学 位 論 文 要 旨

学位請求論文（Dissertation）

題名（Title）STRUCTURAL HEALTH ASSESSMENT FOR ASR-DETERIORATED PC GIRDERS USING STATIC AND DYNAMIC EXAMINATIONS

（和訳）静的および動的載荷試験による ASR 劣化した PC 桁に対する構造健全性評価に関する研究

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Abstract

In the present study, two new damage indicators—displacement assurance criterion (DAC) and displacement based index (DBI)—were proposed and applied in numerous scenarios to determine damage properties. Their performance in the numerical and experimental examinations showed that the indices were potentially useful for the kind of structures analyzed. Moreover, a threshold of DAC index for the sound structure was proposed. This study also presented preliminary considerations for estimating the long-term behaviors of structures affected by alkali-silica reaction (ASR) and attempted to proposed recommendations about measurement noise when using structural responses as input for structural damage detection. Three PC girders were conducted using similar mixtures and exposed to outdoor weather conditions outside the laboratory. This study investigated the combined effect of the changes in the environmental conditions and the ASR-induced deteriorations on the dynamic and static responses of the PC girders in one and a half years. The outcomes revealed that when the temperature and humidity increased, the frequencies and damping ratios decreased in proportion. No clear variation in the mode shapes could be recognized. The ambient temperature gradient strongly affected the changes in the vertical movement of the girders. These findings should be considered in structural damage detection because the environmental conditions might cause unexpected errors in the measured responses.

Chapter 1 General Background, Motivation, and Objectives

The development of a damage identification method performs a significant role in determining the health of a structure. Moreover, it is also essential to assess the relationship between structural performance and state of damage, to conduct maintenance. The responses of a structure, which are divided into the two main groups of static and dynamic responses, are of critical importance.

This study examined a numerical model of a prestressed concrete (PC) girder degraded by various damage scenarios. The outcome deflections at each stage of loading were obtained and used for evaluating two novel damage pointers—displacement assurance criterion (DAC) and displacement-based index (DBI). Numerical studies were further conducted by utilizing finite-element commercial software to verify the correlation of DAC with severities of deterioration and the sensitivity of DBI in stiffness loss localization.

In addition, the effectiveness of employing fly ash to suppress ASR acceleration in structures was discussed and analyzed through experiments and long-term monitoring approaches performed on three full-scale PC girders with similar mixtures. After the destructive bending tests, a significant number of concrete cores were collected to estimate the relationship between mechanical properties of concrete such as compressive strength, static elastic modulus, and ultrasonic wave propagation velocity. Based on the obtained results, this study clarified the mechanical properties of PC girder with and without fly ash affected by ASR deterioration.

The changes in the vibrational and static parameters of the three PC girders were periodically monitored with respect to variations in ambient temperature and humidity, as well as development in ASR-induced cracks in one and a half years. Its vibrational properties, namely frequencies, mode shapes, damping ratios, and temperature-induced displacements were measured together with the ambient temperature during each measurement. The data were then analyzed using linear regression models and were compared with predicted values obtained using finite element analyses and trend line (empirical-linear). This study presents preliminary considerations for estimating the long-term behavior of PC girders and recommendations about noise when using structural responses as input for structural damage detection.

Finally, the feasibility of the proposed DAC approach on practical cases was also evaluated and discussed. From the obtained results of the numerical and experimental approaches, this study aims to introduce a threshold of DAC index for healthy structure in further researches.

Chapter 2 Effects of Fly Ash on Mechanical Properties of PC Girder Using Reactive Andesite Aggregates

During the previous years, the degradation due to alkali-silica reaction (ASR) in concrete structures has become a global concern. It is now generally accepted that an appropriate use of fly ash can prevent expansion due to ASR in concrete. Since the Hokuriku region is currently able to provide a high-quality fly ash stably, the efficient use of fly ash helps improve the concrete durability and reduces the environmental burden as well as promote the regional industry due to the benefits of self-sufficiency. This chapter aims to investigate how the structural properties and load-bearing capacity of PC girders, which were affected by varying degrees of ASR-induced damages, change with and without fly ash. Three full-scale PC girders were conducted by the mixture of reactive aggregates and high strength Portland cement for the present study, as shown in **Fig. 1**. Notably, one of them (girder No.3) was mixed with an additional amount of fly ash (see **Table 1**). After one and a half years of the exposure, destructive bending tests were performed on two of the three girders to clarify the difference in flexural capacity. Besides, after the bending tests, a large number of concrete cores were taken from both girders to estimate the relationship between mechanical properties of concrete. Based on the obtained results, this study clarified mechanical properties of PC girder with and without fly ash affected by ASR deteriorations.

