COMPUTATIONAL STUDY ON STRUCTURAL PERFORMANCE OF ASR DAMAGED RC MEMBERS

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Abstract

In this study, computational investigation of structural performance of ASR damaged RC beams was conducted by finite element analysis. RC beams failed in various modes were analysed by means of integrated analytical method in which ASR expansion analysis and loading analysis were combined. In the analytical method, influences of ASR were taken into consideration as initial strains, initial stresses, initial cracks and deterioration of material properties. And the structural performances damaged by ASR were discussed by focusing on initial flexural stiffness, load carrying capacity and failure mode. As a result, it was confirmed that influences of ASR on the structural performance were different depending on the failure mode of sound beam since the failure mechanisms were different. The importance of the accurate estimation of deterioration and the consideration of failure mechanisms was mentioned.

Keywords: structural performance, ASR expansion analysis, loading analysis, deterioration of material properties, chemical prestress

1 INTRODUCTION

It is well known that mechanical properties of concrete damaged by ASR deteriorate with many cracks due to the expansion. However, for RC members, it has often been observed experimentally that there is no significant effect on the load carrying capacity, rather the flexural stiffness and the ductility of the members are sometimes improved by compressive stress induced by ASR expansion[e.g. 1]. Moreover, ASR cracks on RC members occur in the parallel direction to the reinforcement due to the restraint, in other words, the anisotropy of mechanical properties of concrete may exist depending on the crack direction.

For real structures, since these situations occur more complicatedly, it may be difficult to evaluate the structural performance experimentally. Therefore, computational evaluation of the structural performance of ASR damaged structures is required. In this case, consideration of the damage such as anisotropy of the deteriorated material properties, initial cracks, internal stress and initial strain induced by ASR.

In this study, analytical evaluation of structural performance of ASR damaged RC beams was conducted by finite element analysis. RC beams failed in various modes were assumed and the influences of ASR expansion and damage on the structural performance were investigated by focusing on initial flexural stiffness, load carrying capacity and failure mode. In the finite element analysis, the integrated analytical method proposed by the author[2] was adopted, in which ASR expansion analysis and loading analysis were combined. By using the analytical method, the expansive behaviors due to ASR were predicted and the structural performances were evaluated with considering initial strains, initial stresses, initial cracks and deterioration of material properties.

2 ANALYTICAL MODEL

2.1 General

As described Chapter 1, the integrated analytical method was used in order to evaluate the structural performance of ASR damaged RC beams. In the analytical method, two different analyses, ASR expansion analysis and loading analysis, were combined. The ASR expansion analysis is for prediction of expansive behavior such as deformation, strain and stress due to ASR expansion. The loading analysis is so-called structural analysis and it is for evaluating the structural response subjected to the external load. Different constitutive models of concrete are assumed in each analysis and two analyses are combined by considering the consistency of stress and strain fields.

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2.2 Constitutive model of concrete in the ASR expansion analysis

It has been observed by many researchers that ASR expansion strongly depends on the reinforcement restraint, that is, expansive strain caused by ASR decreases as the reinforcement ratio increases. This means that the internal stresses and deterioration of mechanical property of concrete are also changed by the restraint situation. In order to considering this important characteristics, the ASR expansion model [3] proposed by author was applied to the ASR expansion analysis. The proposed model is based on the damage theory and described as Equation 1.

$$\sigma(t)=(1-\Omega)\ E_{c0}\times(\varepsilon_c(t)-\ \varepsilon_0(t)) \tag{1}$$

where $\sigma(t)$, $\varepsilon_0(t)$ and $\varepsilon_c(t)$ are stress induced on concrete, ASR free expansive strain and expansive strain under restraint, respectively. E_{c0} is the Elastic modulus of concrete. Ω is the damage variable. In the model, it was assumed that the damage accumulated with ASR expansion so that Ω is initially 0 and close to 1.0 immediately as expansive strain $\varepsilon_c(t)$ increases. Then, the damage variable Ω is the function of $\varepsilon_c(t)$ as defined by Equation 2.

$$\Omega=1-(1/(1+1000\times(\varepsilon_c(t)-\ \varepsilon_{cr})^{0.5})),\quad \varepsilon_c(t)>\varepsilon_{cr} \tag{2}$$

where ε_{cr} is the strain at the cracking.

