Analytical evaluation of movement behavior for specimens simulating ASR

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To estimate the behavior of stirrup, which is significant for the fracture around stirrup due to ASR, specimen with expansive mortar cast into the frame of ordinary concrete is conducted. Besides, to reproduce experimental results and further to study the movement mechanisms, FEM analysis is carried out. The ASR-induced circular and elongated deformation around 5.0mm and 3.0mm is generated for both experiment and analysis. From the analytical results, uniform increment of element length due to expansion cause the tensile effect in frame concrete which further induce the elongated deformation; while difference of expansion in different area due to the bending rigidity produce the bending effect and thus circular deformation. In addition, by circular deformation, angular increment near 2.5° is verified for bent part of stirrup. This is responsible for progressing of initial damage until to fracture.

Keywords: ASR, FEM analysis, circular deformation, stirrup fracture

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 beam are frequently fractured1). Due to degradations, elastic modulus of concrete has the possibility to reduce; further, due to the fracture of stirrup, poor anchorage occurs which will further cause influence on bearing capacities of structures. As references in reinforcement work and countermeasures on stirrup fracture, feature and mechanism of external degradation and also its correlation to the behavior of stirrup is significant to evaluate.

This study is focusing on the effect from ASR induced inner expansion on damage of external concrete and stirrup fractures. In general, several years are needed for the obvious damage by ASR. To simulate the ASR induced expansion in a short term, expansive mortar is utilized. Besides, to afford enough adhesion for stirrup, frame of ordinary concrete is made around the section for expansive mortar. Further, for giving reproduction of experimental results and to study the generating mechanism (mechanism for occurrence of external damages), FEM analysis is carried out. In previous researches2,3), circular deformations of

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Fig. 1 Study flow
the specimens were confirmed. This circular deformation which was assumed to generate the opening deformation of stirrup (increase of angular degree in bent part of stirrup due to expansion) is considered to have great significance. However, the generating mechanism for circular deformation has not been studied sufficiently and the stirrup movement with its influence on progress of initial damage has not been evaluated.

Therefore, as presented in Fig. 1, the study objective is to evaluate characteristics and mechanisms of external degradation as deformation and to investigate the behavior of stirrup. The features of deformation conditions induced by the inner expansion are studied. Besides, generating mechanism of deformation conditions is discussed combining to the detailed results from analysis. Further, to investigate the stirrup movement induced by the external deformation directly, states of stirrup are recorded and measured before and after the expansion. The movement behavior for bent part of stirrup is evaluated and contrasted to the result of analysis. As a consequence, by using the integrated evaluation by experiment and analysis, the features and generating mechanisms of external degradation and its relation to behavior of inner stirrup is evaluated; besides, reason for stirrup fracture is further confirmed.

2. SIMULATION CONDITIONS

Herein, the basic considerations and conditions for simulation tests and FEM analysis are discussed; based on these, the corresponding results are evaluated in the next chapter.

2.1 Experimental Conditions

For introducing specimen conditions, Fig. 2 illustrates the shapes and reinforcements of specimens. For sake of simulating the effect from inner ASR expansion on external degradations and fracture of stirrups with concrete restrained, the expansive mortar is cast in the square hollow surrounded by the ordinary concrete as the frame. In this paper, two cases as Case 14 and Case 16 with same casting area for expansive mortar and different size of frame concrete are utilized. As to Case 14 (Fig. 2-(a) and (c)), the external size is 680mm×680mm×1340mm with cross section as 1/4 to that of the actual bridge beam with stirrup fractured4). Further, the dimension of expansive mortar is set as 456mm×456mm for inner expansion. The spacing of stirrups is 285mm with stirrup ratio 0.22% same to the actual bridge beam.

The specimen conditions for Case 16 are illustrated in Fig. 2-(b) and (d). For studying the influence from different restraints of frame concrete, the dimension of cross section for expansive mortar is same with Case 14 as 456mm×456mm; while the size of frame concrete is 230mm greater than 112mm of Case 14. Further, the spacing of stirrups is 200mm to make the identical stirrup ratio as 0.22%. As illustrated in Fig. 2-(c) and (d), 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 (ribs that are aligned in parallel with spacing) based on the old specification (‘old type B’ and ‘old type C’ for short). More details for different rebar types can be referred to former research2).

