ANALYTICAL STUDY ON FLEXURAL STRENGTHENING USING EXTERNAL CABLE SYSTEM FOR ASR-DETERIORATED PC BEAMS

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ABSTRACT

Some PC beams have been found deteriorated by ASR, and how to strengthen them has been an issue on the Hanshin Expressway. This research focused on the external cable system as a strengthening method and investigated the effect of additional axial force on the PC beams through a parametric study using the three-dimensional finite element method. A pushover analysis was conducted on a PC beam specimen, taking expansion and reduction in mechanical properties due to ASR deterioration into account to determine the effect of ASR deterioration on the stress occurring in the compressive fiber of a PC beam. Further investigation was made on the increase rate in compressive fiber stress accompanying the strengthening using the external cable system, by applying additional axial force to the specimen to simulate the effect of external cables. It was found that the impact of the reduction in mechanical properties due to ASR deterioration was minor on the internal stress, and that, under the present test conditions, compressive fiber stress in a PC beam could be lower when expansion was considered. The results also showed that the compressive fiber stress after the increase due to the addition of external cables still fell within the allowable range.

Keywords: ASR, PC Beam, Flexural Strengthening, External Cable System, Design Policy

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1. INTRODUCTION

Cracks caused by alkali silica reaction (ASR) on the Hanshin Expressway were first found in 1982. Since then, the company has implemented surface treatment and other measures to suppress the reaction, conducted follow-up inspections, investigated remedial methods, and developed a maintenance manual for remedial action on ASR-deteriorated structures.

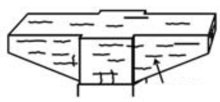
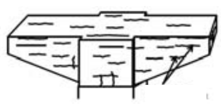
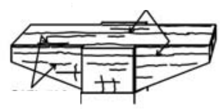
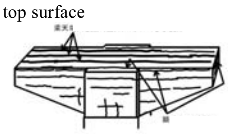
Bridges on the Hanshin Expressway are periodically inspected, and those found with cracks or a certain level of deterioration are examined to classify individual piers which meet either of the following conditions to ASR-affected piers [1]. The piers classified into that category are subclassified into four grades depending on the appearance as shown in Table 1. Beams of the piers with heavier appearance deterioration, graded III or IV, are considered to have reduction in mechanical properties (e.g. compressive strength and Young's modulus) of concrete or other elements. Since this will lead to reduction in stiffness or strength of the beams, remedial action needs to be taken, focusing on their flexural strengthening.

ASR-affected pier classification criteria:

1) Gel is present, and the total length of the cracks (0.3 mm or wider on reinforced concrete (RC) piers, or 0.2 mm or wider on prestressed concrete (PC) piers) in the beam is over 100 m.

2) Gel is present, and the expansion rate (total expansion rate) of the core sample is over 0.1%.

Table 1. Definitions of the appearance deterioration grades for ASR-affected piers and recommended maintenance action.

	I	II	III	IV
Appearance deterioration grades	 Cracks with a maximum width of less than 1 mm	 Cracks with a maximum width of not less than 1 mm partly found	A series of continuous cracks reaching both ends  Clear cracks with a maximum width of not less than 1 mm	Multiple cracks with a maximum width of not less than 3 mm in the top surface  Significant cracks
	Cracks with a maximum width of less than 1 mm occur.	Cracks with a maximum width of not less than 1 mm partly occur.	Clear cracks with a maximum width of not less than 1 mm occur in the top and side surfaces of the beam, and a series of continuous cracks extend to reach both ends of the beam.	Multiple cracks with a maximum width of not less than 3 mm occur in the top surface of the beam, and significant cracks occur in the convex top surface of the column and/or in the end surfaces of the beam.
Recommended action	Examine inspection plans.	Conduct ASR deterioration grade assessment and performance check.	Conduct ASR deterioration grade assessment and performance check.	Conduct ASR deterioration grade assessment (including reinforcement health assessment) and performance check.