Figure 1 shows examples of the results of ASR expansion analyses using the model. The experiments were carried out by Yamura et al. [4] and Koyanagi et al. [5], in which the ASR expansive behavior under uniaxial restraint with different reinforcement ratio were investigated. Good agreements can be seen between the analytical and experimental results for both experiments. By applying this model to orthotropic material, ASR expansive behavior is evaluated not only for the magnitude but also the directionality. Note that this model is a macro model for ASR expansion including the time dependent deformation such as creep and shrinkage. Moreover, cracks are not evaluated directly but considered based on the damage theory.

2.3 Constitutive model of concrete in the loading analysis

Lattice equivalent continuum model was applied to the constitutive model of concrete in the loading analysis [6]. Basic concept of the model is to represent the force flows in the cracked concrete as a system of lattices, which are consisted of main lattice and shear lattice. In each lattice, the uniaxial stress-strain relationships are assumed and the stiffness of the continuum model is built by combining the lattice system.

For stress-strain relationship in the compressive region, Saenz equation was assumed up to compressive strength and stress decreased linearly considering the compressive fracture energy [7] in order to reduce the mesh dependency. On the other hand, for the tensile region, tension softening branch of 1/4 model considering the tensile fracture energy was assumed after cracking.

2.4 Reinforcement model and bond model

Reinforcement was discretized as a truss element in both the expansion analysis and the loading analysis. The stress-strain relationship of reinforcement was assumed as a bilinear model. After yielding, the stiffness of the hardening branch is 1/100 slope comparing with initial Young's modules.

The bond interaction between concrete and reinforcement was represented by a bond element [8]. The bond stress-slip relationship is introduced into the parallel direction to the reinforcement of bond element. The relationship up to the bond strength τ_{max} is modeled by Equation 3 [9].

$$\tau=\alpha\times0.9f'_c{}^{2/3}(1-\exp(-40(s/D)^{0.5})) \tag{3}$$

where s is slip, D is diameter of reinforcement and α is 0.4. The bond strength τ_{max} was the bond stress corresponding to the slip of 0.2 mm and linear softening branch to the bond stress of $0.1\tau_{max}$ corresponding to the slip of 0.4 mm were assumed as shown in Figure 2.

2.5 Procedure for combining the ASR expansion analysis and loading analysis

As described before, the constitutive models of concrete are different with the ASR expansion analysis and the loading analysis. To combine both analyses, two coordinate systems were assumed as shown in Figure 3, that is, σ-ε coordinate and σ'-ε' coordinate which are defined in the ASR expansion analysis and the loading analysis, respectively. In the ASR expansion analysis, since compressive stress occurs with positive strain described as Equation 1, stress and strain are placed in forth quadrant of σ-ε coordinate as shown in Figure 3. Here, it is assumed that the stress and strain obtained by ASR expansion analysis are on the stress-strain relationship defined in σ'-ε' coordinate as an initial state of the loading analysis. Therefore, the loading analysis is regarded as the initial stress and strain problem.

Meanwhile, since the constitutive model of reinforcement is the same in both the AAR expansion analysis and the loading analysis, any assumptions are not needed in order to combine both analyses.