The main results obtained from this study are summarized as follows.

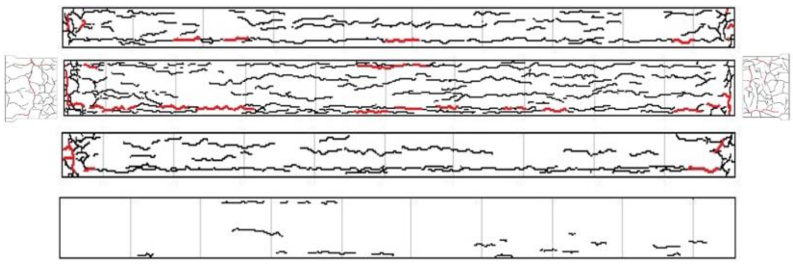
An addition of fly ash played a significant role in mitigating the cracks caused by the expansion due to ASR. On the side and top surfaces of girders No.1 and No.2, numerous cracks developed along the longitudinal direction, as shown in **Figs. 2(a) and 2(b)**. Alligator cracks were also observed at the girder end, where no prestress was introduced. Regarding girder No.3 (**Fig. 2(c)**), because the number of cracks was small, the expansion of concrete was effectively suppressed owing to the fly ash. An increase of convex curvature was observed in the girder without fly ash. The convex displacement increased up to ~13 mm before starting the load test with respect to girder No.2. Meanwhile, almost no change in convex curvature over time was observed in girder No.3 mixed with fly ash. Moreover, an additional amount of fly ash did not only increase the load bearing capacity by nearly 5% but also enhance the initial bending stiffness of the objective PC girder by 10% after more than one year under ASR deteriorations (see **Fig. 3**). The depth of ASR-induced cracks along the girder-axis direction varied from 5 to 20 mm on the side surfaces and the top surface. However, no crack was found out in the area surrounded by stirrups, and no breaking of tendons was confirmed.

Regarding girder No.2, andesite particles from sand and gravel reacted strongly, and many fine cracks occurred from broken pieces of aggregates to cement paste. However, because of the slight reaction of andesite particles, no trace of ASR was observed on girder No.3. When the concrete cores of girder No.2 were soaking in 1N NaOH solution, unreacted andesite particles accelerated ASR leading to high expansion rate. Meanwhile, regarding girder No.3, the expansion rate was significantly low as compared to that of girder No.2. Proportional correlations between the compressive strength, the static elastic modulus and the ultrasonic propagation velocity of the core were found.

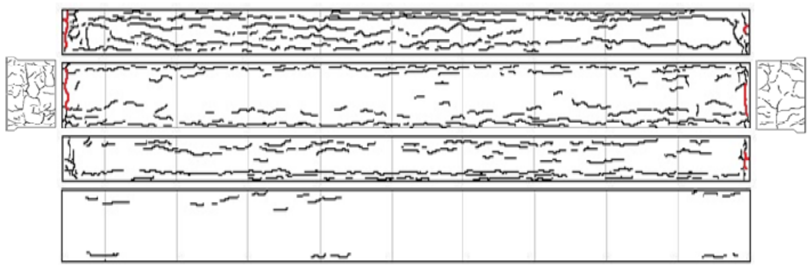
Figure 1 Exposure condition of the PC girders at Kakuma campus

Table 1 Mixture properties.