Typical remedial methods for beams include steel plate bonding, FRP jacketing and the external cable system (Figure 1). Since the progress of expansion and cracks due to ASR will not stop after the strengthening, it is preferred to use any method to enable direct visual inspection afterward. With the ease of maintenance taken into account, flexural strengthening using the external cable system was adopted as a principle remedial method for PC beams in accordance with the Guidelines [2]. However, little practical information was available on the implementation of the technique, such as reduction in mechanical properties due to ASR deterioration, possibility of excessive prestress loss in existing internal cables due to the addition of external cables to an ASR-deteriorated structure, potentially adverse effects of ASR expansion on the stress state of the structure, and other complications caused by multiple factors.

The purpose of this study was to determine what effects the additional axial force from the external cable system would have on PC beams. A three-dimensional finite element (FE) pushover analysis was conducted using a PC beam specimen. Expansion and mechanical property reduction due to ASR deterioration were taken into account, to determine the effect of ASR deterioration on the stress occurring in the compressive fiber of a PC beam. The focus was also placed on the rate of increase in compressive fiber stress accompanying the use of the external cable system, simulating the effect of the external cables by applying the additional axial force to the PC beam specimen.

(a) Steel plate bonding (b) External cable system

Figure 1. Examples of strengthening of PC beams of ASR-affected piers.

2. ANALYSIS CONDITIONS AND CASES

2.1. Target structure

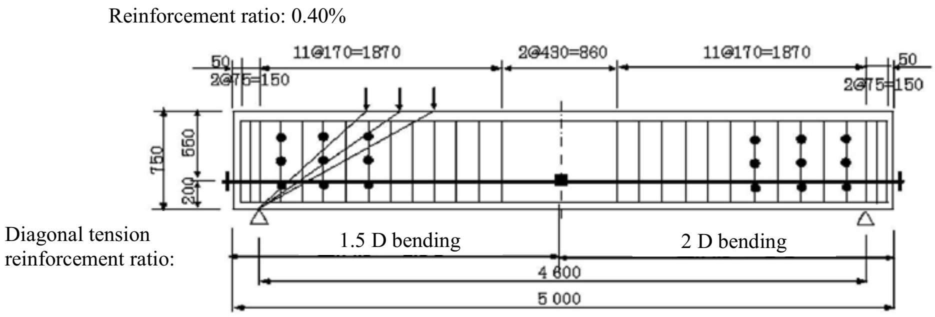
FE analysis was performed on a large size specimen, applying reduction in mechanical properties due to ASR deterioration to investigate the effect of ASR expansion, for the design of strengthening of ASR-deteriorated PC pier beams using the external cable system.

The target structure was a large size beam specimen (750×750×5000 mm) with tendons placed near the bottom which has been under a long term exposure test at Yawata Testing Laboratory of Osaka Institute of Technology [3].

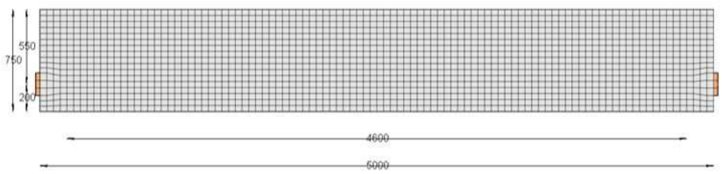
2.2. Analysis model

Figures 2 and 3 show the analysis model which has been generated by precisely modeling the specimen for the three-dimensional nonlinear analysis. Concrete was modeled with solid elements, allowing for assumption of cracks. The main reinforcement was modeled with embedded reinforcement elements, allowing for assumption of bond slip between the concrete and the reinforcement. The shear bars and tendons were also modeled with embedded reinforcement elements, with an assumption of full bond between the concrete and the reinforcement.

The analysis model was divided basically at intervals of 50 mm in the longitudinal direction, and a section was divided into 17 elements each in the height and width directions. The end parts were divided according to the shape of the anchor plates. There were 33,000 nodal points in total in the analysis model.