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. Frame concrete adopts the strength as 27N/mm² being the design strength for the actual bridge beam. By cylinder tests, the real strength is obtained as 35N/mm². For simulating inner expansion from ASR in short time, the lime type expansion agent is used. Besides, the expansion agent is set as 200kg/m³ to simulate the severe degradation condition.

2.2 Analytical Conditions

Corresponding to the experiment conditions, the analytical conditions including analytical model, material model and input of expansion are explained in this section.

To evaluate the sectional deformation of concrete and movement behavior of stirrup, the 2-dimensional elastic-plastic finite element analysis is conducted. Further, for studying the movement features in greater level, Case 14 is chosen as the objective because of the smaller restraint from frame concrete (size as 112mm smaller than 230mm of Case 16). The whole section is applied for modeling as presented in Fig. 3-(a). The expansive mortar with the size as 456mm×456mm is simulated. Referring to the former Fig. 2-(a), the spacing of stirrups for section 2~4 is same as 285mm. Thus, for modeling these three sections, one stirrup is set into the model with depth of the concrete model as 285mm (refer to (1) of Fig. 2-(a) for image, section 3 as instance). Based on observations from experiment, expansion in axial direction is also confirmed. Therefore, four-node quadrilateral isoparametric plane stress elements considering strain in three directions are applied. Besides, point O (Fig. 3-(a)) is fixed in x, y directions to avoid the shift of the central point. For simulating the bent part of stirrup in detail, plane stress elements are also applied (Fig. 3-(c)) with the width as 16mm (diameter) and the depth as 12.4mm (to result the same area to D16 as 198.6mm²).

Fig. 4-(a) presents the stress-strain model of frame concrete. In compression side, para-curve is developed until to the compressive strength as 35N/mm². The Drucker-Prager criterion is used for the biaxial compressive situation. With respect to the

![](image)

**Fig. 3 Analytical models**

![](image)

**Fig. 4 Stress-strain for frame concrete and stirrup**

![](image)

**Fig. 5 Experimental facilities of specimen used for compression test**

![](image)

**Fig. 6 Stress-strain for expansive mortar**
tensile side, the curve grows in linear to the tensile strength. Then considering the softening condition, 1/4 model is used. Besides, the Rankine criterion is applied. Fig. 4-(b) describes the stress-strain model for stirrup. The yield and tensile strength is based on values obtained by tensile test. Further, Von-Mises criterion is adopted.

Considerations to decide the material model of expansive mortar is discussed. As illustrated in Fig. 5, in the research of professor Okamura5), specimens of expansive concrete with amount of expansive agent near to be 67.5kg/m³ and the size as 150mm×150mm×500mm have been manufactured to study the physical properties. For preventing the adhesion, sheath was set around the PC steel bar (diameter as 17mm, restrained ratio around 1.0%). Expansive concrete applied the replacement rate of expansive agent as 0%, 13%, 15% and 20% (replacement rate is the ratio of amount for expansive agent to the sum of amount for expansive agent and cement). After 35 days' water curing in 20°C, PC steel bar was removed to relieve the restraint. Thus, compression test is immediately conducted for the specimen which is in hardening situation. The result of case with replacement rate of 20%, which is the most approaching to 25.8% of current specimen (Table 2), is focused. Refer to the dotted line illustrated in Fig. 6, the maximum strength and corresponding strain are obtained as around 17N/mm² and 1600μ with the elastic modulus to be 10625N/mm².

Further, from the study of Dr. Wu6), the lime type expansive agent being same to that utilized in current specimen is applied and the unit amount is varied from 49~146kg/m³. The un-restrained cylinder specimens with size as Φ100mm×200mm have been made. After 13 days' water curing in 20°C, compression tests have been carried out and the results are plotted in Fig. 7. It is found that from 49kg/m³ to 146kg/m³ of expansive agent, compression strength decreased linearly from near 70N/mm² to around 1/10 times as 7N/mm². Thus, though with different restraint conditions, the physical factors obtained above are considered to be fairly smaller for the current specimen using larger amount as 200 kg/m³. Accordingly, as presented in Fig. 6, 1/10 of the previously obtained elastic modulus and strength is selected as instance for the model of expansive mortar, since slight difference for the deformation behavior has been noticed when using small ratio as 1/5, 1/10 or 1/20.

