APPLICATION OF DIGITAL IMAGE CORRELATION METHOD TO STRAIN RELEASE FOR ASR DETERIORATION

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Abstract

Residual expansion by core boring is one of the methods to estimate the deterioration of ASR. There is also the estimation of future expansion by the stress release of concrete core. However, the stress release method that uses strain gauges can only measure a limited area of the concrete. Two-dimensional evaluation to clarify the influence on ASR deterioration by the restraint of rebar is definitely needed. In this paper, a new stress release method by a Digital Image Correlation (DIC) method was used. The DIC method is an optical full-vision non-contact measurement method. In the DIC method, some digital images on the surface of the concrete before and after core boring were used for calculating the release strain. Multi rosette analysis was used for estimating the residual strain. The relationship between stress release and restraint of rebar by the strain distribution around the core was solved.

Keywords: stress release method, multi rosette analysis, Digital Image Correlation Method, strain energy

1 INTRODUCTION

In Japan, many concrete structures with cracks due to ASR have been found at many places since the 1980s. Those cracks were caused by unusual expansion of reactive aggregate. Furthermore, cracking and fracturing of rebar in the concrete structures began to be found after 1996 [1]. This rebar rupture, which causes great damage, is a serious problem in concrete. Figure.1 shows an example of cracks and rebar rupture by ASR.

Generally, the residual expansion test and the stress release test are used for estimating deterioration such as rebar fractures by ASR. The residual expansion test is used for predicting the expansion of the structures in the future. On the other hand, the stress release method is used for evaluating the amount of the historical expansion of the structures. Both the residual expansion test and the stress release method are important for making appropriate management plans for the structures. The strain gauge method is a contact measurement method as a general stress release method.

This measurement with strain gauges has some of demerits. Examples of the demerits are that only the strain on limited lines or areas is measured, and there is large deviation due to cracks in the gauges. Therefore, the accuracy of the stress release method is lower than that of the residual expansion test. In this study, a brand new stress release method was proposed, and the relationship between the release strain and the

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historical strain were considered. As the new stress release method, the Digital Image Correlation (DIC) method that is an optical full-field non-contact measurement method was applied. The DIC method has been used for calculating deflection and strain in the fields of medical science and mechanics technology since the 1990's. The DIC method usually uses digital images taken by CMOS or CCD cameras, and calculates the deflection and the direction in both images before and after deformation. This method can chase every minute area in the images. The merits of the DIC method are being able to measure the dimensional transportation, and being able to set the area for calculation after the tests. Moreover, multi rosette analysis was applied to improve the stress release method that was unstable. In this paper, the relationship between the strain energy and the historical strain by multi rosette analysis was verified. The parameter was the amount of the ratio of rebar and stirrup.

Two tests were performed in this paper. Test 1 is to verify the application of the DIC method to concrete bars deteriorated by ASR. The surface deformation and strain of the concrete bars in the accelerated expansion test were measured by the DIC method. This result and the crack pattern on the surface of the concrete bars were compared, and the aptitude of the DIC method for the dimensional measurements was checked. In Test 2, the release strains on the large exposure test specimens during coring were measured by the DIC method.

2 MATERIALS AND METHODS

2.1 General

In this chapter, test specimens and methods of the expansion tests of Test 1 and Test 2 were introduced. In Test 1, an accelerated expansion test was applied to small concrete bars including reactive aggregates. This was because the aptitude of the DIC method should be checked in the short-term. In Test 2, large test specimens were used in the exposure test. The images for the DIC method were taken in a constantly bright room.

2.2 Materials and mixture proportions

Table 1 shows the status of the test specimens in Test 1 and Test 2. Figure 2 shows the shape and size of the test specimens which were made of reinforced concrete (RC). The size of the test specimen is 100mm×100mm×300mm. The concrete includes industrial glasses instead of alkali reactive aggregates, due to the accelerated expansion of the test specimen [2]. The compressive stress and Young's modulus of the concrete are 38.2N/mm2 and 3.51kN/mm2 respectively. 30×30×6mm acrylic plates were fastened on both edges of the test specimen to measure the length of the specimen using a dial gauge. The surface of the specimen was painted using oil-based paint to make random patterns for the DIC method. The test specimens were cured at 20 degrees, RH60% for 14 days after casting the concrete. Then, the specimens were settled in 40-degree water to measure the length intermittently.

