# EVALUATION FOR DEFORMATION OF STIRRUPS IN ASR－ <br> SIMULATION SPECIMENS 

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#### Abstract

Using specimen in which expansive mortar is cast，experimental tests simulating ASR are performed． Through observations with time，the general specimen has reproduced the ASR－induced circular deformation．From detailed evaluation，the corner concrete has opening deformation with angular increment around $0.83^{\circ}$ ．By recording stirrup shapes before and after expansion，the bent part of stirrups is verified to have angular variation as $1.85^{\circ}$ ．The opening deformation of stirrups，with rough correlation to that of concrete，is considered to be influential on stirrup fracture．


Keywords：ASR，experiment，movement of stirrup，fracture mechanism

## 1．INTRODUCTION

For recent years，due to the Alkali Silica Reaction， （ASR for short），many concrete structures suffered degradations．It is also reported that the bent part of reinforcing stirrups in bridge pier are frequently fractured from the expansion of ASR［1］．Due to the fracture of stirrup，poor anchorage occurs which might reduce bearing capacities of structures．Thus，to investigate the fracture mechanism is very significant．

Based on the previous study［2］，the opening deformation of stirrup（increase of angular degree in bent part of stirrup due to expansion）is considered to influence the stirrup fracture．So far，this opening deformation，which is estimated indirectly based on the deformations of corner concrete［3］，has not been confirmed directly．Further，to evaluate the possibility for judging the movement of stirrup from external concrete is important for inspection of actual structures．

The study content can be referred to Fig．1．For simulating the influence from ASR expansion on external degradation and stirrups，specimens with expansive mortar cast into the frame surrounded by ordinary concrete are conducted．Therefore，the general deformation of specimen and the angular variation in corner of concrete will be studied firstly．After that，to investigate the stirrup deformation directly，states of stirrup are recorded and measured before and after the expansion．The angular variation for bent part of stirrup will be evaluated．Thirdly，the comparison between the movement of corner concrete and stirrup will be discussed．The possibility for judging the behavior of inner stirrup from external concrete will be evaluated．

## 2．EXPERIMENTAL CONDITIONS

Herein，the experimental conditions including


Fig． 1 Study flow
the specimen condition and material properties will be introduced．

Fig． 2 presents the shape and reinforcements of the specimen．For the sake of simulating the effect from inner ASR expansion on external degradations and stirrups，the expansive mortar is cast in the square hollow part surrounded by the ordinary concrete as the frame．As illustrated in Fig．2－（a），the external size of

[^0]the specimen is $916 \times 916 \times 1600 \mathrm{~mm}$. The dimension of cross section for expansive mortar is $456 \times 456 \mathrm{~mm}$.

The spacing of stirrups is set as 200 mm to make the stirrup ratio as $0.22 \%$ which is same with the actual bridge pier with stirrup fractured. The bending radius is 1.0d (diameter of stirrup). Further, as illustrated in Fig. 2-(b) and Fig. 2-(c), stirrups adopt the D16 rebar with one type using the rib shape based on the current specification ('current type' for short) and two other types using the bamboo joint rib (ribs that are aligned in parallel with spacing) based on the old specification ('old type B' and 'old type C' for short). Besides, old type stirrups have steeper rib shapes than current type and initial damages are easier to occur in them [3].

Further, for the material properties, the mix proportion used for the frame concrete and expansive mortar is presented in Table 1 and Table 2, respectively. For simulating inner expansion from ASR in short time, the lime type expansion agent is used. The frame concrete used the strength as $27 \mathrm{~N} / \mathrm{mm}^{2}$ being the design strength for the actual bridge pier. By cylinder tests, the real strength is obtained as $35 \mathrm{~N} / \mathrm{mm}^{2}$. Besides, the expansion agent is set as $200 \mathrm{~kg} / \mathrm{m}^{3}$ to simulate the severe degradation condition.

## 3. EXTERNAL DEGRADATIONS

During the expansion, external degradations such as cracks and deformations will occur in the appearance of concrete. Herein, the characteristics of them and the deformation in the corner of concrete will be evaluated.

