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# Effect of bond and dowel action on shear capacity of RC beams

Katsumi Kobayashi
*Fukui University, Japan*

ABSTRACT: The effect of the dowel action and the bond deterioration caused by it on the shear capacity and on the failure mode was analytically discussed. Next, the condition of the bond and dowel behavior for obtaining the large shear capacity was also analytically discussed. Based on those discussions, the intensive shear reinforcing arrangement was proposed. And its effectiveness was proved by experiment.

## 1 INTRODUCTION

The shear failure mode of RC beam changes from the shear tension failure mode to the shear compression failure mode and also the ultimate shear strength increases, according to the increase of the amount of shear reinforcement. The shear force causes the inclined shear crack. The dowel shear force acts on the main bar when the inclined shear crack reaches the main bar. If the amount of shear reinforcement is small, the shear crack develops to the splitting crack along the main bar and the bond deterioration occurs in a wide region as shown in Fig.1. Finally the concrete in the compressive zone at beam ends crushes and the bearing force decreases. This is called the shear tension failure and the large shear capacity can not be expected.

If the dowel action would be restrained and the propagation of the splitting crack along the main bar would be also restrained, the shear failure mode would move to the shear compression failure side and also the shear capacity would increase. Of course, it agrees with this thinking to place the large amount of shear reinforcement. The heavy shear reinforcement, however, disturb the good concrete casting.

The objective of this study is to propose the reasonable intensive shear reinforcing arrangement, which can avoid the dense spaced arrangement and can contribute the increase of the shear capacity, considering the effect of the bond and dowel action on the shear capacity and the failure mode.

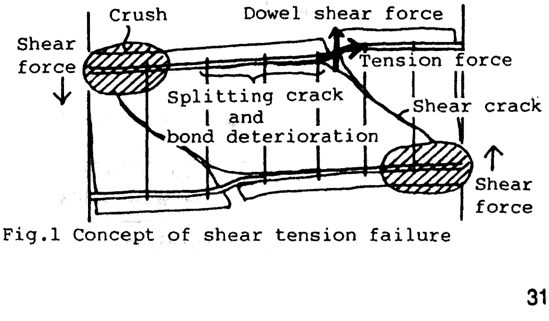


Fig.1 Concept of shear tension failure

## 2 CORRELATION BETWEEN BOND AND DOWEL ACTION

The experiment was carried out simulating the main bar in RC beam which the shear crack crossed. Based on the experimental results, the bond stress-slip relation model was proposed, considering the correlation with the dowel action (Kobayashi 1989,1990).

The proposed model is shown in Fig.2. The maximum bond stress($\tau_{max}$) is 4.9MPa. $\tau_{max}$ is, however, reduced in the region of 2 to 3 times of bar diameter(d) from the position where the crack crosses the bar. Initial bond stiffness($K_v$) is 98KN/cm$^3$. The second degrading bond stiffness($\alpha \cdot K_v$) is affected by the positional relation between the crossing crack and the stirrup, and by the magnitude

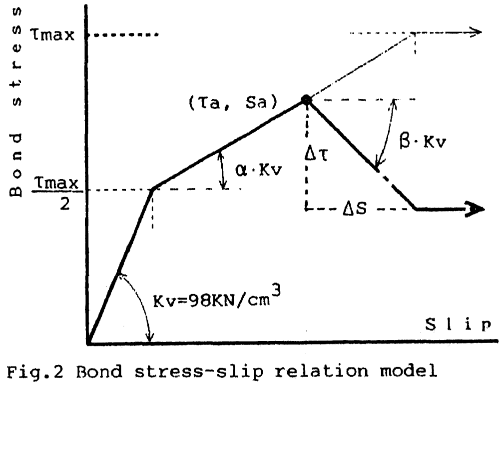


Fig.2 Bond stress-slip relation model

of dowel shear force. If there is no dowel affection $\alpha$ is 0.2. And $\alpha$ increases up to 1.0, according to the increase of dowel affection. When the splitting crack along the main bar occurs, immediately the bond deteriorates from ($\tau_a$, $S_a$). The deterioration of bond stress($\Delta\tau$) was formulated as $\Delta\tau = \tau_a - \tau_a^2 / \tau_{max}$ based on the experimental results. As for the increasing slip($\Delta S$), no correlation could be found with any parameter. Here the experimental average value ($\beta$=0.2) was adopted.