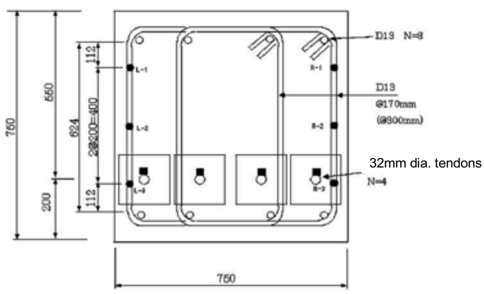


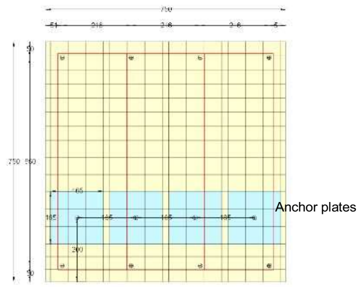
(a) Target structure



(b) Analysis model

Figure 2. The target structure and the analysis model (side view).





(a) Target structure (b) Analysis model

Figure 3. The target structure and the analysis model (sectional view).

2.3. Material models

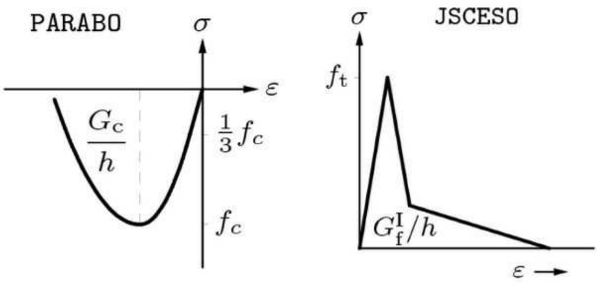
2.3.1. Concrete

Table 2 shows the values of mechanical properties of concrete used in the analysis. The stress-strain relationship was expressed by using a parabolic model for compression and, for tension, the one-fourth model presented by Japan Society of Civil Engineers (JSCE) in the Standard Specifications for Concrete Structures (2012) as shown in Figure 4, with expectation of mitigating mesh dependence by considering failure energy.

Cracks were represented by the smeared crack model combined with the orthogonal fixed crack model. A constant shear transfer model (β=0.2) was used for shear transfer after cracking, with compressive strength of concrete in the direction orthogonal to a crack reduced as specified in the JSCE Standard Specifications for Concrete Structures (2012). Considerations were also given to the increase in compressive strength under multi-directional restraint and the reduction in Poisson's ratio due to the cracks. The anisotropic behavior of concrete properties was not considered in this study.

Table 2. Mechanical properties of concrete in the analysis.

	Unit	Control	Deterioration	Remarks
Compressive strength	N/mm^2	47.1	33.0	Control: measured value on the specimen Deterioration: control × 70%
Young's modulus	N/mm^2	27,000	13,500	Control: measured value on the specimen Deterioration: control × 50%
Compressive failure E	N/mm	60.2	50.4	
Tensile strength	N/mm^2	3.0	2.4	
Tensile failure E	N/mm	0.098	0.087	



(a) Compression softening (b) Tension softening

Figure 4. Compression and tension softening curves of concrete.

2.3.2. Steel

Table 3 shows the mechanical properties of the steel materials in the analysis. The bilinear stress-strain relationship shown in Figure 5 was given to the reinforcement. The bond-slip relationship between the main reinforcement and the concrete was modeled so that the bond properties were defined as a function of the expansion rate of the concrete as shown in Figure 6. The main reinforcement was anchored at the ends.

Table 3. Mechanical properties of the steel materials in the analysis.

	Unit	Reinforcing bars	Tendons	Remarks
Young's modulus	N/mm^2	200,000	200,000	Reinforcing bars: measured values on the specimen Tendons: typical values
Poisson's ratio	--	0.3	0.3	
Yield stress	N/mm^2	338.4	930	
Cross sectional area	mm^2	126.7*4 =506.8	804.2*4 =3216.8	Four (4) 13 mm diameter reinforcing bars each at the top and bottom fibers Four (4) 32 mm diameter tendons

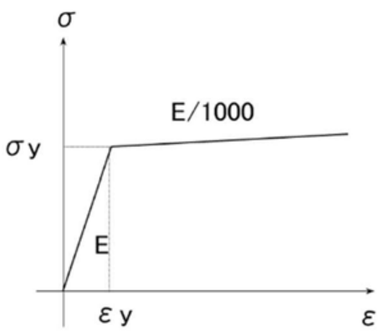


Figure 5. Stress-strain relationship of the reinforcement.