### 3.1 Crack Conditions

Fig. 3 illustrates the evolution of crack conditions in the profile of concrete. No great difference was found for tendencies of crack developments in different surfaces. Thus, as a representative, the east surface (Fig. 2) is selected for explanation. For comparison, the authors defined the corner area as the frame concrete area and the center area as the other area. Cracks with maximum width as 0.25 mm occur in the center area after 2.80 h (hours) of expansion as presented in (1) of Fig. 3-(a). While, corner area mainly produces cracks with width smaller than 0.20 mm . After the expansion of 3.25 h , new cracks occur in both center and corner area, with the maximum crack width in center as 1.10 mm ((2) of Fig. 3-(b)) and in corner as 0.35 mm ((3) of Fig. 3-(b)). At the final state, almost no new cracks generate for the two areas. The maximum crack width has increment to be 1.30 mm ((4) of Fig. 3-(c)) for center and 0.70 mm ((5) of Fig. 3 -(c)) for corner, respectively. For general, due to smaller restraints in the lateral direction, main cracks are developed in the longitude direction of specimen.

### 3.2 General Deformation Conditions

The deformation conditions in appearance of concrete due to the inner expansion will be studied in this section. Fig. 4 illustrates the measuring method of deformations for the specimen. All 8 cross sections with stirrups arranged are the measuring objectives. As shown in Fig. 4-(a), fixed frame is set around each


Fig. 2 Specimen condition
Table 1 Mix proportion of frame concrete

| $\mathrm{G}_{\max }$ <br> $(\mathrm{mm})$ | W/C <br> $(\%)$ | $\mathrm{s} / \mathrm{a}$ |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Unit $\left(\mathrm{kg} / \mathrm{m}^{3}\right)$ |  |  |  |  |  |  |
|  |  | W | C | S | G | Admi- <br> xture |  |
| 20 | 46 | 43 | 175 | 381 | 718 | 1018 | 1.142 |

Design strength: $27 \mathrm{~N} / \mathrm{mm}^{2}$
Table 2 Mix proportion of expansive mortar

| W/C <br> $(\%)$ | Unit $\left(\mathrm{kg} / \mathrm{m}^{3}\right)$ |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | W | C | S | Expansion Agent |
| 40 | 231 | 575 | 1150 | 200 |



Fig. 3 Evolution of crack conditions
cross section. To measure the length from fixed frame to concrete surface, measuring scale is settled in the fixed frame at the position 40 mm away from endpoint in the corner and then followed by each 100 mm . By calculating the difference value of lengths before and after expansion, the deformation can be obtained.

Based on the measuring method, the evolution of deformations ( $5^{\text {th }}$ cross section from upside is chosen for an instance) is shown in Fig. 5. From the beginning
to the expansion after 2.80 h , the deformation is shown in Fig. 5-(a). It is found that the deformations have increments with the maximum value as 5 mm and 2 mm in center and corner, respectively. For the deformation when after 3.25 h (Fig. 5-(b)), the values in center change to the maximum as 6 mm while maximum value in corner keeps no variation as 2 mm . Further, for the final state when after 7.75h (Fig. 5-(c)), the general deformation has increment while the maximum values remain no change for both corner and center.

From the variation of deformations, it is confirmed that deformations in the center of four sides are greater than those in corners. In the other word, the general cross sections have circular deformation. Further, specimens using reactive aggregates and the size as $340 \times 340 \times 670 \mathrm{~mm}$ are also conducted by authors [4]. Observation is conducted for around 1113 days with crack density about $5.39 \mathrm{~m} / \mathrm{m}^{2}$ (cracks and deformations have tendencies to converge at the moment). Deformations in center of each cross section have greater level with maximum around 1.0 mm and the circular deformation is confirmed. The current specimen, using expansive mortar for simulating the inner expansion, also has greater deformation with maximum as 6 mm occurred in center of cross section. Therefore, the current specimen is considered to have reproduced the similar circular deformation with the ASR specimens.