## 3 BOND AND DOWEL BEHAVIOR IN SHEAR FAILURE

### 3.1 Analytical model

The analytical model for the discussion is shown in Fig.3. The dimensions were assumed to be those of the tested beam shown in Fig.6. The concrete truss connected by nodes A, B, C and D represents the diagonal stress transfer called the arch action. The other elements construct the beam mechanism.

The boundary elements, which consisted of two springs, were introduced between A-E and A-C, and between B-F and B-D. It is assumed that the spring, which is orthogonal to the main bar, is sufficiently rigid against the compressive force and carries some tensile force. If the tensile force exceeds the tensile strength, however, the tensile force disappear and the splitting crack opens. The spring, which is parallel to the main bar, represents the bond resistance and has the characteristics shown in Fig.2.

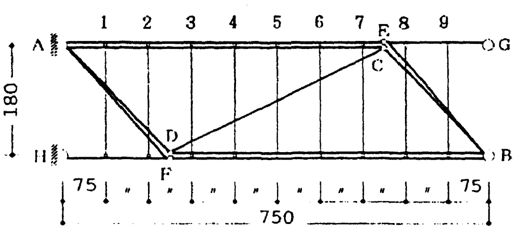

Fig.3 Analytical model

The properties of each element should be given some general values. In this study, however, they were roughly given from the viewpoint to investigate the qualitative behavior. Elements A-E and B-F had the equivalent axial and flexural rigidities considering the compression bar and the cover concrete. Elements E-G and F-H represent the tension bar. Its axial rigidity was given the same value as that of elements A-E and B-F. Its flexural rigidity was infinitely large. The shear reinforcement has the elasto-plastic behavior and its yield stress of 588MPa was given. The sectional area of C-D element was determined considering the tensile stress in beam web. As for the elements A-C, A-D, A-F, B-D, B-C and B-E, the area was decided so that the truss consisted of these elements was approximately equivalent to the strut of the arch mechanism proposed by AIJ guidelines (AIJ 1990). The properties of element are listed in Table 1.

Table 1 Properties of elements

| Elements | E ($\times 10^5$MPa) | A ($cm^2$) | I ($cm^4$) |
|---|---|---|---|
| A-E , B-F | 1.96 | 8.5 | 18.0 |
| E-G , F-H | 1.96 | 8.5 | ∞ |
| A-C , B-D | 0.196 | 40.0 | ∞ |
| C-B , D-A | 0.196 | 40.0 | 0.0 |
| C-D | 0.196 | 320.0 | 0.0 |
| E-B , F-A | 0.196 | 40.0 | 0.0 |
| Shear Reinf. | 2.058 | 0.56 | 0.0 |

The nodes A and H are pin-supported. The same vertical displacements were given to the nodes G and B, keeping their horizontal displacement equal. Then, the anti-symmetric bending moment condition was produced.

### 3.2 Analytical result

The analyzed relation between the shear capacity($Q_u$) and the amount of shear reinforcement($P_w \cdot {}_w\sigma_y$) is shown in Fig.4. The ultimate state was judged when the stress of A-C and B-D reach some critical value. In the analysis, the interval of the shear reinforcement was fixed and the area was changed. Here, $P_w$ is the shear reinforcement ratio and ${}_w\sigma_y$ is its yield strength.

When the area of shear reinforcement is large, the tensile stiffness becomes large and the elongation becomes small. Then, the dowel displacement of main bar and the opening of splitting crack are much restrained. As a result, the core concrete and the main bar act in a body together with the cover concrete. Then, the compressive stress of concrete becomes small and the crush of concrete delays. That leads to the increase of the shear capacity.

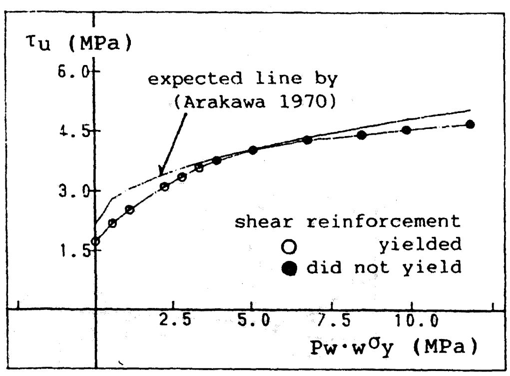

Fig.4 Analyzed $Q_u$ - $P_w \cdot {}_w\sigma_y$ relation

The expected line by Arakawa formula (Arakawa 1970) is also indicated in Fig.4. The general characteristics of the relation between $Q_u$ and $P_w \cdot {}_w\sigma_y$ could be well explained by this analytical model.