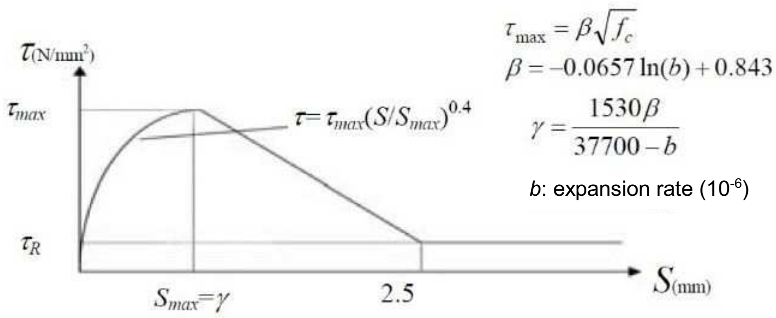


Figure 6. Relationship between the bond stress and the amount of slip.

2.3.3. Tendons

An elastic stress-strain relationship was given to the tendons, and full bond was assumed for the tensile force transfer in the tendons.

2.4. ASR expansion evaluation method

In the investigation of the effect of ASR expansion, the expansion was expressed with a pre-strain in steel. Tension in a tendon is considered to increase as the tendon is stretched by the strain from ASR expansion. The increment in tension can be regarded as a compressive force of the expansion. The method used here is to increase the tensile force to be applied to the tendon for that amount from the beginning.

The amount of expansion was set by referring to test results and analysis data in a previous study using large size specimens [4]. Hiroi made an FE analysis on the material test results of the control and ASR-deteriorated specimens for the approximation of expansion in the ASR-deteriorated specimens. For the present analysis the tensile force was increased by the amount equivalent to the pre-strain in steel used by Hiroi. Table 4 shows the values. Since the present study is focused on investigating the magnitude of the effect of ASR expansion on the internal stress, no validation is made on the amount of expansion used in the analysis.

Table 4. Material test results and analysis data of the stress in steel.

	Control (N/mm^2)	FE analysis (N/mm^2)	Increase ratio (FE analysis/control)
Previous test on large size specimens	631	744	1.18
Present study	684	807	1.18

2.5. Load and restraint conditions

The target structure was supported at two points, and concentrated load was applied to the midspan point.

Initial loading was made as follows: apply the dead load of the target structure; apply the tensile force to the tendons, with the amount equivalent to ASR expansion added for the ASR expansion cases; and, apply the tensile force to the external cables for the case retrofitted with external cables. The tensile force in the external cables was expressed by applying a distributed load to each end of the beam over the whole surface.

The concentrated load was then applied to the midspan point, incrementally increasing from the initial load state.

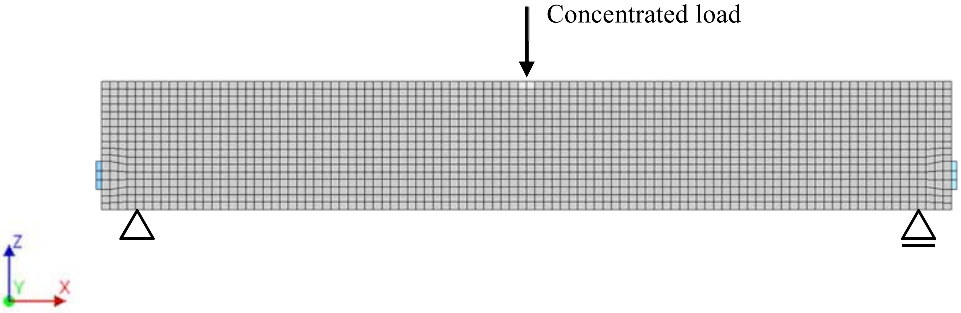


Figure 7. Load and restrain conditions.