In addition, to simulate the time depended expansion in the model, the inner temperature in specimen is measured. As presented in Fig. 8 (Case 16), before expansion, a recording thermometer is input in the central point of the cross-section which is located at 800mm from the upper side (to be the middle cross-section). Therefore, based on the reordering results, it is learned that the temperature increases acutely from the initial value as around 37°C until to 4.50hr for the maximum as 106°C. After that, the temperature values begin to decrease due to the converging of reaction. Besides, learning from the general consistency between variation trends of inner temperature and the Compressive Strength in 14 Days

![Fig. 7 Variation of physical factors](image)

![Fig. 8 Input of expansive strain](image)

![Fig. 9 Maximum free expansive strain](image)
expansion of expansive agent\(^7\), the time variation of recorded temperature is non-dimensionalized and used for time variation of thermal expansion acting on the model of expansive mortar (Fig. 3). The coefficient of expansion as \(1.0 \times 10^{-5} / \degree \text{C}\) is applied. Additionally, Fig. 9 displays the results of maximum free expansive strain for expansive concrete, which is also provided by experimental tests of Dr. Wu\(^6\). The un-restrained rectangular columns with size as 100mm×100mm×400mm have been manufactured and under water curing with 20\(^\circ\text{C}\) for 13 days. Illustrated in Fig. 9, the maximum free expansive strain is around 21000\(\mu\) when the unit amount is 146kg/m\(^3\). Further, learning from the approximate linear relation between strain and unit amount, the corresponding maximum free expansive strain is estimated as roughly around 30000\(\mu\) using different extrapolation methods for the 200kg/m\(^3\) in current specimen. The experimental tests utilized relatively great amount of expansive agent and provided reliable data. Thus, though with different curing condition, the estimated maximum free expansive strain as 30000\(\mu\) is adopted to the current specimen for the general evaluation.

3. MOVEMENT BEHAVIOR OF CONCRETE

In this chapter, the evaluation of results combining experiment and analysis is conducted to study the movement features and mechanisms of external concrete induced by inner expansion.

3.1 Crack Conditions

To study the crack conditions, measuring method illustrated in Fig. 10 is utilized in specimen. Measuring lines with interval as 100mm have been drawn in the transverse direction to the main rebar before expansion. The measuring objectives are cracks with width greater than 0.05mm. Further, for studying the characteristics of cracks in different regions, evaluating areas are divided. Corner area is defined as area of frame concrete and center area is the other region, referring to Fig. 10.

From Fig. 11, which presents the final crack forms for Case 14 & 16 (‘final’ herein is decided by the time point after which no more obvious crack propagation was confirmed), it is noted that longitude cracks occur in both corner and center areas. Additionally, regarding to the actual bridge beam, cracks are also confirmed to occur in both center and corner of profile along with main rebar\(^8\). In comparison with Case 14, the cracks of Case 16 have similar form; while, as mentioned above, Case 16 has greater restraint due to the larger size of frame concrete. The general crack widths of Case 16 are in smaller level, with the maximum for center and corner as 1.3mm and 4.0mm contrasted to the 3.0mm and 8.0mm of those from Case 14. Besides,

\[\text{Fig. 10 Measuring method of cracks (Case 14 for instance)}\]

\[\text{Fig. 11 General crack form}\]

\[\text{Fig. 12 Classification for crack types}\]
according to Fig. 11, it is observed that cracks are generally connected between the upper and the lateral sides.

To investigate features of cracks, the classification for crack types are attempted herein. Fig. 12 presents the image for cracks in upper section together with the possible generating mechanism. As illustrated in Fig. 12-(a), from the inner expansion, positive bending moment will act on the center area of frame, which induces crack generates from exterior (Type $a$). Simultaneously, due to the rigid constraint from corner concrete, negative bending moment will also impact on regions closing to corner areas, which causes crack propagates from interior (Type $b$). Besides, the image for cracks in corner part is presented in Fig. 12-(b). Affected by the uniform inner expansion, uniform tension ($T$) is also generated which will induce crack to spread throughout in the diagonal direction (Type $c$). Additionally, to study the reinforcing method for preventing cracks caused by drying shrinkage, experimental tests using L-shape corner part of RC structure are performed by professor Nakano$^9$. 7 RC specimens with different reinforcing methods like scroll bar or without reinforcement have been made. The monotonic loading in each side of the corner part is applied to make sure the tensile stress generate in corner part and be symmetric about the diagonal direction. Therefore, as illustrated in Fig. 12-(c) which is the case without reinforcement for instance, it is clarified that cracks grow in around 45 degrees for all specimens. This crack form is similar to that presented in Fig. 12-(b). Further, based on the authors, it is considered that these cracks are induced by the action of tensile stress same as that illustrated in Fig. 12-(b) due to the uniform inner expansion.