### 3.3 Intensive shear reinforcing

In Fig.3, the most effective place is the position where the shear crack cross the main bar, in order to restrain the dowel displacement and the propagation of splitting crack. Here the beam, whose $P_w \cdot {}_w\sigma_y$ was 3.38MPa in Fig.4 was selected for the discussion. The No.3 and No.7 stirrups of Fig.3 were replaced by large size reinforcement.

Table 2 shows the shear force carried by the shear reinforcement, the dowel action and the other factors. It is characteristic of the intensive shear reinforcing that the shear force carried by the dowel action increases. It is natural that the shear capacity increases by the intensive shear reinforcement. The increase of shear capacity was, however, larger than that by the uniformly dispersed shear reinforcement.

Figure 5 shows the strain distribution on main bar and shear reinforcement. Not so much difference can be seen, because the shear reinforcement does not yield. Even in such a case, the intensive shear reinforcing increase the dowel shear force of main bar.

Table 2 Shear transfer ratio

| Case | $P_w \cdot {}_w\sigma_y$ (MPa) | $Q_u$ (KN) | Shear Reinf. (KN) | Dowel (KN) | Others (KN) |
|---|---|---|---|---|---|
| A | 3.38 | 87.71 | 49.38 | 29.65 | 8.68 |
| B | 3.38+ISR | 97.12 | 46.13 | 43.32 | 7.67 |
| C | 4.10 | 93.10 | 56.98 | 31.93 | 4.19 |

ISR:Intensive Shear Reinforcement.
Case-A and Case-C have the uniformly placed shear reinforcement.
Case-B and Case-C have the same amount of shear reinforcement

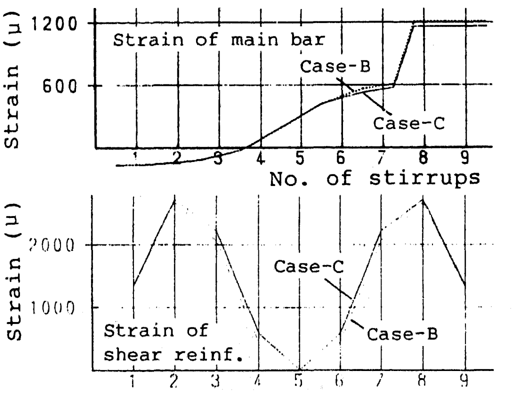


Fig.5 Strain distribution on main bar and shear reinforcement

If the intensive shear reinforcement is placed at the position of No.2 and No.8 in Fig.3, they act as the shear reinforcements as well as the confining reinforcements against the dowel action and carry the shear force directly. Any way, the intensive shear reinforcement has more effectiveness than the uniformly placed shear reinforcement.

## 4 EXPERIMENT SERIES-I ON INTENSIVE SHEAR REINFORCING

### 4.1 Specimens

The cross section (bxD) is 13cm x 25cm and the shear span to depth ratio is 1.5. The specimens were longitudinally reinforced by deformed bars of 16 mm in diameter. Fifteen stirrups of 4 mm in diameter were arranged in the clear span. No.1 specimen, whose stirrups are uniformly placed, is shown in Fig.6. The tested specimens are listed in Table 3. In the specimen No.2 to No.4, three to five stirrups were bundled and placed at the same position. The interval of the stirrups became wide according to the number of the bundled stirrups. The mechanical properties of reinforcing bars and concrete are summarized in Table 4 and Table 5.

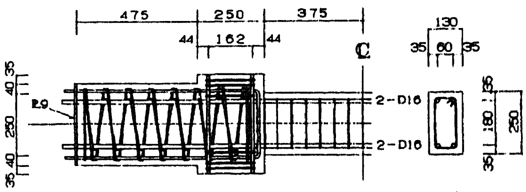


Fig.6 Test specimen (No.1)