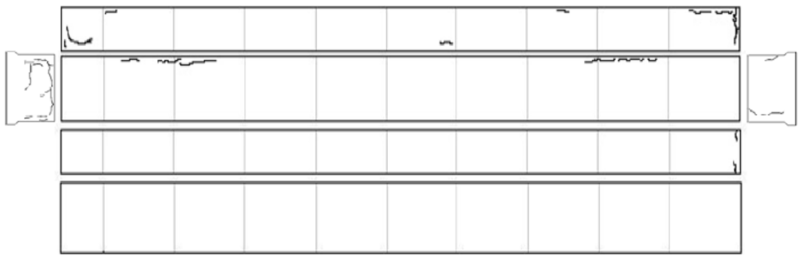
Girder	Water-binder ratio W/B (%)	Fine aggregate percentage s/a (%)	Unit (Kg/m^3)					
			Water W	Binder B		Sand S	Gravel G	NaCl
				Cement C	Fly ash FA			
No.1	38.7	46.3	150	388	-	822	955	18.87
No.2	38.7	46.3	150	388	-	822	955	25.5
No.3	34.8	44.6	150	366	65	770	955	25.5



(a) Girder No.1



(b) Girder No.2



(c) Girder No.3

Figure 2 Crack patterns of the three girders (From top to down: north side surface, top surface and both surfaces near both ends, south side surface and bottom surface).

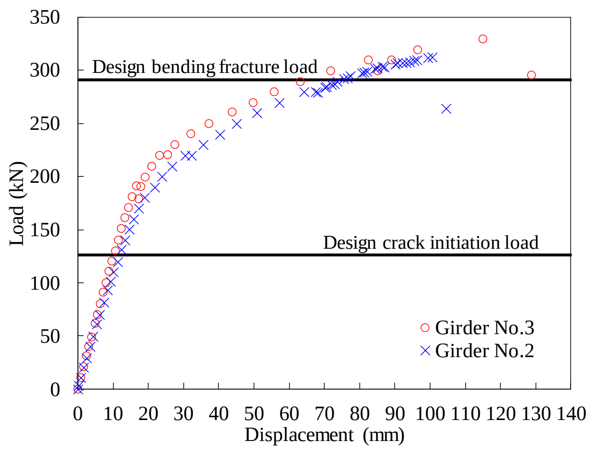


Figure 3 Load-displacement relationship at midspan.

Chapter 3 Nondestructive Damage Detection in Deteriorated Girders Using Changes in Nodal Displacement

New damage indicators, DAC (**Eq. 1**) and DBI (**Eq.2**), based on changes in the displacement of observation points, have been proposed. A numerical model of a prestressed concrete (PC) girder degraded by various damage scenarios was examined to reveal the relationship between deterioration state and static responses. The outcome of numerical studies showed that, although its variation was relatively small, the DAC value decreased when the applied load increased and cracks occurred in the structure (**Fig. 4**). Therefore, there was a correlation between changes in DAC and damage state, and the decrease in DAC could indicate the occurrence of damage in structures. Moreover, the number of measurements did not play a significant role in the change in DAC when there were more than seven observation points. Consequently, when considering the effectiveness and the economy of using the DAC coefficient to identify the occurrence of structural damage, the seven-point measuring system could provide relatively reasonable judgments. Another damage indicator, DBI was proposed as a suitable factor to identify damage locations, as the results of the numerical study reveal that all damages, with different characteristics and for two different static structures, could be accurately located. As another outcome worth mentioning, DBI showed a good performance for damage localization in all load cases utilized in this study. For example, **Figures 5(a) and 5(b)** represent a damage scenario of a two-span continuous girder and its corresponding DBI detection graph, respectively. However, it is also important to note that limitations on measured static data played a significant role in the accuracy of DBI, and a sufficient number of points provided more accurate results than a rough measurement case. Moreover, the most critical factors for determining damage location were the selection of observed points at or near the damage locations, and the accuracy of measurements. For preventing uncertainty in the results, it was suggested that the number of measures should be as fine as possible. The DBI method was effective for damage detection only when the measurement noise was less than 0.1%. Therefore, the nodal displacement should be measured with high accuracy when using DBI for identifying structural deterioration.