2.6 Consideration of ASR damage

In the loading analysis, ASR damages of concrete were taken into consideration by the deterioration of material properties and initial crack. It was assumed that the compressive strength, Young's modulus and tensile strength decreased with an increase of the expansive strain. In order to consider the anisotropy, the deterioration of material properties was introduced to three directions of principal strain independently in each gauss point. Decreasing rate μ of each property was assumed as Equation 4.

$$\mu=(1+10000\times\varepsilon_c{}^*)^{\gamma} \tag{4}$$

where $\varepsilon_c{}^*$ is the principal strain of initial state in the loading analysis and γ is a parameter. By changing the parameter γ, the deterioration curve of each material property can be set depending on their tendency. Strain at the peak stress $\varepsilon_{c0}{}^*$ was also changed in order to keep the consistency of stress-strain relationship in compressive region as Equation 5.

$$\varepsilon_{c0}{}^*=\varepsilon_f\times(1-\exp(-\varepsilon_c{}^*/\varepsilon_{c0}))+\varepsilon_{c0} \tag{5}$$

where ε_{c0} is the strain at the peak stress of sound concrete. $\varepsilon_{c0}{}^*$ becomes closer to $\varepsilon_f+\varepsilon_{c0}$ by increasing of $\varepsilon_c{}^*$.

Since constitutive model in the loading analysis, lattice equivalent continuum model, is based on the fixed crack model, initial cracks were defined in each gauss point by fixing the coordinate system to the principal stress direction obtained from the ASR expansion analysis. However, initial crack width of these cracks set to 0 in the analysis. Note that, another cracking under loading was allowed by considering non-orthogonal coordinate system besides the initial crack coordinate in multi cracking model.

3 ANALYSIS OF ASR DAMAGED RC BEAMS

3.1 Outlines of RC beams

Four RC beams, having same cross section and different shear span ratio, were assumed. Outlines of their dimensions are summarized in Table 1. Rectangular section, width of 120mm and height of 200 mm were assumed in every beams and 2 reinforcing bars, D13 (nominal area = 126.7mm^2), were arranged at an effective depth of 170mm. Reinforcement ratio is 1.24%. Length of shear span were set to 160, 360, 520 and 680mm for each beam and shear span to effective depth ratio (a/d) are 0.94, 2.12, 3.06 and 4.00, respectively. No stirrup was assumed to be arranged. The beams were assumed as simple support during both the ASR analysis and the loading analysis. In the loading analysis, concentrated load was applied at the center of the span. Steel plates of 40mm width were put at loading point and supporting points.

For all beams, compressive strength, tensile strength and Young's modulus of concrete were set to 30.0MPa, 2.22MPa and 28.0GPa, respectively. Yield strength and Young's modulus of rebar was set to 350MPa and 190GPa, respectively.

3.2 Outlines of analysis

RC beams were modeled as follows: Concrete is modeled by 8 node isoparametric element. All elements were cubic shapes and sizes of them were 20×20×20mm. The reinforcing bars were modeled by truss element and their nodes were independent of concrete nodes. Bond property between concrete and rebar was assumed as described in section 2.4. However, no slip was assumed in both ends of rebar by modeling anchor of bent bars.

The analysis was conducted as following procedures. Firstly, free expansive strain was introduced into all gauss points as the initial strain in the ASR expansion analysis. The free expansive strains were set to 1000, 2500 and 5000μ, and introduced linearly in increments of 50μ. Note that although the magnitude of free expansive strain is the same for all gauss points in each analysis, the expansive strains, which are the response of the analysis, become different in each gauss point.

After the ASR expansion analysis, the load was applied at the center of the span in a displacement control manner. In the loading analysis, deterioration curves of material properties were assumed as shown in Figure 4. The parameter γ in Equation 4 were set to -0.08, -0.30 and -0.20 for compressive strength, Young's modulus and tensile strength, respectively. The parameter ε_f in Equation 5 was set to 2000μ. Note that deterioration of material properties is defined based on not the free expansive strain but the expansive strain. Therefore, the anisotropy of the deterioration due to ASR damage can be considered by means of results of the ASR expansion analysis. For bond property between concrete and rebar, two cases were assumed; one case is that the bond property does not change due to ASR and another case is that the bond property deteriorates due to ASR and the bond strength decreases to the half for all rebar uniformly. They are denoted as "D" and "DB". Moreover, only expansion case was assumed. In this case the material properties don't deteriorate and only initial strain, initial stress and initial cracks were taken into consideration. It is denoted as "E". Analytical cases are summarized in Table 2.