Proportions of the mixed concrete used are shown in Table 2. Alkali reactive coarse aggregate, limestone crashed-sand of non-reactive aggregate and normal portland cement were used in the test specimen in test 2. Sodium hydroxide was added to the water to control the amount of Alkali in the concrete to 6.0 kg/m^3. The water to cement ratio was 0.47. Steel deformed rebar whose diameter was 13mm and 6 mm steel round bar were used as the restriction units. Table 3 shows the type of the test specimens, and Figure 2 shows the details of the specimens. The size of the test specimens are either 250×250×600mm or 300×300×600mm. Type 1 has neither rebars nor stirrups to restrict the concrete. Type 2 has 4 rebars to restrict the concrete along the longitudinal direction only. Type 3 and Type 4 have both 4 rebars and 5 stirrups to restrict along the longitudinal and latitudinal direction. Steel plates were welded to both sides of the rebars to restrain a decrease of bond strength with expansion by ASR. Epoxy resin having a width of 2mm was pasted on the surface of 250×250mm and 300×300mm. Test specimens were exposed in a seawater shower at the Port and Airport Research Institute since the 56th day after casting the concrete. The period of exposure was 538 days. After the exposure test, all of the surfaces of the test specimens were washed to make the random patterns for the DIC method.

2.3 Methods for assessment and analysis

General

In Test 1 and Test 2, strain gauges and dial gauges were used for contact strain measurement. This contact strain measurement was used for evaluating the accuracy of conventional measurement and for measuring the strain on the rebars that are inserted in the test specimens. The DIC method was applied to calculating the deformation with expansion and the strain distributions after making a core. Multi rosette analysis was applied at 26mm to 36mm from the center of the core.

Contact strain measurement method

In Test 1, acrylic plates were pasted on the surface of the edge for measuring shift of the longitudinal length. The base length for calculating strain was 300mm.

In Test 2, 2 mm strain gauges made of polyester were pasted on the rebar to evaluate the expansion property by ASR. Also, brass contact chips were set on the surface of the test specimen to measure shift in both the longitudinal and lateral length. The pitch of contact chips was 100 mm. The masterpiece of the strains was the average of the result in each direction. 30 mm trimetric strain gauges made of polyester were pasted on center of the core as the contact stress release method. In this method, release strain was calculated based on the difference between before and after making the core. The strain gauges were connected again after coring. Figure 4(a) shows the circumstances of taking images for the DIC method.

Digital Image Correlation Method

The digital image correlation method takes a digital image of a surface pattern before and after deformation by a digital camera to obtain the amount and direction of deformation of the specimen from the brightness distribution of the digital image obtained. In the analysis of the digital image correlation method, the fact that pixels in the monochrome digital image are generally of 256 tones, is utilized [3]. When point A is shifted to point A’ in Figure 5 (a), a very small region (called as subset, hereinafter) around the center point A before deformation is focused. As the point A’ after the shift exists in the image after the deformation, the subset showing high correlation to the brightness distribution of the subset before deformation is searched for in the image after deformation by numerical analysis. If there is a strong similarity between the subsets before and after deformation, the shift can be identified, and thus the direction and distance of the shift of the point can be calculated. This subset can be set to have any size necessary for the measurement in the image. For the analysis methods, there are two kinds of methods; a coarse search where displacement is calculated with measurement accuracy of a unit of one pixel, and a fine search where displacement is calculated with accuracy of a unit smaller than one pixel. In the coarse search, the correlation function C is obtained by the residual minimization method as shown in Equation (1) and Figure 5 (b).

$$C\left(X+u,Y+v\right)=\sum_{i=-M}^{M}\sum_{j=-M}^{M}I_d(X+u+i,Y+v+j)-I_u(X+i,Y+j)| \quad (1)$$

where, Iu(X,Y) and Id(X+u, Y+v)are the image strength before and after deformation, respectively, and X and Y are the center coordinates of the subsets, u and v are the amount of the shift in the X direction and Y direction, respectively, and N=2M+1.