The present results are obtained purely from the numerical analyses, this work is a start point for a simple damage identification based on only displacement curve evaluation, and further research is needed on the subject. Regarding long-term prospects, further research should be carried out to apply DAC and DBI in actual situations, and future projects can target improvements in relation to dynamic strain and displacement influence lines.

$$DAC = \frac{\left(\sum_{j=1}^{n+1} \psi_{Fj}\psi_{Hj}\right)^2}{\sum_{j=1}^{n+1} {\psi_{Fj}}^2 \sum_{j=1}^{n+1} {\psi_{Hj}}^2} \tag{1}$$

where ψ_{Fj} $(j=1\sim n+1)$ is the normalized displacement of the j^{th} point caused by the external applied static load at a reference state. ψ_{Hj} (*j=1~n+1*) is the normalized displacement of the j^{th} point caused by the external applied static load at a different state of the structure, and n indicates the number of observation points.

$$DBI_j = max\left[0, \frac{\Delta u_j - mean(\Delta u_j)}{std(\Delta u_j)}\right] \quad (2)$$

where u_{dj} (*j=1~n+1*) and u_{ij} (*j=1~n+1*) stand for nodal displacements in the deteriorated and the normal girders, respectively. In addition, $mean(\Delta u_j)$ and $std(\Delta u_j)$ illustrate the mean and the standard deviation of Δu_j, in that order.

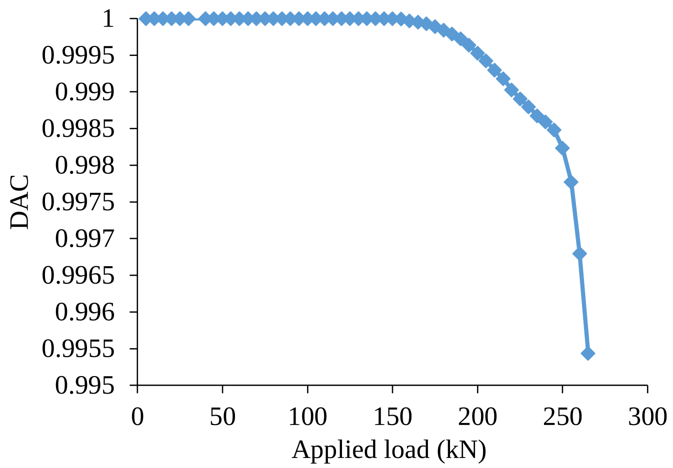
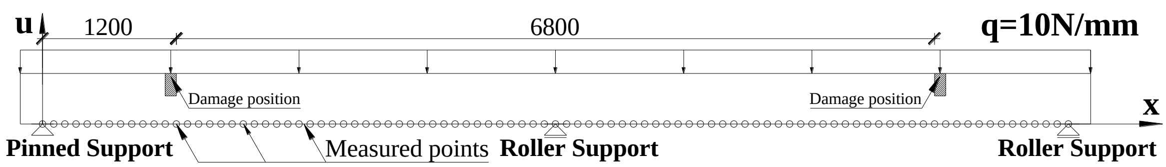
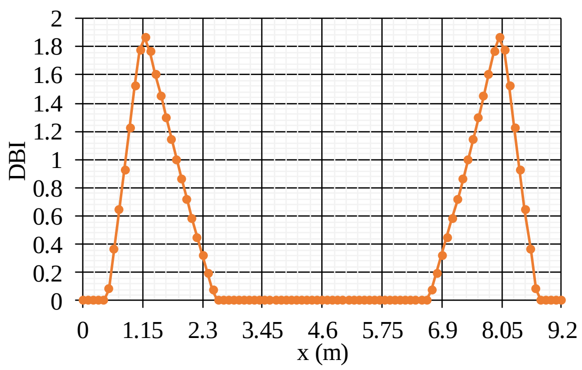


Figure 4 Decrease of DAC with the increasing of applied load



(a) Damage Scenario 5



(b) Damage localization chart of Scenario 5

Figure 5 A damage scenario for the two-span continuous girder (unit: mm).