Figure 5 shows load and deflection relationship of sound beams obtained from the loading analysis. They are recognized as initial structural performances. Failure modes of each specimen were different, that is, N4 was failed in flexure, N3 was failed in diagonal shear and N2 and N1 were failed in shear compression. Influences of ASR on these structural performances will be discussed in following sections.

3.3 ASR expansion of RC beams

Strain distributions obtained by the ASR expansion analysis

Figure 6 shows expansive strain distributions obtained by the ASR expansion analysis. Since the longitudinal reinforcement arranged in bottom part, the ASR expansion were restrained and the strain gradient appeared to vertical direction in all cases. When the free expansive strain increased, the expansive strain in upper part also increases. The tendency of strain distributions was almost the same in all cases in spite of the differences of shear span ratio. This means that the deformations of RC structures depend on its structural dimensions since local deformations such as a curvature are independent from them. Since strains in some elements near supports and loading point were strongly restrained by steel plates, computational procedure might be necessary to improve.

Initial state in the loading analysis

Figure 7 shows initial stress distributions of the loading analysis obtained through the procedure described in section 2.5. The stress gradient also appeared to vertical direction. However, their tendency with an increase of free expansive strain was different from that of the strain distributions. Compressive stresses in bottom part of the beam increased by an increase of the free expansive strain. On the other hand, in middle part, compressive stresses were independent of it. Tensile stresses occurred in upper part since warpage deformation occurred in the beam. Compressive stresses in the case of 5000μ of free expansive strain were about 12MPa in the bottom part and 2.0MPa in the middle part. These compressive stresses are so-called "chemical prestress" by the ASR expansion.

3.4 Structural performances of ASR damaged RC beams

RC beam failed in flexure (a/d = 4.00)

Figure 8 shows load and deflection relationships for the case of a/d= 4.00, which failure mode of the sound beam was flexural failure. In the case of "E", since the deterioration of material properties was not taken into consideration and chemical prestress were introduced, crack initiation delayed and the flexural stiffness after bending cracking become greater by an increase of the free expansive strain. In spite of the magnitude of the free expansive strain, the beams were failed in flexure. In the case of "D", initial flexural stiffness changed depending on the free expansive strain. Flexural stiffness after cracking and load carrying capacities were depending on the chemical prestress. Failure mode of them changed to diagonal shear. On the other hand, when the bond strength was assumed to decrease due to ASR, load carrying capacities increased and more ductile behaviors were obtained. Therefore, the estimation of the bond strength as well as the deterioration of material properties is important for evaluating the structural performance of RC beams failed in flexure.

RC beam failed in diagonal shear (a/d = 3.06)

Figure 9 shows load and deflection relationships for the case of a/d= 3.06, which failure mode of the sound beam was diagonal shear. In the case of "E", crack initiation delayed and the flexural stiffness after bending cracking become greater depending on the magnitude of the free expansive strain as same as the case of a/d= 4.00. Failure mode was changed from diagonal shear to flexural failure by an increase of the free expansive strain because of the positive effect of chemical prestress. In the case of "D", load carrying capacities, which were corresponding to the initiation of diagonal cracks, drastically decreased compared to that of the sound beam. Since decreasing of the bond strength led the decreasing of the flexural stiffness, large deflection occurred in maximum load of ASR damaged beam. Shear capacity of RC beam failed in diagonal shear is generally affected by its concrete strength and its failure mechanisms depend on the bond property. Moreover, introducing of prestress increases shear capacity. Therefore, failure mechanism of ASR damaged RC beam becomes more complicated compare to sound beam. Since the assumption of deterioration curves and bond strength damaged by ASR affects the structural performances sensitivity, the results obtained in this study is one example of the prediction. It is suggested that accurate estimation of deterioration due to ASR is most important for the evaluating the structural performances of ASR damaged beam failed in diagonal shear.