The coordinates to give the minimum value of Equation (1) become the closest location to the point where the center of the subset shifted. However, as the actual distance of the shift is shorter than the distance of one pixel, it frequently occurs that the peak of correlation comes between pixels. Thus it is necessary to calculate the distance of the shift with accuracy of a distance shorter than one pixel. As a fine search method, there is a method in which a correlation value at the pixel point is utilized, or a method in which the location to give the best correlation is calculated by interpolating the strength values between the discrete pixel points. In this study, discrete strength distribution of the measured image is interpolated by linear or quadratic curves, and the location to give the maximum of the correlation function is calculated. Equation (2) shows the cross-correlation method used in the fine search.

$$C\left(X+u,Y+v\right)=\frac{\sum_{i=-M}^{M}\sum_{j=-M}^{M}I_d(X+u+i,Y+v+j)\times\sum_{i=-M}^{M}\sum_{j=-M}^{M}I_u(X+i,Y+j)}{\sqrt{\sum_{i=-M}^{M}\sum_{j=-M}^{M}\left\{I_d(X+u+i,Y+v+j)\right\}^2\times\sum_{i=-M}^{M}\sum_{j=-M}^{M}\left\{I_u(X+i,Y+j)\right\}^2}} \quad (2)$$

Strain release method used by DIC method

In Test 2, the stress release method by the DIC method was tried. The outside diameter of the core for stress release was 52 mm. At first, the random pattern was distributed on the surface of the specimens using black, yellow and white spray paint. The area with the least cracks in the painted fields was regarded as the place for making the core. Some images of this area were taken using a digital CMOS camera. The number of pixels of the camera was 14 million(4,800×2,800) pixels, and the area taken by the camera was 280mm×180mm. The length of a pixel is 0.06mm. After taking the images, the core was made using a wet type boring machine. The depth of the core was 100mm and was twice as long as the diameter of the core. Then, some images of the surface around the core were taken using the same camera. The condition for taking the image was the same before and after the boring. Figure 4(b) shows the example of the images for DIC method. Scale of the subset was 30×30 pixels.

Multi rosette analysis

The principle of Multi rosette analysis is shown in Figure.6 [4]. At first, the calculation method of the change ratio of the hole diameter will be explained. As shown in Figure.5, analysis points will be arranged in a concentric pattern. In this case, the number of analysis points is 64 points. Two analysis points that are symmetric with respect to the center point of the hole will be selected. The change in distance between two points will be calculated using the images before and after deformation and 32 calculated data are obtained. In these calculated data, a combination of 0, $\pi/4$, and $\pi/2$ rad along the x-axis will be selected and the maximum and minimum of the ratios of the change in distance will be obtained using rosette analysis. Then multiple rosette analysis will be performed as the combination will be changed and the average maximum and minimum of the ratios of the change in distance that reduce the error will be obtained. In Test 2, the diameter of the core was 890pixels, and the pitch along the normal vector was 5 pixels.

3 RESULTS

Figure 7 shows the strain distribution in the X and Y axial directions in Test 1. Black lines in each figure show the cracks that are more than 0.1 mm. The initial length to calculate the strain was defined to be 8 mm. The images at 7 and 49 days in 40-degree water during the curing period were used for the DIC method. In Figure 7 (a) and (b), expansion areas with yellow green intersperse. Figure 7 (b) particularly has the yellow green area along the X axial direction. At 7 days, no cracks on the surface of the concrete were found. From Figure 7 (c) and (d), red areas which showed large expansion more than 0.5%, were found at 49 days. From

Figure 7 (c), red areas in the upper side are larger than that in lower areas. In Figure 7 (d), red areas exist in the upper side along X axial direction.

Table 3 shows the result of the strains measured by strain gauges and the DIC method in Type 4 of Test 2. The strains along the longitudinal direction and the lateral direction at the end of the exposure period are shown in this Figure. The strain on the surface of the rebar was 1410 ×10-6, and the strain on the surface of the concrete measured by the dial gauge was 2080×10^{-6}. On the other hand, the strain measured by the strain gauge of the stress release method was 47×10^{-6}, and the strain measured by same way of the DIC method was 1809×10^{-6}. The strain on the surface of the concrete measured by the dial gauge along the lateral direction was 3570×10^{-6}. The strain measured by the strain gauge of the stress release method was -71×10^{-6}, and the strain measured by same way of the DIC method was 1653×10^{-6}.