Chapter 4 Long-term Vibration Monitoring of the Effects of Temperature and Humidity on PC Girders with and without Fly Ash considering ASR Deterioration

Studying the environmental effects on the structural properties is essential to apply the monitoring methods to civil engineering structures effectively. Among the different laboratory approaches employed for evaluating the changes in the vibration properties concerning the environmental conditions, simultaneous effects of structural degradation over the monitoring period on the observation data has not been explicitly reported. This study investigated the impact of environmental conditions on the vibrational properties of prestressed concrete (PC) girders, which were affected by varying degrees of deteriorations induced by an alkali-silica reaction (ASR), as introduced in Chapter 2. Because the environmental conditions produce complicated uncertainties in the structural responses, this study only examined the variations in the frequencies, mode shapes, and damping with respect to the changes in the temperature and humidity. To obtain free damped vibrations of the three PC girders, 14 accelerometers were placed on the girder with a constant interval of 1.15 m, as shown in **Fig. 6**. During each test, the impact excitations were applied alternately via a person jumping vertically from a chair (see **Fig. 7**) at four locations depicted as "x" in **Fig. 6**. The vibration parameters of the PC girders were extracted from the measured data using the eigensystem realization algorithm. Moreover, the ambient temperature and humidity were recorded simultaneously during the test using a thermometer. To track the variation in the vibrational parameters due to the environmental effects and ASR, eight tests were performed from May 2015 to September 2016 with 192 valid sets of vibration data.

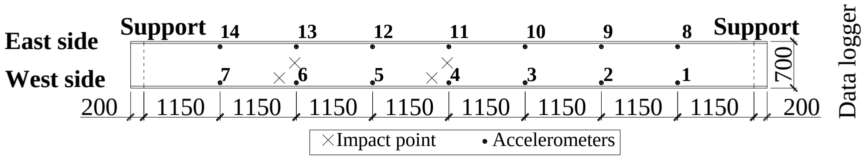
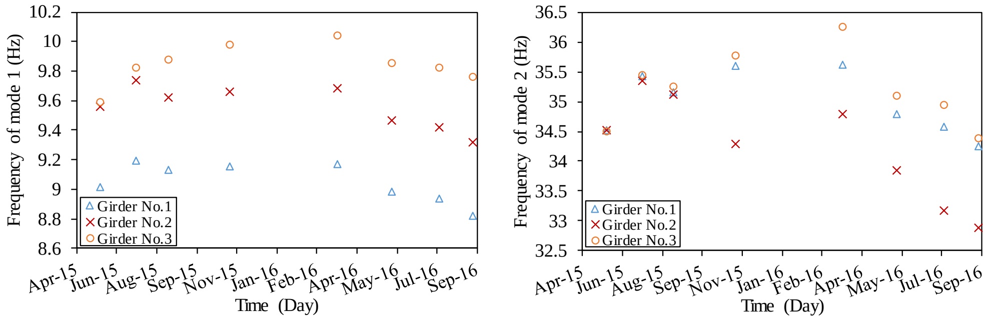


Figure 6 Sensor layout on the PC girder.

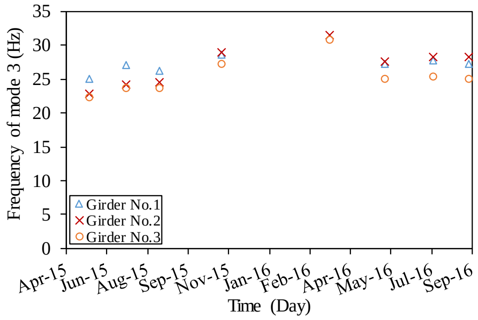
Figure 7 Impact test and sensor layout on the PC girder.

The main conclusions drawn from this study are as follows.

As the results of linear regression models, the temperature and humidity increased in proportion with the decreases in the frequency and damping ratio, whereas no apparent correlation of the mode shapes with the changes in the temperature and humidity could be observed. The error analysis showed that the bending modes could be estimated more accurately than the torsional mode because the error ratio of the torsional mode was higher than that of the bending modes. Besides, different dynamic behaviors were well observed in the three PC girders over the monitoring period, as shown in **Fig. 8**. Along with fewer ASR-induced cracks, the girder with fly ash exhibited higher vibration frequencies and lower damping ratios compared to the girders without the fly ash. Thus, the fly ash significantly affected the vibration properties of the PC girders subjected to the ASR-induced deteriorations. Another objective of this study included performing validation tests of the numerical analyses against the results of the measurement by assuming Young's modulus of concrete as a function of the temperature. The results showed that the validation model provided reasonable illustrations for the changes in the natural frequency of the vibration modes due to the changes in the ambient temperature (see **Fig. 9**). During the monitoring period, the bending modal frequencies of girder No.3 fluctuated in the range of ~3–5%, which is considerable compared to those due to structural damage. Hence, the effects of the environmental conditions should be examined thoroughly when using the variation in the vibrational frequency to assess the health of structures.