RC beam failed in shear compression (a/d = 2.12 and 0.94)

Figure 10 and 11 show load and deflection relationships for the cases of a/d= 2.12 and 0.94, which failure mode of the sound beam was shear compression. For both cases, when the deterioration of material properties was not taken into consideration, all beams were failed in shear compression and structural performances such as flexural stiffness, load carrying capacity and deformability increased because of the chemical prestress. However, the tendency changed if material properties deteriorated, that is, chemical prestress did not have an influence on the structural performances and flexural stiffness and load carrying capacity decreased. For D case of a/d = 0.94, load carrying capacities decreased so much. For DB case of a/d = 0.94, load carrying capacities decreased by an increase of the free expansive strain. Shear compression failure is generally affected by compressive strength. The reason of different tendency between a/d = 0.94 and 2.12 was not clear. Further research is needed to clarify about their failure mechanisms.

4 CONCLUSIONS

In this study, the influences of ASR on the structural performances of RC beams were investigated by finite element analysis. Influences of ASR were taken into consideration as initial strains, initial stresses, initial cracks and deterioration of material properties in the analytical method, then the initial flexural stiffness, the load carrying capacity and the failure mode of ASR damaged beams were discussed. As a result, it was confirmed that influences of ASR on the structural performance were different depending on the failure mode of sound beam since the failure mechanisms were different. The result obtained in this study is one example of the predictions and different result will be predicted if the analytical assumption changes. For the evaluating structural performance of ASR damaged structures, the accurate estimation of the deterioration of material properties is important and its effect on failure mechanisms should be considered in detail. Further research regarding to combine diagnosis, evaluation and simulation is necessary for the safety evaluation of ASR damage structures reasonably.

5 REFERENCES

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[1] Inoue, S., Fujii, M. Kobayashi, K. and Nakano, K. (1989): Structural behaviors of reinforced concrete beams affected by alkali-silica reaction. Proceedings of 8th International Conference on AAR, Kyoto, Japan: 727-732.

[2] Ueda, N., Nakamura, H. and Kunieda, M. (2008): Analytical evaluation of the effects of AAR on structural performance of RC beams and slabs. Proceedings of 8th International Conference on Creep, Shrinkage and Durability of Concrete and Concrete Structures(CONCREEP8), Ise-Shima, Japan: 1163-1169.

[3] Ueda, N., Sawaabe, S., Nakamura, H. and Kunieda, M. (2006): The damage evaluation analysis of RC structures due to AAR expansion. Proceedings of The Tenth East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-10); Materials, Experimentation, Maintenance and Rehabilitation, Bangkok, Thailand: 255-260.

[4] Yamura, K., Nishibayashi, S. and Tanaka, S. (1989): Study of the effect of steel reinforcement on alkali silica reaction of concrete. Proceedings of the Japan Concrete Institute, 11(1): 135-140. (In Japanese).

[5] Koyanagi, W., Uchida, Y., Iwanaga, T. and Asano, Y. (1998): Restraint effect of ASR expansion in RC members with small reinforcement ratios. Cement Science and Concrete Technology, (52): 786-791. (In Japanese).

[6] Tanabe, T. and Ishtiaq, A.S. (2001): Development of lattice equivalent continuum model for analysis of cyclic behavior of reinforced concrete. Modeling of inelastic behavior of RC structures under seismic loads, ASCE: 297-314.

[7] Nakamura, H. and Higai, T. (2001): Compressive fracture energy and fracture zone length of concrete, Modeling of inelastic behavior of RC structures under seismic loads: ASCE: 471-487.

[8] Tanabe, T. (2004): Nonlinear analysis and its program for RC structures considering initial stress. Gihodo. (in Japanese).

[9] Suga, M., Nakamura, H., Higai, T. and Saito, S. (2001): Effect of bond properties on the mechanical behavior of RC beam, Proceedings of the Japan Concrete Institute, 23(3): 295-300. (in Japanese).

TABLE 1: Dimensions of RC beams.