Table 3 Test specimens

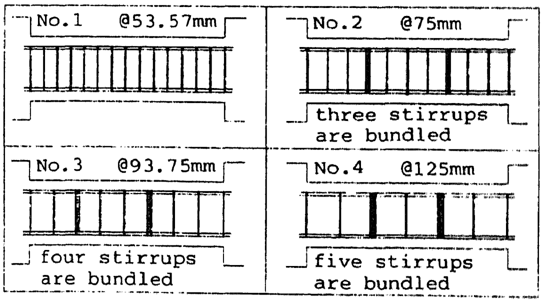


Table 4 Properties of reinforcing bars

| Bar | ${}_s\sigma_y$ (MPa) | ${}_s\sigma_{max}$ (MPa) | ${}_sE$ ($\times 10^5$MPa) | Elongation (%) |
|---|---|---|---|---|
| D16 | 940.8 | 1009.8 | 1.89 | 13 |
| 4φ | 289.0 | 363.1 | 2.04 | 36 |

Table 5 Properties of concrete

| Age (days) | $_c\sigma_B$ (MPa) | $_c\varepsilon_B$ (%) | $_cE(1/3)$ ($\times 10^4$ MPa) | $_c\sigma_t$* (MPa) |
|---|---|---|---|---|
| 42-46 | 28.1 | 0.3082 | 1.83 | 2.4 |

* Splitting tensile strength

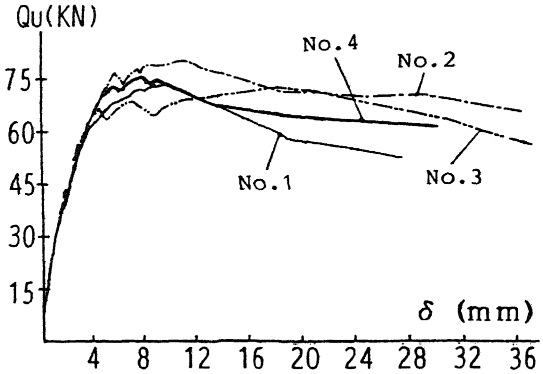

Fig.8 The envelope curves of Q-δ relations

4.2 Loading and measuring method

The loading apparatus is shown in Fig.7. The same value of the load (P=2Q) was given on the stubs and the anti-symmetric bending moment condition was produced. The load(P) was monotonously applied up to the shear failure point and after that the cyclic load was given to one direction, gradually increasing the deflection. The applied load was measured by the load cell. The deflection (δ) was measured as the relative displacement of the stubs. The strain of shear reinforcement was measured by strain gages.

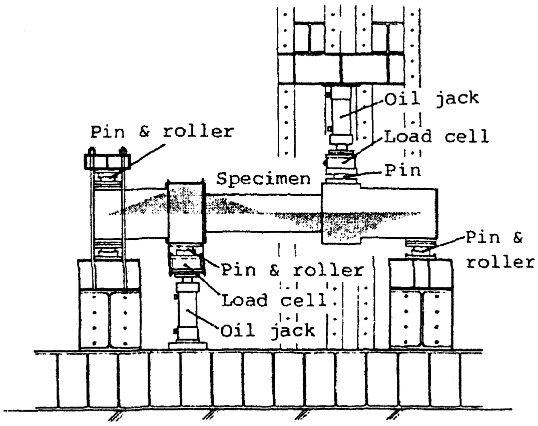

Fig.7 Loading apparatus

4.3 Experimental results

The envelope curves of Q-δ relations are shown in Fig.8. All the specimens had almost same shear capacity and reached the maximum load at about 10mm of deflection. The bundled shear reinforcement was resisting the decrease of shear capacity and the loss of the bearing force after the maximum load, even when the shear reinforcement was arranged at a fairly large interval.

The crack patterns and the strain distributions on the shear reinforcement are shown in Fig.9 and Fig.10. In No.1 specimen without intensive shear reinforcement, the shear crack propagated to the splitting crack along the main bar and much opened. In No.3 specimen with intensive shear reinforcement, the shear crack did not propagate beyond the position of the intensive shear reinforcement, may be, because of the restraint of the dowel displacement of main bar. The strain of shear reinforcement of No.1 specimen had a couple of mound shape distribution. On the other hand, that of No.3 specimen had a suspension bridge shape distribution and it was found that the dowel displacement of main bar and the crack opening were remarkably restrained. These strain distributions well corresponded to the crack patterns.

If the intensive shear reinforcement does not so much transfer the shear force because of the positional relation with the shear crack, the shear capacity of beams with large spaced shear reinforcement shall be reduced. The experimental results, however, indicated the almost same shear capacity regardless of the interval of shear reinforcement. So, there must be the other contribution to the shear capacity, except for that of shear reinforcement. The shear force carried by the dowel action of main bar, that carried by the aggregate interlock on the shear crack surface and so on could be expected.