Fig. 5-(d) illustrates the crack conditions in upper section of the final state. Combined with the cracks and deformations, it is considered that due to the circular deformation, the cracks in the centers are developed from the exterior to the interior; meanwhile, the cracks in the corners are developed due to the opening deformations in the corner of concrete, which will be evaluated in the next section.

### 3.3 Deformation for Corner of Concrete

For investigating the deformation in the corner of concrete, Fig. 6 presents the enlarge of part A in Fig. 5 for instance. Herein, the meaning for the deformation values will be explained. As shown in (1) of Fig. 6, the length between the fixed frame and the concrete surface is 47 mm and 44 mm for the initial and the final state, respectively. Thus, the deformation is 3 mm as their difference. Therefore, from the deformation in the final state (Fig. 6-(b)), it is known that from the corner point, deformation increases toward to the center area. The corner concrete is confirmed to have the opening deformation compared with the initial state.

Hence, the angular variation of corner concrete due to the opening deformation will be studied. Fig. 7 shows one instance for the measuring method. Refer to the former Fig. 4, measuring points are set for obtaining the deformation of concrete. As illustrated in Fig. 7-(a), coordinate system is established with the origin $O$ point in the center of the initial cross section. Thus, coordinates of the measuring points can be obtained. (for example, the corner point in A of Fig. $7-(\mathrm{a})$ is ( $458 \mathrm{~mm},-458 \mathrm{~mm}$ ) ).

The part A of Fig. 7-(a) is enlarged for presenting the initial state. Three measuring points $a, b, c$

(a) Positions for measurement
(b) Method for measurement

Fig. 4 Measuring method for deformations


Fig. 5 Evolution of deformations

(a) Initial state

(b) Final state

Fig. 6 Deformations in corner concrete
are chosen for evaluating the angular variation. The initial spacing of $a b$ and $a c$ is 240 mm , being similar to the width of frame concrete (width is 230 mm , defined as corner area, refer to Fig. 2 and Fig. 3). Thus, the initial coordinate is $(458,-458)$, $(218,-458)$ and (458,-218) for points $a, b, c$, respectively. After expansion, the final state is illustrated in Fig. 7-(b). Based on the deformation values in measuring points, the coordinates for $a, b$ and $c$ change to be ( $461,-460$ ), ( $218,-462$ ) and $(462,-218)$, respectively. As a result, the spacing values of $a b, a c$ and $b c$ are 242.01 mm , 243.02 mm and 346.48 mm , from which, the angle degree of corner concrete is $91.18^{\circ} .1 .18^{\circ}$ is increased, which verifies the opening deformation of the corner concrete. Further, the deformations used here are only considering the value in perpendicular direction to the concrete surface while those in direction along with the concrete surface are not used. However, based on the former research [2], little influence for the angle value is confirmed by additionally considering the deformation along with concrete surface.

Thus, the same measuring method is conducted to all 16 corners of concrete containing old type $B$ and C stirrups ( 2 multiply 8 cross sections, refer to Fig. 2). Fig. 8 presents the results of angular variation for corner concrete. The maximum value is around $1.65^{\circ}$. Except for the point (1) with negative angle as $-0.94^{\circ}$, it is known that all corner concrete has angular increment with the average around $0.83^{\circ}$. The entire corner concrete is confirmed to have the opening deformation, which is considered to be caused by the general circular deformation shown in last section. Further, the possible reason of point (1) will be evaluated later in Fig. 12.

On the other hand, it is considered that stirrups in the cross sections might also have the opening deformation corresponding to that in the corner concrete. Therefore, the movement of stirrups will be investigated in the next chapter.

## 4. MOVEMENT OF INNER STIRRUPS AND COMPARISON WITH CONCRETE

Reflecting to the opening deformation of corner concrete, movement of stirrup will be investigated in this chapter. After that, the relation between movement of stirrup and corner concrete will be evaluated.