Figure 8 shows the relationship between the distance from the center of the core and the principal strain measured by the stress release method in Type 1, Type 2 and Type 3 of Test 2. The outside edge of the core was located at 26 mm from the center. The maximum value of the principal strain was on the outside edge of the core. On the circumference 10 mm from the outside edge of the core, every principal strain was less than 50% with respect to the maximum value.

Figure 9 shows the strain energy in Type 1, Type 2, and Type 3 in Test2. The results of the strain energy of the three test specimens showed almost the same values. The strain energy in Type 1 consisted of that by the free expansion only. On the other hand, more than 10% of the strain energy in Type 2 and Type 3 occurred by the stress release.

Figure 10 shows the relationship between the strain energy by expansion during the exposure period in the restrained concrete, and the difference between the strain energy of the free concrete measured by equation (4). All of the plots located on the same line showed y=-1.35 + 0.273.

4 DISCUSSION

At first, the aptitude for measurement of the strain on the surface of concrete by the Digital Image Correlation method was considered. From Figure 7, cracks due to ASR were found where the local strain occurred at elastic transformation. It was obvious that ASR expanded continuously where the concrete transformed at the beginning of the deterioration. It was also shown that the DIC method was a suitable tool that would be able to evaluate the deterioration of concrete in the two dimensions.

From the result of the measurement of expansion during the exposure period in Table 3, the strain on the concrete was larger than that of the rebars, and the strain along the longitudinal direction was larger than that in the lateral direction. Generally, the expansion property of concrete that is in the frame of rebars and stirrups is different from that of concrete that is out of the frame because of the restraint by the rebars and stirrups. So, many cracks tend to occur around the surface of the concrete. If the ratio of the rebars was much more than that of the stirrups, many cracks along the longitudinal direction would occur, and the strain across the longitudinal direction would increase. For the expansion property during the exposure period, the direction property of the expansion by the effect of restraint was confirmed.

For the measurement by the stress release method, the strain measured by the DIC method was close to the strain by the dial gauge, but the strain measured by the strain gauge was remarkably small. This is because the result of the strain gauge was measured inside the core where the cracks tended to vary by making the core. On the other hand, the area for the DIC method was outside the core outside, where the cracks did not tend to vary by making the core. So, the result of the stress release method by the DIC method was precise. This means that the release strain by stress release method of the DIC method has a relationship with the strains of the rebar and concrete during the exposure period.

From Figure 8, the strain tended to be large around the outside of the core, because a relaxation of the stress concentration occurred when the core was made. The strain far from the outside, if the core was smaller than that near the outside of the core, and the effect by the stress concentration disappeared. This means that the stress release method measured by the DIC method can evaluate the shift of the strain on the surface of the concrete.

The maximum principal strain (ε_{max}) in Type 1 was smaller than that in Type 2. The difference between ε_{max} and the minimum principal strain (ε_{min}) also has the same tendency. In Type 2, the release strain was large because the expansion force was accumulated by the restraint of ASR expansion.

In theory of the structural engineering, the shear principal strain did not occur during isotropic transformation, because the difference between ε_{max} and ε_{min} ($\Delta\varepsilon$) was 0. On the other hand, the shear principal strain tends to increase during anisotropic transformation. From the results of this experimentation, $\Delta\varepsilon$ in Type 1, which has neither the rebars nor the stirrups, was a minimum, and that in Type 2, which has the rebars only, was a maximum. This showed that the characteristics of the expansion direction by ASR were different due to the restraint of the rebars, and the stress release method of multi rosette analysis could explain this result.