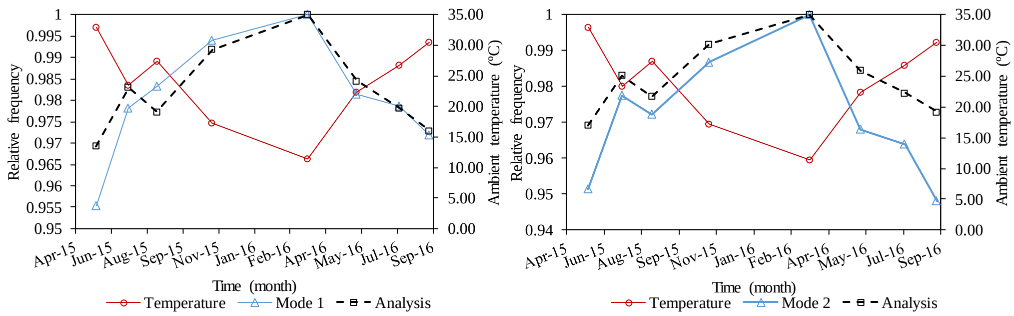


(a) The 1st bending mode (b) The 2nd bending mode



(c) The 1st torsional mode

Figure 8 Difference in natural frequencies of three girders.



(a) The 1st bending mode (mode 1) (b) The 2nd bending mode (mode 2)

Figure 9 Variations in two bending modal frequencies of girder No.3 over one and a half year.

Chapter 5 Long-Term Monitoring of the Variation in Temperature-Induced Camber of PC Girders with and without Fly Ash Considering ASR Deterioration

This chapter presents the long-term camber behavior at midspan of full-scale PC girder affected by ASR considering fluctuations due to change in the ambient temperature gradient. The present study reports the camber behaviors of girders No.1 and No.3. **Figure 10** shows a graphic of the laboratory set-up used to investigate this upward movement. To obtain the temperature-induced displacements, seven displacement meters were mounted at different points under the girder with a constant interval of 1.15 m, as shown in **Fig. 11**. Moreover, the ambient temperature was recorded simultaneously during the test using a thermometer. To track the variation in camber owing to diurnal temperature, the signal was collected once automatically from the sensor every 30 minutes, 24 hours for an observation day. Seven measurements were performed from October 2015 to September 2016 in Kakuma campus with 14762 valid sets of data. The obtained data were then analyzed using linear regression models concerning the variations in measured ambient temperature. Moreover, the measured cambers were compared to predicted values obtained using finite element analysis procedures and trend line (empirical-linear). The finite element method was employed for conducting the analysis utilizing the computer code DIANA. This study presents preliminary considerations for estimating the long-term displacement behavior of PC girders and attempts to proposed recommendations about measurement noise when using static responses as input for structural damage detection.

Figure 10 Experiment layout

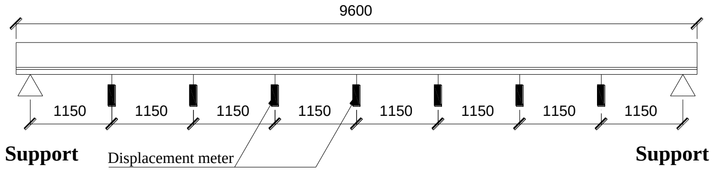


Figure 11 Measured point layout under the PC girder (Unit: mm)

The main conclusions drawn from this study are as follows.