Subsequently, based on these definitions, crack types for Case 14 and Case 16 can be referred in Fig. 11-(a) and (b), respectively. It is clarified that Type $a$ takes as the main occupation in the center area while Type $c$ are the main crack type in the corner. By increasing the size of frame concrete in Case 16, no great change is found for production of crack types.

As a result, it is obtained that occurrences of cracks are caused by the combining effect of bending and tensile effects by the inner expansion. Moreover, shown in Fig. 12, the effect from bending moment will possibly cause the circular deformation to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig13}
\caption{Measurement of deformations}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig14}
\caption{General deformation forms}
\end{figure}
produce in the central area; while the influence from tensile effect might also lead to the elongated deformations occurred. Therefore, the corresponding deformation conditions which is considered to be further influential on the movement of stirrup is discussed in the following contents.

### 3.2 Deformation Conditions

The feature of external deformations are studied herein. For learning the deformation conditions in the cross sections of stirrups, Fig. 13 illustrates the measuring method. Cross sections located in the same position with 5 stirrups are the measuring objects. As shown in Fig. 13-(a), for measuring deformations of the specimen, fixed frame is set around each cross section. To obtain the length from fixed frame to the concrete surface, measuring scale is set in the fixed frame at the position 40mm away from endpoint of the corner and then followed by each 100mm (refer to Fig. 13-(b) & (c)). From calculating the difference value of lengths before and after expansion, the deformation can be obtained (eg., by the length difference, vertical deformation from point $a_1$ to $a_2$; and from $b_1$ to $b_2$ is 3.0mm and 8.0mm, respectively). Furthermore, it is considered that deformation is composed of elongated deformation and circular deformation. The deformation $a$ (vertical displacement from $a_1$ to $a_2$, Fig. 13-(c)) in corner point is defined as the elongated deformation; while the difference between the maximum deformation $b$ (vertical displacement from $b_1$ to $b_2$, Fig. 11-(c)) and the deformation $a$ is defined as circular deformation (5.0mm is obtained as the difference of 8.0 and 3.0mm).

Thus, the final state of external deformation for Case 14 and 16 are presented in Fig. 14. The value illustrated in the figure is the average deformation in each profile. Concentrating on Case 14 (Fig. 14-(a)), it is noticed that from the corner point, deformation increases gradually toward to the center area. All cross sections are confirmed to have circular deformation. Further, in the two ends of specimen (cross-section 1 & 5), the average deformation has greater value as 7.66mm and 9.48mm than those of the other cross-sections. This is due to the lesser restraints from stirrups in two ends inducing the mortar to expand more easily.

On the other hand, for the condition of Case 16 (Fig. 14-(b)), as the maximum deformation is occurred in the center of profile, the general circular deformation is also confirmed. Similar to that described above, the deformations in two ends of specimen have greater level. However, induced by the greater external restraint from frame concrete, the deformation values are in smaller degree with the average in each profile from 1.3mm to 6.5mm (values of Case 14 are from 5.0mm to 9.5mm).

Additionally, time history for deformation of Case 14 is presented to study the varying feature in Fig. 15. Herein, due to the slight variation of deformation form and values between cross-section 2, 3 and 4 (refer to Fig. 14-(a)), the average deformation in each corresponding point is applied as the data from experiment. After 8.0hr of expansion, the deformation
shape is illustrated in Fig. 15-(a). Value in profile (like A in Fig. 15-(a)) signifies the maximum deformation of each profile; while values in corners (like B) mean the deformations in x and y direction of corner points. Thus, the elongated deformation is observed as 0.50mm (average of 8 deformation values in corners). Furthermore, the average circular deformation is 0.84mm (circular deformation is 0.81, 0.56, 0.81 and 1.16mm for south, east, north and west profile, respectively). Besides, it is noted that the maximum deformation is 1.71mm and 0.88mm for center and corner of profile, respectively. Together with the further expansion after 10.0hr (Fig. 15-(b)), the general deformations have been expanded with the maximum in center as 4.50mm while in corner varies to be 2.33mm. The elongated and circular deformation has separately raised to be 1.48mm and 2.84mm. At last, for the ultimate state when after 24.0hr (Fig. 15-(c)), the general deformation has further increment with the maximum changes to be 8.85mm and 4.21mm in center and corner. In addition, the elongated deformation raises to be the maximum as 3.33mm and the circular deformation as 5.00mm.