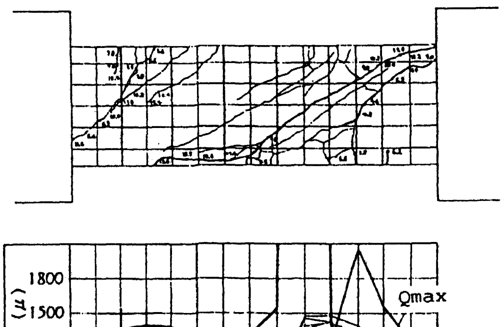

Fig.9 Crack pattern and strain of shear reinforcement of specimen No.1

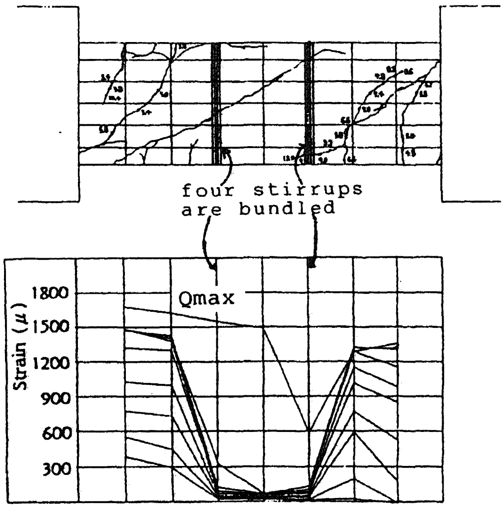


Fig.10 Crack pattern and strain of shear reinforcement of specimen No.3

5 EXPERIMENT SERIES-II ON INTENSIVE SHEAR REINFORCING

5.1 Outline of experiment

The dimensions and the reinforcing arrangement are same as those of No.4 specimen in series-I. The bundled stirrups were replaced by single 4mm stirrup in diameter, single 6mm, single 9mm and double 9mm respectively. And the specimen with no stirrup was included. The test specimens are listed in Table 6. The concrete strength was 28.75MPa and the splitting tensile strength was 2.4MPa. The properties of intensive shear reinforcement were listed in Table 6. The other materials were same as those in series-I. The loading and the measuring method were also same as those in series-I.

5.2 Experimental results

The envelope curves of Q-δ relations are shown in Fig.11. The shear capacity increased according to the amount of intensive shear reinforcement. That effect, however, could not be seen at the amount of over single-9ϕ, that is, BC-9. The crack pattern and the strain distribution on the shear reinforcement of the specimen BC-9 at the maximum load are shown in Fig.12. The tensile force converted from the strain was also indicated in the figure.

In the specimens BC-9 and BC-9W, the intensive shear reinforcement did not yield and their carrying tensile force had not so much difference. So, it was proved that there was a limit in the carrying force of the intensive shear reinforcement.

From the results of series-I, it was supposed that the contribution of dowel action to the shear capacity would increase by the intensive shear reinforcement. In series-II, the strain of main bar was measured in detail. As the results, the big dowel shear force did not observed. In the crack pattern of Fig.12, the intensive shear reinforcement crosses the inclined crack and it was seemed to have behaved mainly as shear reinforcement and to have transferred the shear force directly.