The ambient temperature not only varied from season to season but also throughout any given day. All values measured from displacement meters had positive correlations with temperature. As the result of the linear regression model, the ambient temperature gradient strongly affected the changes in the cambers of the girders because the correlation coefficients between the variables were high, as computed using the linear model (**Fig. 12**). The measured camber of girder No.1 increased by ~0.21 mm – ~0.41 mm when ambient temperature increased by one degree, this variation of girder No.3 was observed as ~0.23 mm – ~0.5 mm. Approximately ~81% – ~93% of measured displacement could be accounted for by measured temperature. This conclusion should be considered in structural damage detection using only changes in displacement data in practice because the environmental conditions might cause unexpected errors in measured responses in the measurement field. In this study, cambers in PC girders were accurately modeled and predicted in finite element simulations, as shown **Fig. 13**.

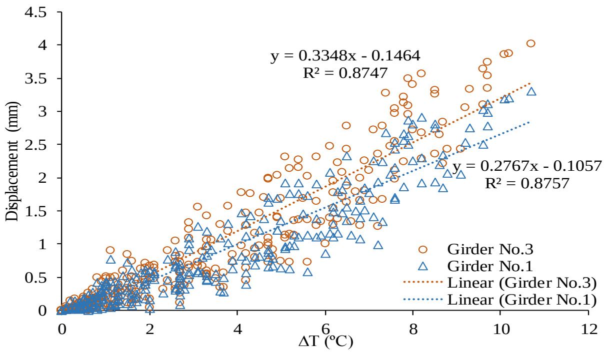


Figure 12 Linear relation between the camper and the ambient temperature in Sep 2016

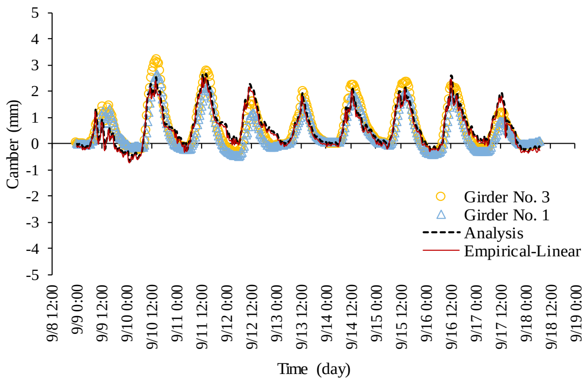


Figure 13 Comparison of measured and computed camber.

Chapter 6 Application of Damage Detection Method Using Displacement Data for Deteriorated Girder

Efforts have been performed to utilize Displacement Assurance Criterion (DAC) proposed in Chapter 3 on practical cases. Destructive tests on the PC girders were carried out to evaluate the feasibility of DAC approach on damage detection by analyzing the displacement curves obtained from the experiments. During the destructive test presented in Chapter 2, the vertical displacement was measured at seven pointed on the lower extreme fiber for calculating the deflection curve at each loading step. Then, the obtained curves were analyzed to estimate the variation in the DAC value. Besides, nonlinear finite-element models of the PC girders were produced to verify the relation between the variations in DAC with respect to structural degradation owing to applied loads in practice. From the obtained results of the numerical and experimental approaches, this study aims to propose a threshold of DAC index for the sound structure.

The main conclusions drawn from this chapter are as follows.

The decreases in the analytical results of DAC of girders No.2 and No.3 in **Fig. 14** agreed well with the results of loading test. DAC values of girder No.3 were higher than those of girder No.2, and the deviations increased significantly with the increased loading. These results demonstrated that there was a relation between damage severity and changes in nodal displacement, represented as the DAC index. In addition, the employed approach for numerical calculation could reproduce the loading tests on the PC girder affected by ASR and provide reasonable results. From now on, by employing the DAC value obtained by the loading test as the threshold value (such as 0.9985), there is a possibility that the proposed method that can express change of displacement shape due to change of rigidity as one numerical value and find abnormal value. In the future, further studies about DAC need to be implemented in practice in order to produce the most accurate threshold value for DAC index.