### 3.3 Comparison to Analytical Results

Herein, the deformation behavior which is more influential on stirrup movement is mainly contrasted. Fig. 16 illustrates the comparison of external deformations between analysis and experiment in the final state as 24.0hr of expansion for Case 14. Values presented in Fig. 16 possess the same meanings to those in Fig. 15. Thus, concentrating on the center area, it is noted that the maximum deformation generates as 8.85mm in experiment similar to 7.35mm in analysis. Further, for corner area, value of experiment is varied from 2.39mm to 4.21mm, being slightly greater than 2.69mm of analysis. In general, it is known that similar circular deformation form is reproduced by analysis.

Applying the definitions of classification for deformations described in Fig. 13, the comparison of elongated deformation as the deformation in corner point is illustrated in Fig. 17. As a whole, for the experiment, the deformation value is observed to have acute increment in the initial state and thus smaller raise after around 11.0hr due to the converging of reaction. It is noted that roughly similar time variation trend is generated with the maximum elongated deformation as 3.33mm and 2.69mm for experiment and analysis, respectively. Besides, the comparison of circular deformation is described in Fig. 18. Close time variation trend is also obtained between analysis and experiment. Further, the maximum circular deformation is 4.66mm for analysis near to 5.00mm of the experiment.

In addition, regarding the difference of deformation values between analysis and experiment like in point (1) for 8.0hr and (2) as 10.0hr of expansion (Fig. 17 and Fig. 18), variation of deformation from experiment seems to have a small time lag contrasted to that of analysis which is based on the time history of inner temperature. This small time lag is similarly confirmed for results of Case 16 and can also be inferred between inner temperature and expansion from the test of expansive agent7). However, viewing the roughly identical time variation trend and the similar ultimate deformation values, the analysis is considered to have roughly reproduced the movement behavior of external concrete.

### 3.4 Generation Mechanisms

The generation mechanism of external deformation is learned in this section. To process the essential evaluation, the deformation behavior of the inner expansive mortar as the motive power of expansion is concentrated. Fig. 19-(a) illustrates the deformation condition for 1/4 cross-section of expansive mortar in the initial state (4.0hr of expansion for instance). Fig. 19-(b) demonstrates that of the final state (24.0hr of expansion). Thus, as displayed in Fig. 19-(a), it is found that general circular deformation is produced for the expansive mortar. Moreover, due to the symmetry, 6 elements named as A to F are adopted for representative to study the detailed movement. The element displayed by dotted line and solid line is the situation before and after expansion, respectively. In addition, the value illustrated in
the figure signifies the vertical deformation for node points in left side of element. Take element B in Fig. 19-(a) as an instance, 0.40mm is the vertical deformation for point \( a \) and 0.42mm is for point \( b \).

Thus, as to element D in Fig. 19-(a), deformation values in node points are confirmed as 0.22mm and 0.20mm. From the difference of them, it is known that 0.02mm is increased for the element length. Similarly, the same increment of element length as 0.02mm is also verified for element E and F. Consequently, the uniform increment of element length due to expansion is confirmed and this is considered to be responsible for generation of uniform tension in frame concrete and further the elongated deformation.

Additionally, with respect to the element C in Fig. 19-(a), the increment of element size is validated to be 0.05mm from the difference of its deformation as 0.54mm and 0.49mm. However, the change of element length is smaller as 0.02mm and -0.01mm for element B and A, respectively. Due to the flexural rigidity in the frame concrete, the expansion becomes much easier from element A near the corner toward to the element C in the center. Therefore, this difference of expansion level from corner to center due to the flexural resistance is supposed to be responsible for the production of bending action in the frame and further the circular deformation. With regard to the Fig. 19-(b) for the final state, the general circular deformation of expansive mortar becomes more distinct. Furthermore, the uniform increment of length as around 0.31mm is confirmed for element D, E and F; while the difference of length variation is also learned for element A to C (-0.56mm for A, 0.14mm for B and 0.61mm for C).

