td>
<td>55.10</td>
<td>S</td>
</tr>
</tbody>
</table>

* Failure mode (B: Splitting bond failure, S: Shear failure)