No.	a/d	width b (mm)	height h (mm)	effective depth d (mm)	shear span a (mm)	reinforcement ratio (%)
1	0.94	120	200	170	160	1.24
2	2.12	120	200	170	360	1.24
3	3.06	120	200	170	520	1.24
4	4.00	120	200	170	680	1.24

TABLE 2: Analytical cases.

type	a/d	deterioration of material	bond strength	abbreviation in legend #
Sound	0.94	-	τ_{max}	N1
E		-	τ_{max}	A1E10, A1E25, A1E50
D		○	τ_{max}	A1D10, A1D25, A1D50
DB		○	$0.5\tau_{max}$	A1DB10, A1DB25, A1DB50
Sound	2.12	-	τ_{max}	N2
E		-	τ_{max}	A2E10, A2E25, A2E50
D		○	τ_{max}	A2D10, A2D25, A2D50
DB		○	$0.5\tau_{max}$	A2DB10, A2DB25, A2DB50
Sound	3.06	-	τ_{max}	N3
E		-	τ_{max}	A3E10, A3E25, A3E50
D		○	τ_{max}	A3D10, A3D25, A3D50
DB		○	$0.5\tau_{max}$	A3DB10, A3DB25, A3DB50
Sound	4.00	-	τ_{max}	N4
E		-	τ_{max}	A4E10, A4E25, A4E50
D		○	τ_{max}	A4D10, A4D25, A4D50
DB		○	$0.5\tau_{max}$	A4DB10, A4DB25, A4DB50
#: **10, **25 and **50 denote free expansive strain of 1000, 2500 and 5000μ				

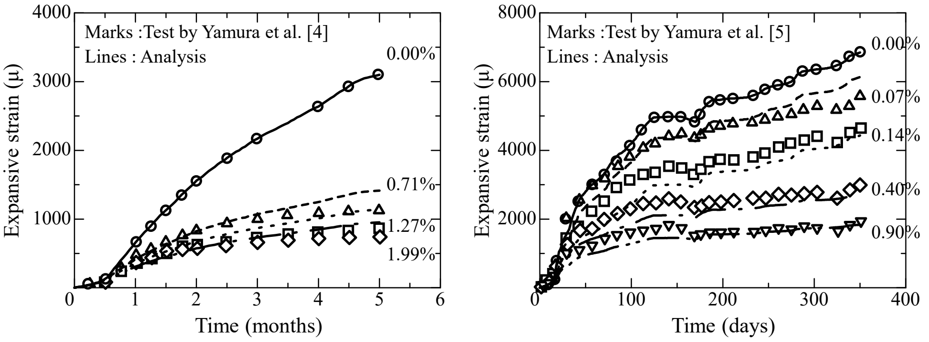

FIGURE 1: Example of the ASR expansion analysis for uniaxial restrained specimen. (left: tested by Yamra et al.[4], right; tested by Koyanagi et al.[5]).

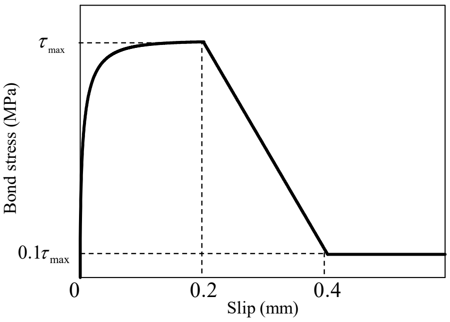

FIGURE 2: Bond stress and slip relationship.

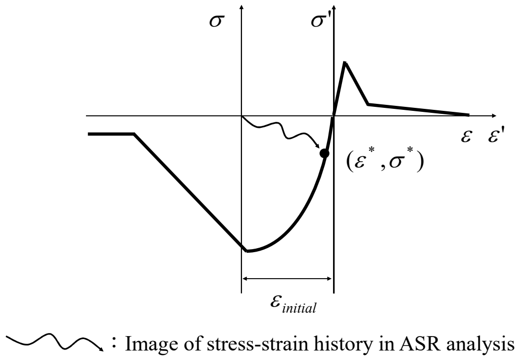

FIGURE 3: Assumption of the coordinate system in ASR expansion analysis and loading analysis.