Subsequently, to study the corresponding movement
conditions of frame concrete together with that of the inner expansive mortar, the similar evaluation is carried out for frame concrete as illustrated in Fig. 20. Corresponding to the element A, B, C in expansive mortar (Fig. 19), 6 elements are selected in the frame. As an instance, A1, A2 in Fig. 20-(a) are located in bottom and top line of frame within the same row to element A of expansive mortar in Fig. 19-(a). Hereby, concentrating on the initial state in Fig. 20-(a), it is observed that circular deformation is generated for the general frame likewise to the expansive mortar shown in Fig. 19-(a). Concentrating on the element C1 in Fig. 20-(a), deformation is identical as 0.53mm in the node points without difference. The same situation is also verified for other 5 elements. Thus, it is learned that there is no variation of element length for the frame part. Further, the maximum deformation as 0.54mm of element C (Fig. 19-(a)) is transferred to C1, C2 in frame as around 0.53mm (Fig. 20-(a)) without great change. Hence, deformation of element in expansive mortar is transferred to the element in frame entirely. Besides, for the final state in Fig. 20-(b), the general circular deformation of frame becomes more obvious. In accordance with the initial state, the element length is hardly varied because of the similar deformation values in node points. Moreover, the deformation from element in expansive mortar is also noted to be directly delivered to those in the frame.

On the other hand, to check the actual effects acted on the frame concrete corresponding to the behavior of the inner expansion, the strain distribution are studied. The vectors of maximum principle strain (like section A in Fig. 21-(a)) in the central frame of the 1/4 cross-section is concentrated. Fig. 21-(a) and (b) illustrates the initial and the final state, respectively. Therefore, for the initial state from Fig. 21-(a), it is observed that great strains mainly generate around section A to C which infers occurrences of cracks. For evaluating numerically, the detailed strain distribution in x direction is studied. The strain herein is the value in the nodal point, which is the average of extrapolation strains from the Gauss integral points nearby. Around the section A (A of Fig. 21-(a)), it is found that the general value is almost linearly changed from 0.0149 in the top line ($\varepsilon_{\text{max}}$) to -0.0012 in the bottom line ($\varepsilon_{\text{min}}$) of the great strain values nearby as shown in A-enlarge of Fig. 21-(a). Thus, as in A' of Fig. 21-(a), it is noted that strains are divided by two parts as those from tensile effect (0.0069 as avg. of 0.0149 and -0.0012) and bending effect (0.0080 as 1/2 for the difference of them). For section B and C (refer to B' and C' in Fig. 21-(a)), similar form is confirmed while the strain from bending in the upper section is negative due to the minus moment occurred from the restraint in corner part.

Besides, as to the final state in Fig. 21-(b), it is observed that strains in section A to C have obvious increment due to the inner expansion. Further, great strain fields are confirmed to newly occur at section D and E in the center area of frame. Compared to initial state in Fig. 21-(a), though with increment of strain values and strain area for the final situation, strains can also be classified by those from bending action and tensile action (refer to A’ to E').

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![Fig. 21 Strain distributions in frame concrete](image1)

**Fig. 21** Strain distributions in frame concrete

**Tensile Effect:**

$\varepsilon_{\text{max}} = 0.0149$  
$\varepsilon_{\text{min}} = -0.0012$  
$\varepsilon_{\text{avg}} = 0.0069$

**Bending Effect:**

$\varepsilon_{\text{max}} = 0.0080$  
$\varepsilon_{\text{min}} = -0.0012$  
$\varepsilon_{\text{avg}} = 0.0069$

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![Fig. 22 Inverse computations from strain](image2)