2.6. Analysis cases

Table 5 shows the four cases investigated in the analysis. Case 1 is the control, and Cases 2 to 4 are the ASR deteriorated cases, with mechanical properties of concrete reduced to 70% in compressive strength and to 50% in Young's modulus. The pre-strain in steel is included in Cases 3 and 4 to consider expansion, and Case 4 is the case with the additional tensile force due to the external cables.

Table 5. Analysis cases.

		Case 1	Case 2	Case 3	Case 4
		Control	Deterioration	Deterioration and expansion	Deterioration, expansion and external cables
Method		FEM	FEM	FEM	FEM
Mechanical properties	σck (N/mm^2)	47.1 (100%)	33.0 (70%)	33.0 (70%)	33.0 (70%)
	Ec (N/mm^2)	27,000 (100%)	13,500 (50%)	13,500 (50%)	13,500 (50%)
ASR expansion		No	No	Yes	Yes
External cables		No	No	No	Yes

3. FE ANALYSIS RESULTS

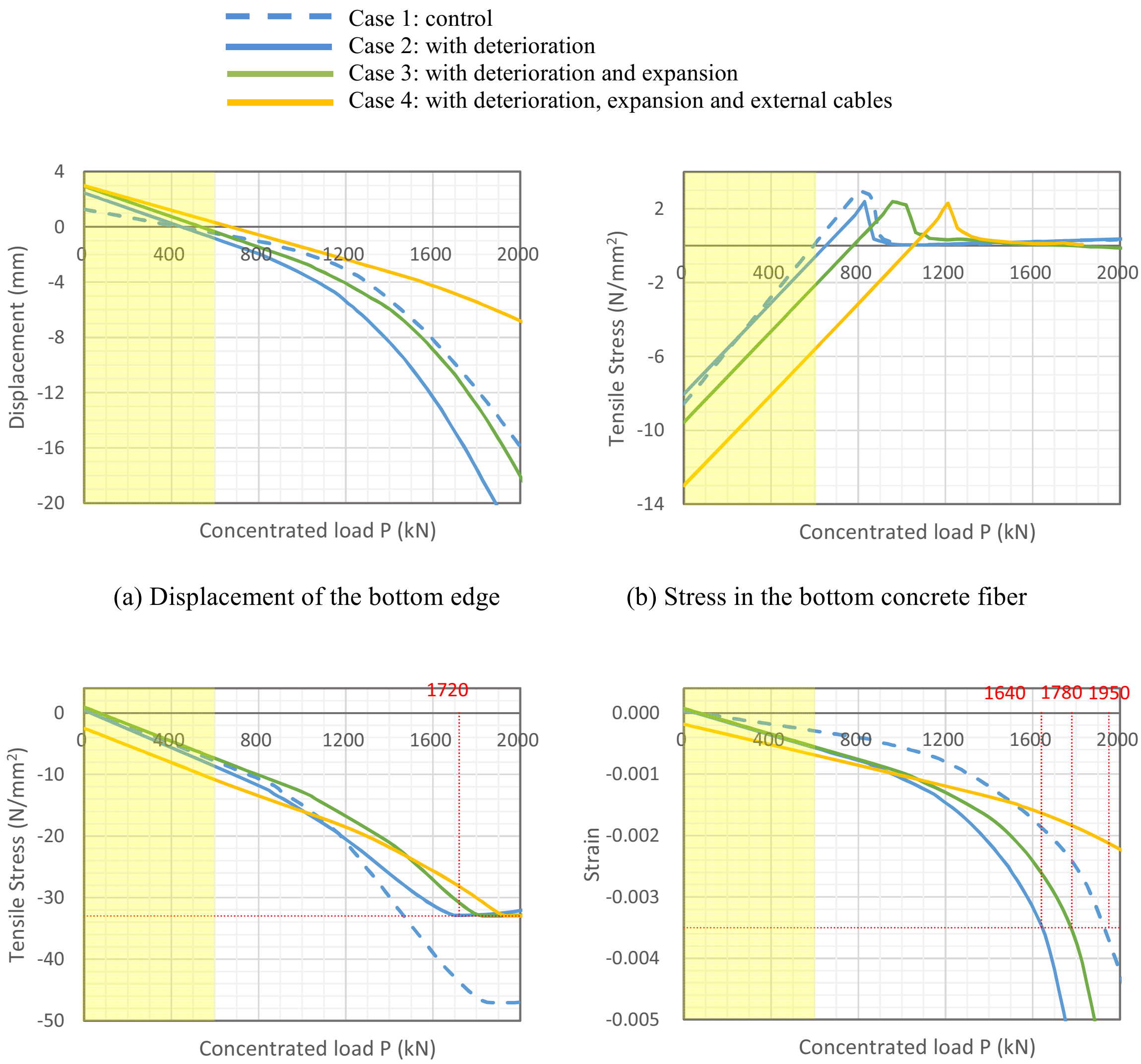
Figure 8 shows changes in various responses, making comparisons between the four cases. Figure 9 shows normal stress distributions in the longitudinal direction of the member obtained by the FE analysis. The yellow-colored zone in each diagram of Figure 9 is an elastic region where full section compression is reached, indicating a region of serviceability limit state of highway bridges.