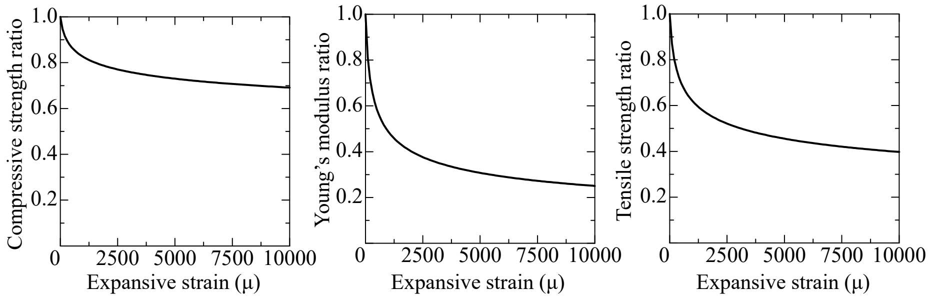

FIGURE 4: Relationships between expansive strain and deterioration of material properties.

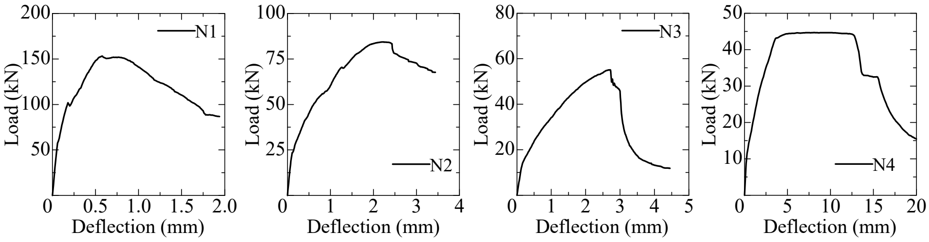

FIGURE 5: Load and deflection relationships of sound RC beams.

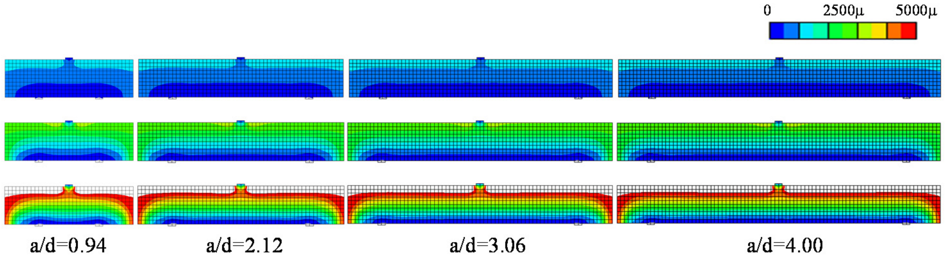

FIGURE 6: Distribution of expansive strain in RC beams obtained by the ASR expansion analysis. Free expansive strains are 1000, 2500 and 5000μ for upper, middle and bottom, respectively.

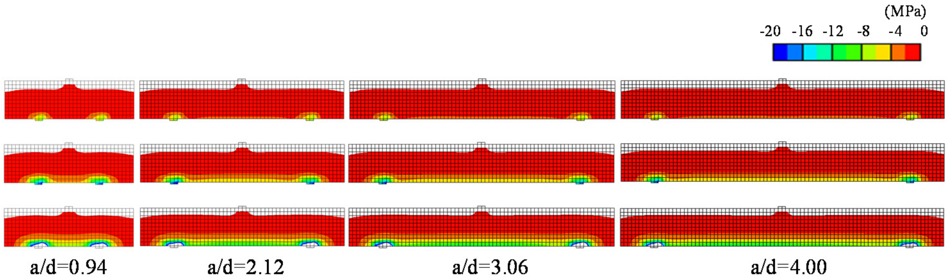

FIGURE 7: Distribution of initial stress in RC beams for the loading analysis. Free expansive strains are 1000, 2500 and 5000μ for upper, middle and bottom, respectively.