**Fig. 22** Inverse computations from strain
To further evaluate the generation mechanism, the inverse computations from strains are carried out shown in Fig. 22. The final state with larger strain values are utilized as representative. As presented in Fig. 22-(a), strains from tensile effect ($N$ of Fig. 21-(b)) in the 5 sections are summed to be 0.247 (0.0537 for A, 0.0271 for D, 0.0541 for E, 0.0487 for B and 0.0630 for C). From the product of the summed strain and equivalent length (determined as 10mm based on element size), it is obtained that deformation from tensile effect is 2.47mm which is close to the elongated deformation as 2.69mm (Fig. 17). Additionally, both the positive bending effect ($M$ in Fig. 21-(b)) in section A, D, E and the negative bending effect in B, C are considered to promote the generation of flexural deformation. Thus, the average strain and the negative bending effect in B, C are considered to promote the positive bending effect. Moreover, both the positive bending effect ($M$ in Fig. 21-(b)) in section A, D, E and the negative bending effect in B, C are considered to promote the generation of flexural deformation. Thus, the average strain distribution is computed for those of section A, D, E ($\varepsilon_{avg}$) and for section B, C ($\varepsilon_{avg}$) as presented in Fig. 22-(b). Based on the elevation angle ($\theta_1, \theta_2$) of the average strain distributions, the sum of them is got and multiplied by half of the side length for expansive mortar as 228mm. Thus, the corresponding deformation is obtained as 4.23mm similar to the circular deformation of 4.66mm.

As a conclusion, uniform increment of element length due to expansion cause the tensile effect in frame concrete which further induce the elongated deformation; while difference of expansion in different area due to the bending rigidity produce the bending effect and thus circular deformation. Moreover, it is considered that circular deformation induce the corner part of stirrup to have opening deformation. In the former study, circular deformation is confirmed and thus opening deformation of stirrup is supposed to generate. However, this opening deformation, which is influential on stirrup damage, has not been verified distinctly. Therefore, this movement is also studied by the combination of experiment and analysis to make clear the fracture mechanism.

### 4. MOVEMENT BEHAVIOR OF STIRRUP

Corresponding to the behavior of external concrete, the movement for bent part of stirrup, which is influential on stirrup damage, is evaluated. Further, combined with results of analysis, the fracture reason of stirrup is discussed.

#### 4.1 Observed Damage from Experiment

The movement of stirrup accompanied by the previously mentioned deformation behavior is studied. For learning the movement directly, the shapes of stirrups are recorded before casting the expansive mortar and after the end of expansion. The change of angles in the bent part of stirrups is evaluated. As illustrated in Fig. 23-(a), before casting the expansive mortar, 3 points ($o$, $p$, $q$) are selected and marked in the actual stirrup. The spacing value of $op$, $oq$ and $pq$ is measured as 92.64mm, 87.86mm and 142.43mm, respectively. Thus, the degree of $\theta$ (angle $poq$) can be obtained as 105.93°. Further, after expansion, the same stirrup is taken out and the spacing value is confirmed.
as 94.91mm, 89.29mm and 146.05mm, respectively. Thus, the degree of the angle $\theta'$ is got to be 107.55°, presented in Fig. 23-(b). Therefore, the increasing degree of stirrup is obtained as 1.62°, which is the difference between $\theta'$ and $\theta$.

Moreover, applying the same method, 16 corners for old type B and C stirrups of Case 16 (2 multiply 8 cross sections, refer to Fig. 2-(b) and (d)) have been measured\. Thus, from the angular variation results illustrated in Fig. 24, it is confirmed that the angle degrees of stirrup has the maximum increment as 4.22°. Most of the 16 stirrups have angular increment with the average as 1.85°. Further, it is known that the minimum value (point A of Fig. 24) is occurred for the stirrup B as -0.34°. This negative value indicates that the corresponding angle changed little after the expansion. From the increment of angle in the bent part, it is considered that the stirrup produces the opening deformation, which is corresponding to the general circular deformation of external concrete.

Additionally, it is learned that initial cracks are occurred in bent part of stirrup due to the bending operation. Therefore, induced by the opening deformation of stirrup, initial cracks have great possibility to progress. Consequently, to confirm this estimation, the progressing conditions of cracks in bent part of stirrups are investigated. Herein, the old type C stirrup (locations can be referred to Fig. 2) with the most fractures occurred is utilized as representative. To measure the initial crack length, 6 samples are selected from rebar which are used for stirrups in specimen. After the bending operation, each sample is cut along with the longitudinal direction of rebar and the initial cracks are observed under a microscope. Therefore, the average of the maximum initial crack ratio (ratio of crack length to stirrup diameter as 16mm) in each test sample is confirmed to be 2.56% as presented in Fig. 25.