In this study, the energy per unit volume (U), which occurred in the concrete by the ASR expansion, was defined as the strain energy with respect to the expansion. If the concrete was an elastic body, U would be expressed as sum of the strain energy by the expansion during the exposure period and the strain energy at the stress release as shown in Equation(3).

$$\mathrm{U} = \int^{x} \sigma \, d\varepsilon + \int^{x'} \sigma' d\varepsilon = \frac{1}{2} E \, \varepsilon^2 + \frac{1}{2} E \, \varepsilon'^2 \quad (3)$$

where, E means the Young Modulus of the concrete. σ and ε stand for the stress and the strain by the expansion during the exposure period, and σ’ and ε’ are the stress and the strain which were released at the stress release.

In theory, the strain energy U among Type 1, Type 2, and Type 3 is the same. During free expansion, the strain energy at the stress release was 0, and U is only the strain energy due to the expansion during the exposure period (U_{free}). On the other hand, the strain energy reserved in the concrete under the restrained condition was shown as the difference between the strain energy of the free concrete (U_{sr}) and the strain energy due to the expansion during the exposure period in the restrained concrete (U_{res}). This energy was released at the stress release. This theory is shown in equation (4).

$$U_{sr} = U_{free} - U_{res} \quad (4)$$

where, U_{sr} stands for the strain release energy in the concrete under the restrained condition, and U_{free} is the strain energy due to the expansion during the exposure period. U_{res} is the strain energy due to the expansion during the exposure period in the restrained concrete.

From Figure 9 and 10, the sum of both the strain energy by the expansion during the exposure period and the strain energy at the stress release was almost same among all of the specimens. This result conformed to Equation (3). This means that Equation (3) can be applied to the expansion by ASR. Besides, U_{sr} is relative to U_{res} among Type 1, Type 2, and Type 3. In conclusion, the strain energy reserved under the restrained condition might have the relationship to the strain energy released by the stress release, and the strain energy reserved due to the expansion during the exposure period might be able to be shown by the stress release method. It was shown that the multi rosette analysis by the DIC method might be a suitable analysis against the expansion property of ASR included in the expansion during the exposure period.

5 CONCLUSIONS

In this paper, the properties of the stress release method calculated by multi rosette analysis with respect to the expansion of a concrete unit deteriorated by ASR were considered.

The Digital Image Correlation (DIC) method was applied to the calculation of the multi rosette analysis. The results of this paper are as follows.

(1) The DIC method can detect dimensional deformation by ASR.

(2) Accuracy of the strain measured by the stress release method of the DIC method was higher than that of the strain gauge method.

(3) Principal strain measured by multi rosette analysis can evaluate the anisotropy of the expansion by ASR.

(4) Strain energy calculated by multi rosette analysis can evaluate the property of the expansion by ASR.

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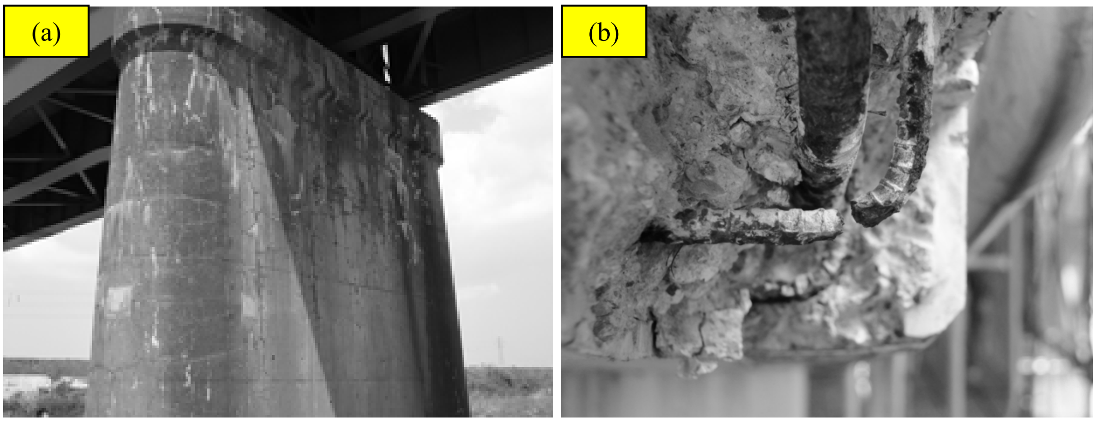


FIGURE 1: (a) Example of a pier deteriorated by ASR. Many cracks with ASR gels and free lime were found on the upper side of the pier. (b) Example of the rebar ruptures by the expansion of ASR. Some of stirrups were ruptured at the corner of the beams and footings.