### 4.1 Movement of Stirrups

For studying the movement directly, the shapes of stirrups are recorded before and after the expansion. The variation of angles in the bent part of stirrups will be evaluated.

The measuring method of angular variation will be explained. Fig. 9 presents one measuring example. Before casting the specimen, 3 points ( $o, p, q$ ) are determined and marked in the actual stirrup, shown in Fig. 9-(a). The spacing values of $o p, o q$ and $p q$ are measured as $92.64 \mathrm{~mm}, 87.86 \mathrm{~mm}$ and 142.43 mm . Thus, the degree of $\theta$ (angle poq) can be calculated as $105.93^{\circ}$ Further, after expansion, the same stirrup is taken out (concrete around bent part of stirrup is chipped carefully and then the stirrup was cut immediately) and

(a). Initial of internal section

(b). Final of internal section

Fig. 7 Measuring method for angular variation of corner concrete


Fig. 8 Results for angular variation of corner concrete
the spacing values of three points are measured again. The spacing value is $94.91 \mathrm{~mm}, 89.29 \mathrm{~mm}$ and 146.05 mm , from which, the degree of angle $\theta^{\prime}$ can be calculated as $107.55^{\circ}$, presented in Fig. 9-(b). Therefore, the increasing degree is obtained as $1.62^{\circ}$, which is the difference between $\theta^{\prime}$ and $\theta$. From the increasing of angle in bent part, it is considered that the stirrup has opening deformation.

Therefore, the same measuring method is conducted to old type B and C stirrups. Fig. 10 presents the results for angular variation of stirrup. It is confirmed that the angle degrees of stirrup has the maximum increment as $4.22^{\circ}$. Most of the 16 stirrups have angular increment with the average as $1.85^{\circ}$. Further, it is known that the minimum value (point (2) of Fig. 10) is occurred for the stirrup B as $-0.34^{\circ}$. This negative value indicates that the corresponding angle changed little after the expansion.

As a result, similar with the corner concrete, the increments of angles for bent part of stirrup illustrate that stirrups have opening deformation due to the inner expansion. This opening deformation is considered to be influential on fracture of stirrups. Further, to evaluate the possibility for judging the movement of inner stirrup from concrete, the comparison between their movements will be conducted in the next section.

### 4.2 Comparison for Movements between Concrete and Stirrups

In inspections to the ASR damage of actual structures, the movements of stirrups cannot be observed directly. Thus, to evaluate the possibility for estimating the movement of stirrup based on the damage condition of concrete is significant.

Fig. 11 illustrates the comparison of angular variations for stirrup and corner concrete based on the results described above. As illustrated in the horizontal axis of Fig. 11, the maximum increment for corner concrete is around $1.65^{\circ}$, being smaller than that of stirrup as $4.22^{\circ}$. The point (1) with negative value for corner concrete and point (2) for stirrup in Fig. 11 is same to the point (1) in Fig. 8 and point (2) in Fig. 10. Apart from the two special points, the angular variation between stirrup and corner concrete is considered to have correlation with the ratio near 2.13 (Fig. 11). Therefore, it is considered that the movements of inner stirrups can be estimated roughly from the deformation of concrete in appearance.

In addition, for investigating the influence from crack conditions on the angular variation, Fig. 12 illustrates the possible crack conditions in cross section. Fig. 12-(a) shows the condition with no great crack and dislocation occurred. The crack condition is based on the point (3) which is locating in the average line of Fig. 11; Fig. 12-(b) present one of the condition with dislocation in the appearance of concrete, which is based on the crack states in part B of former Fig. 5. Fig 12 -(c) is another condition with dislocation occurred. In Fig. 12-(a), it is considered that the angular variation of corner concrete $\theta_{1}^{\prime}$ (increment of angle $\theta_{1}$ ) can be roughly calculated by the ratio $\delta / r_{1}$ ( $\delta$ is the deformation of concrete in corresponding position of