3.1. Effect of ASR expansion

Cases 1 and 2 in Figure 8 showed very similar values in the elastic region in both extreme fiber stresses. Case 2 with the degraded mechanical properties showed a higher sensitivity in displacement and strain which were likely to be susceptible to the influence of compressive strength and Young's modulus.

As compared to Case 2, Case 3 showed "improvement" on the tension side in the bottom fiber stress and on the compression side in the top fiber stress. Similar results were found in the top fiber strain. Load P at an assumed ultimate strain of 0.0035 (in accordance with the Specifications for Highway Bridges [5]) was 1780 kN on Case 3, which was higher than 1640 kN on Case 2. This suggested that flexural strength would "improve" when expansion was taken into account under the current analysis conditions. The likely reason for this was that the pre-strain in steel included in the tensile force to express expansion contributed to the flexural strength, due to the eccentric layout of the tendons which were laid near the bottom fiber of the large size specimen in this analysis. Similar results will be obtained in actual structures if tendons are placed near the top fiber of a PC pier beam.

Consequently, it was confirmed that reduction in mechanical properties due to ASR deterioration would not have significant effect on the internal stress, and that compressive fiber stress in a PC beam would decrease under the current analysis conditions when expansion was taken into account.



(a) Displacement of the bottom edge (b) Stress in the bottom concrete fiber

(c) Stress in the top concrete fiber (d) Strain in the top concrete fiber

Figure 8. Response changes in the analysis under incremental loading.