TABLE 1 : Material property of aggregates. Glass cullet was used to the imitation of reactive aggregates.

Materials	Density	Water absorption	FM	Remark
	kg/m^3	%		
Non-Reactive Coarse Aggregate	2730	0.42	6.5	Andesite
Reactive Coarse Aggregate	2690	1.83	-	Andesite
Non-Reactive Sand (Test1)	2580	1.38	2.7	Sea sand
Non-Reactive Sand (Test2)	2650	-	-	Crushed lime stone
Glass Cullet	2500	-	3.9	-

TABLE2: Proportions of the concrete mixes used

Expansion Materials	G max	Slump	Air	W/C	s/a	W	C	Non-Reactive		Reactive		Glass Cullet	AE WRA	SP	Na_2O
								S	G	S	G				
	mm	cm	%	%	%	kg/m^3									
Test1	20	10±2	5±1	35	45.0	170	486	286	371	0	0	926	0.00	7.29	4.86
Test2	20	11±2	4±1	47	42.4	165	351	742	0	0	1064	0	0.88	0	6.00

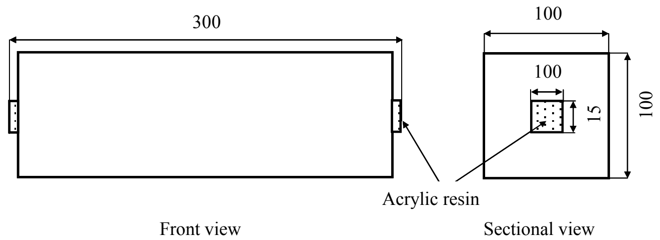


FIGURE 2: Shape of the test specimen in Test1. Glass cullet imitated the deterioration by ASR was in the specimen.

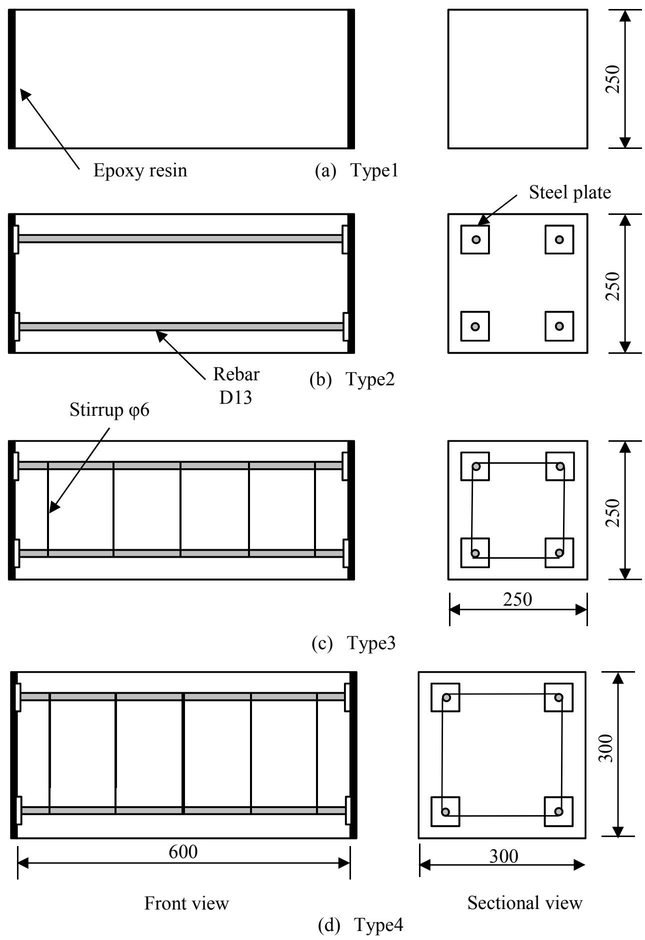
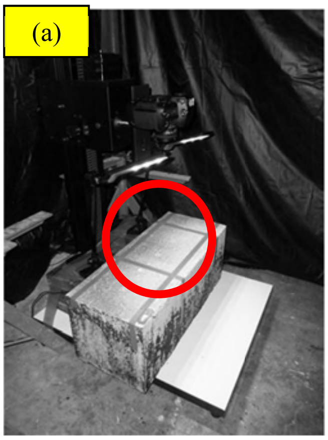


FIGURE 3: Shape of the test specimens in Test2. Type1 has no steel bars. Type2 has 4 rebars along the longitudinal direction. Type3 and Type4 have 4 rebars and 5 stirrups inserted across the longitudinal direction.