Fig. 9 Measuring method of angle in stirrup


Fig. 10 Results for angular variation of stirrup


Fig. 11 Comparison for variation of angles between corner concrete and inner stirrup
measuring point $p$ in stirrup; $\mathrm{r}_{1}$ is the distance from the corner point to the position). As there is no influence from cracks, the stirrup is supposed to have same deformation $\delta$. Thus, the angular variation of stirrup $\theta_{\text {s }}^{\prime}$ is approximate to be $\delta / \mathrm{r}_{\mathrm{s}}\left(\mathrm{r}_{\mathrm{s}}\right.$ is the spacing value between measuring points of stirrup, $o p$ or $o q$ in Fig. 12-(a)). The ratio $\theta_{s}^{\prime} / \theta_{1}^{\prime}$ is then decided by $\mathrm{r}_{1} / \mathrm{r}_{\mathrm{s}}$. Due to the influence from different measuring scopes, the spacing $r_{s}$ in stirrup is smaller than the $r_{1}$ in concrete. As illustrated in Fig. 12-(a), the ratio $r_{1} / r_{s}$ is then calculated as 1.9 ( $r_{1}$ is around $240-70=170 \mathrm{~mm}$ and $\mathrm{r}_{\mathrm{s}}$ is around 90 mm , refer to Fig. 9), similar with the ratio 2.13 shown in Fig. 11. Therefore, due to the different measuring scopes in the experiment, the angular increment in stirrup is around 2 times of that in concrete. However, due to the dislocation condition 1 (Fig. 12-(b)), the evaluating point $c_{2}$ will move outward compared with the point $c_{1}$. Thus, the measured angle $\theta_{2}$ (angle $b_{2} a_{2} c_{2}$ ) will be in greater level than $\theta_{1}$. Further, the corresponding value to this condition is point (4) in Fig. 11, which is the maximum value of corner concrete as $1.65^{\circ}$. Moreover, the dislocation condition 2 presented in Fig. 12-(c) is the state with different direction of dislocation to that illustrated in Fig. 12-(b). This situation is based on the special point (1) with negative angle for corner concrete in Fig. 11. The evaluating point $c_{3}$ shift inward compared with point $c_{1}$. Hence, the evaluated angle $\theta_{3}$ (angle $b_{3} a_{3} c_{3}$ ) will be in smaller level or even smaller than the initial state.

As a result, it is thought that for the condition without great dislocation, the movement level of stirrups roughly has correlation with that in concrete.

## 5. CONCLUSIONS

For the sake of simulating the damages caused by ASR, the specimen with expansive mortar cast into the hollow frame of ordinary concrete were conducted. The characteristics of external degradations have been evaluated. At the same time, the movements of inner stirrups have been investigated directly. Additionally, the relation between movement of inner stirrup and corner concrete is also evaluated. Therefore, the following conclusions can be obtained:
(1) After the beginning of expansion, the evolution of general deformations for specimen is recorded. It is found that for each time point, maximum deformations occur in middle of each side in the cross section of specimen. The general specimen has produced the circular deformation.
(2) From the study of deformations in corner concrete, the angles have increment with the average around $0.83^{\circ}$. Opening deformation is confirmed for the corner concrete due to the inner expansion.
(3) During the experiment, the movement of stirrup was recorded and investigated directly. Caused by the inner expansion, it is observed that the bent part of stirrup has the average angular increment of $1.85^{\circ}$. The angular increment verifies that the bent part of stirrups has opening deformation,

| ........ Initial shape | $-\cdots$ Ultimate for no dislocation |
| :--- | :--- |
| _- Ultimate shape | -- Dislocation |


(a). No dislocation

(b). Dislocation 1 (refer to Fig. 5-B)

(c). Dislocation 2

Fig 12 Influence from dislocation in corners
which is considered to be very influential on the fracture of stirrup.
(4) As a whole, it is considered that the general specimen has circular deformation, which further induces the opening deformation and the angular increment in the corner concrete. Thus, due to the influence from different measuring scopes, the stirrup has angular increment around 2 times of that in concrete. It is considered that for condition without great dislocation, the movement level of stirrups roughly has correlation with concrete.

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