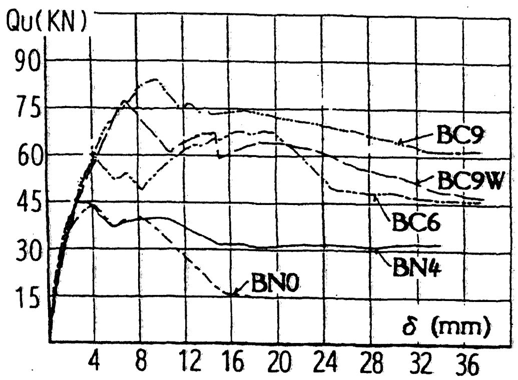


Fig.11 The envelope curves of Q-δ relations

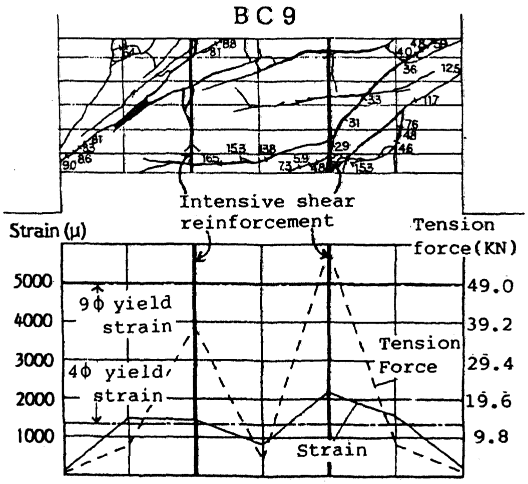


Fig.12 crack patterns and the strain distribution on the shear reinforcement

Table 6 Test specimens

| Name | Intensive shear reinforcement | | | | | |
|---|---|---|---|---|---|---|
| | Size | $a_w$ ($cm^2$) | $_w\sigma_y$ (MPa) | $_w\sigma_{max}$ (MPa) | $_sE$ ($\times10^5$MPa) | $a_w \cdot {}_w\sigma_y$ (KN) |
| BN-0 | | | | | | |
| BN-4 | 1-4 | 0.25 | 289 | 363 | 1.89 | 7.2 |
| BN-6 | 1-6 | 0.56 | 578* | 646 | 2.04 | 32.4 |
| BC-9 | 1-9 | 1.28 | 613* | 661 | 2.06 | 78.5 |
| BC-9W | 2-9 | 2.56 | 613* | 661 | 2.06 | 156.9 |

* 0.2% Proof stress

5.3 Discussion on the maximum amount of intensive shear reinforcement

The shear strength is assumed to be the summation of the contribution of shear reinforcement and the arch action. Here the other contributions are provisionally ignored. The contribution of shear reinforcement was calculated from the tensile force of shear reinforcement which crossed the shear crack. This value was subtracted from the experimental shear capacity and the balance was considered to be the contribution of the other factors, mainly the arch action. The results are shown in Fig.13.

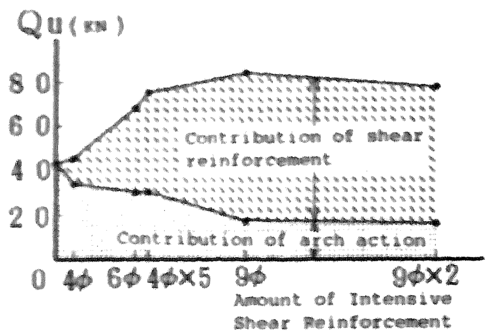


Fig.13 Contribution of arch and beam mechanism

As shown in Fig.12, the intensive shear reinforcement has the larger tensile force comparing the other stirrups. Then the shear transfer mechanism can be assumed to be presented by the macro truss model shown in Fig.14, that is, the arch mechanism of A-B element and the beam mechanism of the other elements. The concrete strut of A-B element has the sectional area of $bD/2/\cos\theta$ (AIJ 1990).

If it can be assumed that all the shear force of the specimen with no shear reinforcement(BN-0) is transferred by the arch action, the critical stress of the A-B strut is 16.2MPa. In the specimens of BC-9 and BC-9W, the arch action transfers about 16.2KN of shear force. The corresponding stress of the strut is 6.2MPa. The inclination of the A-B strut of the arch mechanism is different from that of the E-B and D-A struts in beam mechanism. If the critical stress for the shear failure could be considered by the simple summation of the stress of the struts of two mechanism, however, the critical stress of the E-B and D-A strut in the beam mechanism is 10MPa. If the sectional area of E-B and D-A strut could be decided, the maximum amount of intensive shear reinforcement could be calculated. The determination of the sectional area must be a problem in future.

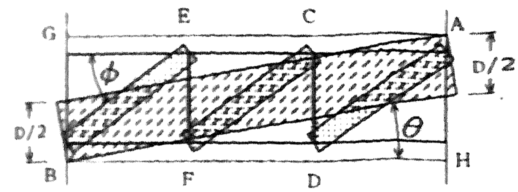


Fig.14 Macro truss model

6 CONCLUSION

The effect of the bond and dowel action of main bar on the shear capacity of RC beams was analytically discussed. If the dowel displacement would be restrained, the propagation of the splitting crack along the main bar would be minimized and the less bond deterioration would occur. As a result, the large shear capacity could be expected. From such a analytical result, the most effective intensive shear reinforcing method was proposed and that shear reinforcing effect was experimentally proved.

There would be a possibility to get the sufficient shear reinforcing effect, avoiding the dense spaced shear reinforcing arrangement in such a case that the shear design would be critical.

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