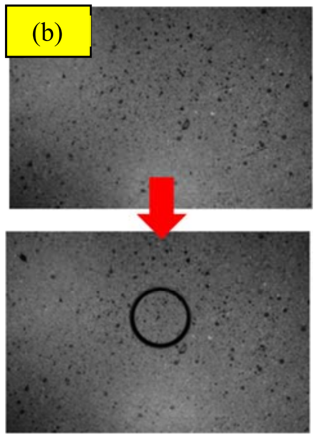


FIGURE 4: Circumstances of taking images for DIC method in Test2. (a) A test specimen was on a camera stand, and a digital camera was set above the test specimen. Two stand lights illuminated the specimen. Area of images was in the red circle. (b) Example of the image before and after making the core

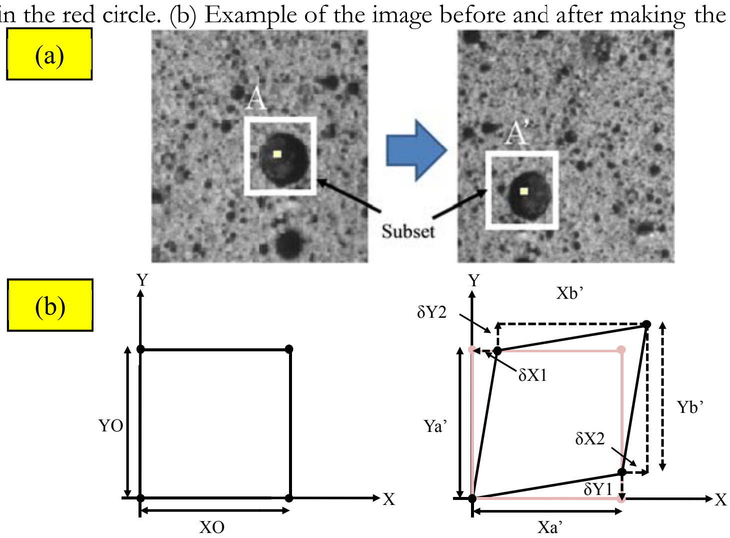


FIGURE 5: Principle of the Deformation of subsets (a) Subset shift (b) Before and after the deformation

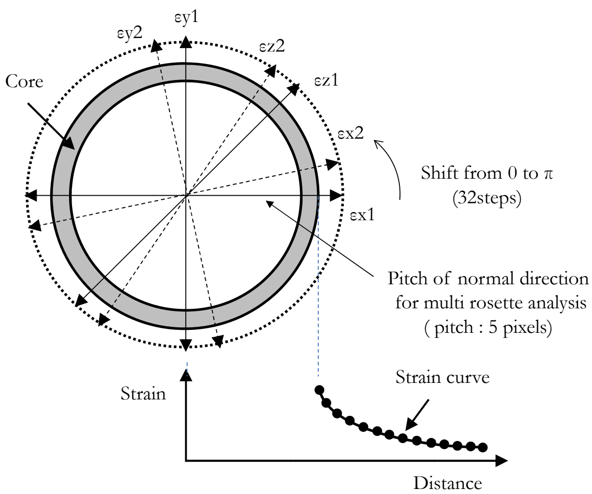


FIGURE 6: Principle of the multi rosette analysis and example of relation between distance from the edge of the core and strain. X, Y and Z axial for the analysis rotate from 0 to π. Steps of the rotation are 32.