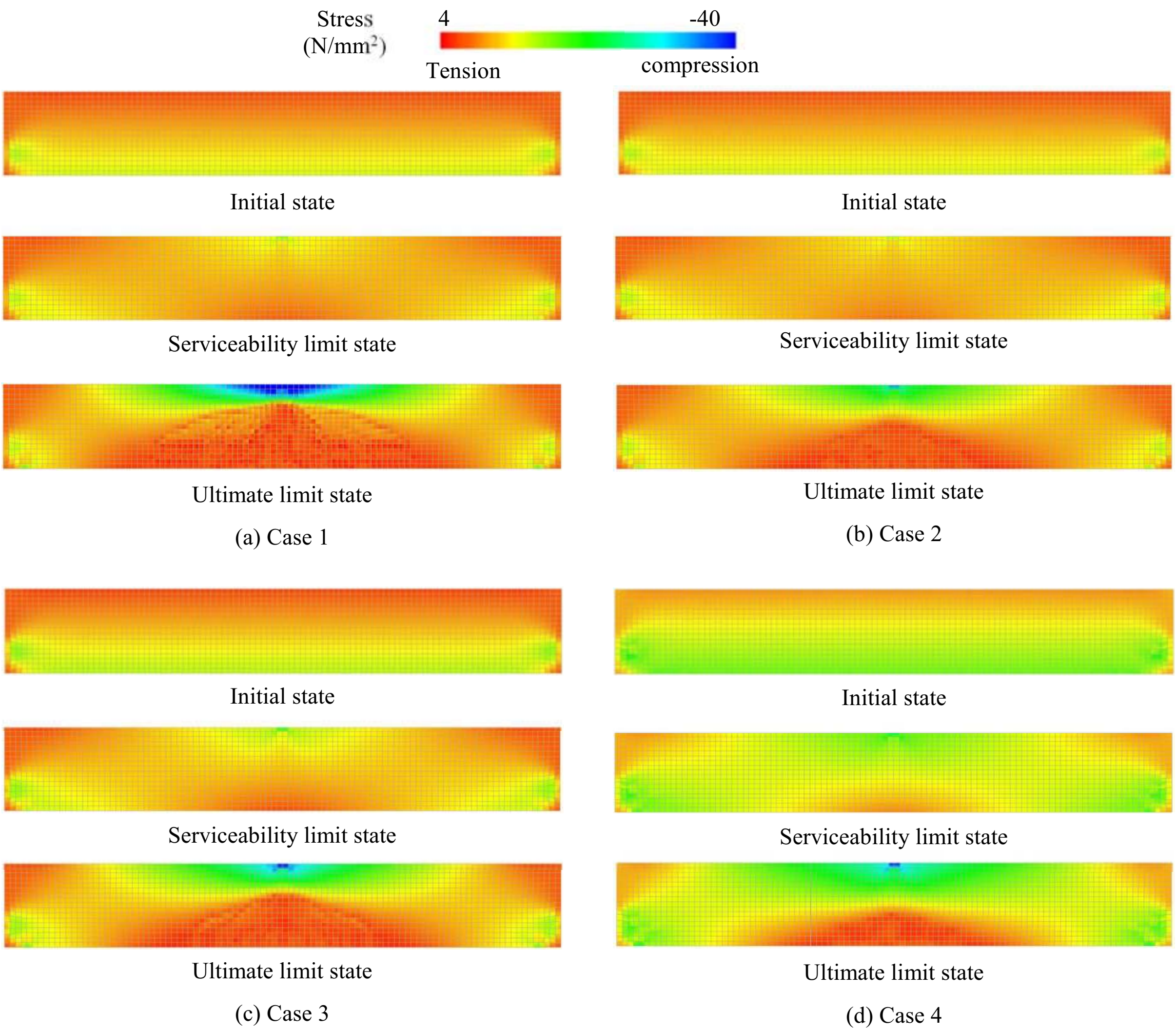


Figure 9. Comparison of contours of normal longitudinal stress.

3.2. Effect of the external cables

A comparison between Cases 3 and 4 in Figure 9 revealed that there was a shift in stress from tensile to compressive in extreme fibers in Case 4 retrofitted with the external cables, leading to the remarkably improved flexural strength shown in Figure 8. The external cables prevented yielding of the longitudinal reinforcing bars and tendons placed on the tension side, which reduced the compressive fiber strain. As a result, strain was about 0.0018 in Case 4 under P=1780 kN where the ultimate strain of 0.0035 was reached in Case 3.

Consequently, it was confirmed that, although the addition of the external cables would increase the stress in the compressive fiber, the compressive strain would still fall within the allowable range.

4. CONCLUSION

The purpose of this study was to investigate the effect of additional axial force on PC beams for the application of the external cable system. A three-dimensional finite element analysis was performed, using the parameters of presence/absence of reduction in mechanical properties due to ASR deterioration, presence/absence of ASR expansion, and presence/absence of the external cable system. The results showed that reduction in mechanical properties due to ASR deterioration would not have significant influence on the internal stress, and that the compressive fiber stress in a PC beam would decrease when expansion was taken into account under the present analysis conditions. It was also confirmed that, although the addition of the external cables would increase the stress in the compressive fiber, the compressive strain would still fall within the allowable range. Since quantification of ASR expansion is not easy, it should be also considered that a larger safety margin will be provided when evaluation is made without taking expansion into account.

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