Besides, the progressing cracks in stirrup after expansion are also studied. Type C stirrups in 18 corners (2 corners × 5 cross-sections for Case 14 and 1 corner × 8 cross-sections for Case 16, refer to Fig. 2) are taken out from the specimens after the end of expansion. By using the same measuring method with initial cracks, the maximum crack ratio in each corner is also shown in Fig. 25. It is attained that induced by the opening deformation of stirrup, there are two stirrups fractured (positions can be referred from (2) and (3) in Fig. 2-(a)). Furthermore, compared to the initial crack ratio 2.56%, cracks in 11 of total 18 stirrups (61%) have been progressed with the general average crack ratio after expansion as 17.70%. Therefore, it is thought that due to the opening deformation of stirrup, the initial cracks could be progressed to generate further damage or even fracture.

### 4.2 Evaluation from Analysis

In regard to the analysis, the behavior of inner stirrup is also investigated. Herein, focusing on the movement of stirrup by inner expansion, initial crack has not been introduced in the analysis. Based on the same definition of that adopted in the experiment (Fig. 23), three points $poq$ with the spacing value of $op, oq$ around 90mm are selected in the model of stirrup (Fig. 26). Therefore, through the coordinates for three points, the detailed spacing values among them are obtained before and after expansion. Further, angle $poq$ is confirmed to be changed from 99.3° before expansion to 101.8° after expansion with the angular variation as 2.50°.

Additionally, refer to Fig. 27, which shows the time variation for angular change of Case 14, it is noted that from 8.0hr to 24.0hr of expansion, the angular increment for bent part of stirrup changes from 1.53° to 2.50°. The similar variation trend to that of the deformation is verified (refer to Fig. 17 and Fig. 18). Besides, for stirrup movement, as measurement has been only conducted for Case 16 in experiment, the average angular increment 1.85° based on measured results is used herein for comparison. The maximum angular increment 2.50° of Case 14 is a little greater than 1.85° of Case 16 due to the small restriction from the thinner frame concrete. However, for both the analysis and experiment, the opening deformation with angular increment can be confirmed for the bent part of stirrup.

As a result, it is concluded that due to the bending effect,
circular deformation occurs in the external concrete. Therefore, the opening deformation with angular increment is verified for bent part of stirrup. In addition, initial crack is produced by the bending operation and thus the opening deformation of stirrup is considered to induce promotion on progressing of the initial damage until to fracture.

5. CONCLUSIONS

To estimate the movement behavior of external concrete and stirrup, which is significant for the fracture around stirrup due to ASR, experimental tests and FEM analysis are conducted. Specimen with expansive mortar cast into the frame of ordinary concrete is made. Combined with analysis, features of deformation in external concrete are evaluated. The generating mechanism and further the influence from external deformation on movement of inner stirrup are studied. Therefore, the following conclusions can be obtained:

1) Between experiment and analysis, the movement form of external concrete are compared. It is found that for the ultimate state, maximum deformation as 8.9mm for experiment and 7.4mm for analysis occur in center of cross-sections. The ASR-induced circular deformation is generally reproduced.

2) To evaluate the movement features of external concrete, deformation is simply classified as circular deformation and elongated deformation. From results of experiment and analysis, it is clarified that both two kinds of deformations generate along with the inner expansion; the maximum elongated deformation is 3.3mm and 2.7mm while circular deformation is 5.0mm and 4.7mm for experiment and analysis, respectively.

3) To study the generating mechanism, the evaluation of element deformations from analytical results are performed. The uniform increment of element length in inner expansive mortar around 0.3mm is confirmed due to uniform expansion; this is estimated to cause the tensile effect in frame concrete and further the elongated deformation; while difference of expansion in different area with the increment of element length varied from -0.56mm to 0.61mm due to the bending rigidity results in the bending effect in frame and the generation of circular deformation.

4) For estimating the behavior of stirrups, movement for bent part of stirrup is studied. It is confirmed that together with the circular deformation, bent part of stirrup produces opening deformation with the maximum angular increment near to be 1.85° for experiment and 2.5° for analysis. Additionally, this opening deformation in bent part of stirrup is considered to be responsible for the propagation of initial damage in the stirrup until to fracture.

References

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