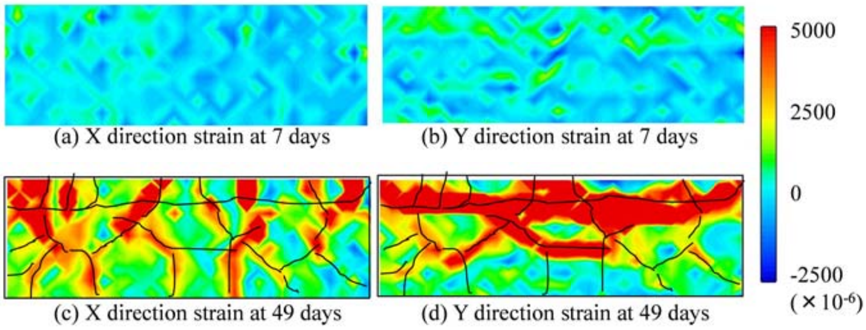


FIGURE 7: Strain distribution on Test1 at 7 days and 49 days after casting. Black lines mean the cracks which are more than 0.1mm.

TABLE 3 : Results of strain measured by strain gauges and DIC method in Test2.

Direction	Longitudinal				Lateral		
Place	Rebar	Concrete			Concrete		
Measure-ment	log of Expansion	log of Expansion	Stress release	Stress release	log of Expansion	Stress release	Stress release
	Strain gauge	Dial gauge	Strain gauge	DICM	Dial gauge	Strain gauge	DICM
Unit	10E-6				10E-6		
Type4	1410	2080	47	1809	3570	-71	1653

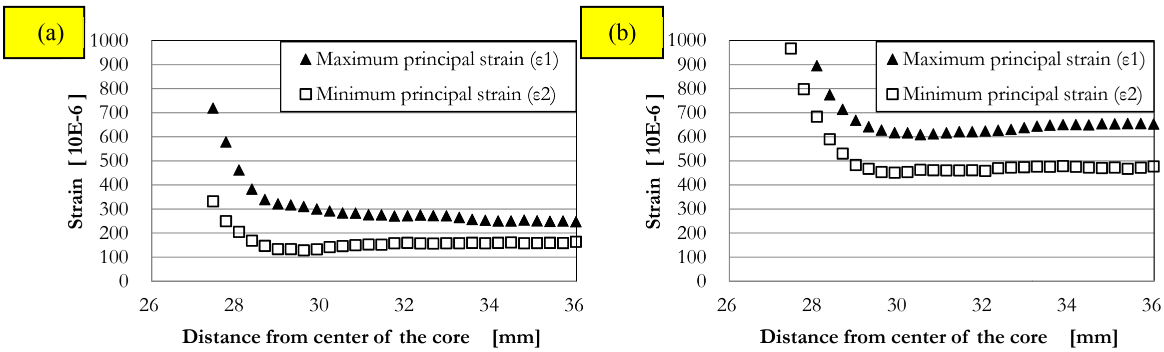


FIGURE 8: Relationship between the distance from center of the core and strain in Test2. (a) Type1 (b) Type2

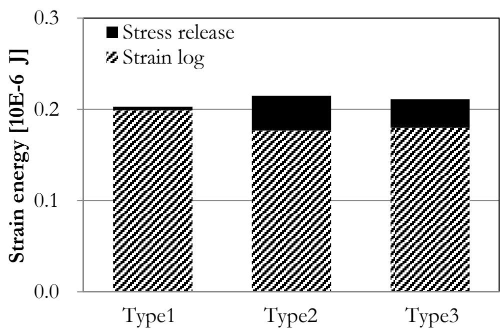


FIGURE 9: Compare of the strain energy in Test2.

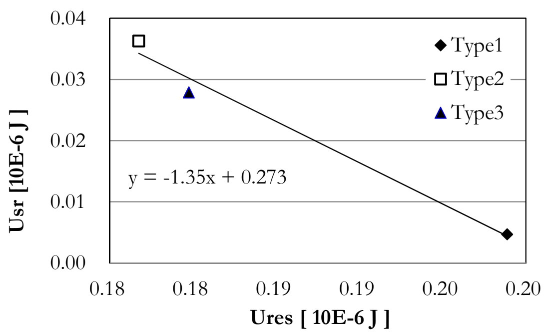


FIGURE 10: Relationship between Ures and Usr.