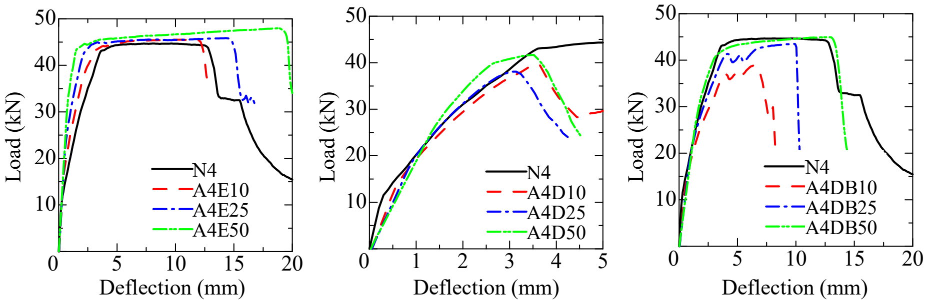

FIGURE 8: Load and deflection relationship of ASR damaged RC beams for a/d = 4.00.

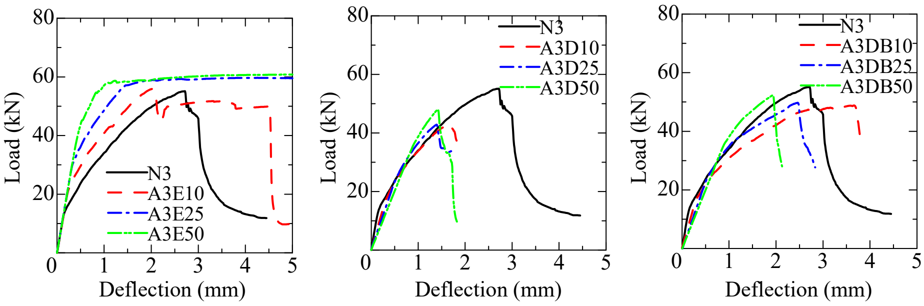

Figure 9: Load and deflection relationship of ASR damaged RC beams for a/d = 3.06.

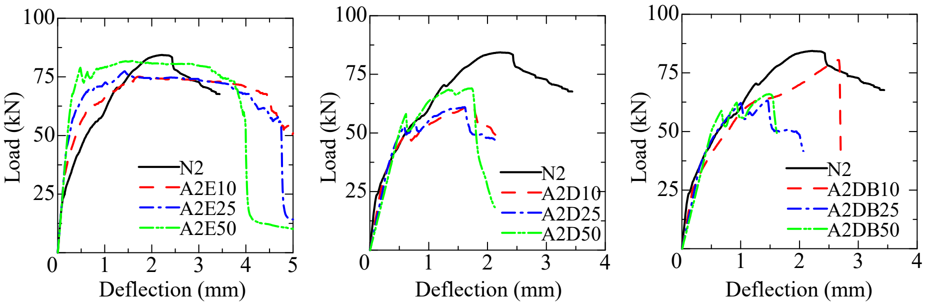

Figure 10: Load and deflection relationship of ASR damaged RC beams for a/d = 2.12.

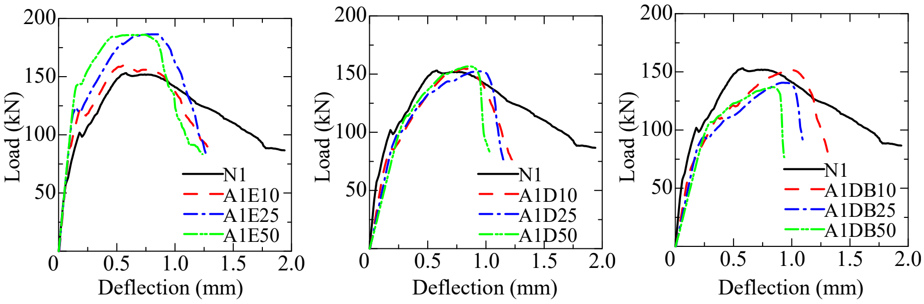

Figure 11: Load and deflection relationship of ASR damaged RC beams for a/d = 0.94.