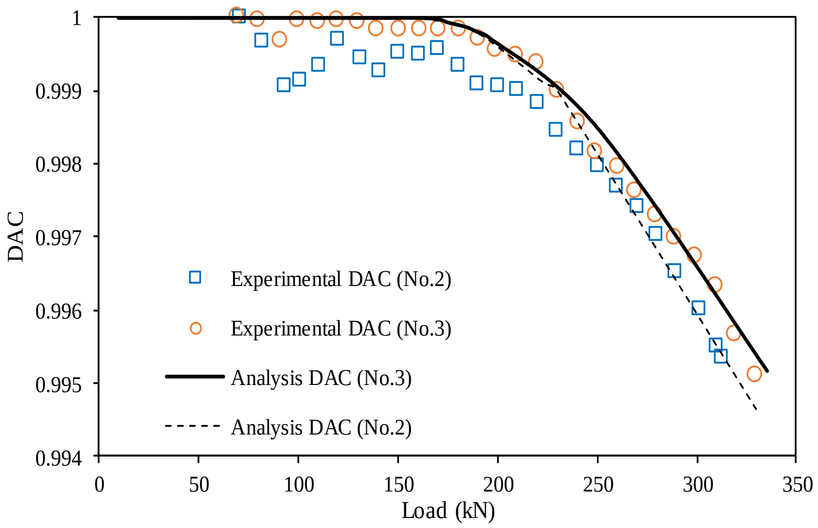


Figure 14 Variation in DAC with respect to the increased loading

Chapter 7 Conclusion

With the aim of contributing to efficient structural health monitoring approaches, the present study attempts to develop an evaluation approach that employs only displacement data for recognizing structural damage. Two new damage indicators—displacement assurance criterion (DAC) and displacement based index (DBI)—were introduced and employed in numerous scenarios to determine damage properties. Parametric studies performed by a finite-element analysis showed that DAC could properly indicate the occurrence of degradation in structures and DBI could be utilized as a suitable pointer for damage localization. Regarding actual examinations, destructive loading tests were conducted on full-scale PC girders. From the obtained results of the numerical and experimental methods, this study proposed a threshold of DAC index for the sound structure. For long-term prospects, further studies about DAC need to be implemented in practical cases in order to obtain the suitable DAC threshold value for each kind of structure.

Besides, structural responses have been used as inputs in the evaluation procedures of civil structures for many years. With regards to lab-scale efforts, the combined effect of the changes in the environmental conditions and the ASR-induced deteriorations on the dynamic and static responses of the three PC girders was considered. It was found that when the temperature and humidity increased, the frequencies and damping ratios decreased in proportion. However, no apparent variation in the mode shapes could be identified. Besides, the ambient temperature gradient strongly affected the changes in the vertical movement of the girders. All values measured from displacement meters had positive correlations with the ambient temperature. In other words, the amplitude of the camber increased with respect to the growth in the ambient temperature. These outcomes should be considered in structural damage detection using changes in structural responses in practice because the environmental conditions might cause unexpected errors in measured responses in the measurement field.

From results of the long-term exposure and the tests on the PC girders, the flexural strength and the rigidity of the specimen with fly ash were not degraded while ASR was also suppressed efficiently. Moreover, because the dynamic and static behaviors of the three girders were observed to be different during the monitoring period, the fly ash significantly affected the performances of the PC girders under the ASR damage.

When assessing the load-carrying capacity and mechanical properties of PC girder under ASR deterioration, it is necessary to make appropriate corrections according to the confinement degree due to prestressing instead of using measured values of the concrete core as they are.

This study is a start point for two simple damage identification based on only displacement curve evaluation, and further research is needed on the subject. Regarding long-term prospects, further research should be carried out to enhance the accuracy of DAC and DBI in actual situations, and future projects can target improvements in relation to dynamic strain and displacement influence lines.

平成30年　1月31日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

STRUCTURAL HEALTH ASSESSMENT FOR ASR-DETERIORATED PC GIRDERS USING STATIC AND DYNAMIC EXAMINATIONS

静的および動的載荷試験によるASR劣化したPC桁に対する構造健全性評価に関する研究

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3．審査結果の要旨（600～650字）

本学位申請論文に対して，審査員全員による口頭試問を行うとともに，論文の内容について精査した．また，平成30年1月31日に開催した口頭発表および同日に開催した審査委員会において協議した結果，次のとおり判定した．本学位申請論文は，北陸地方で特に問題となっているASRや塩害などの早期劣化を生じた橋梁の維持管理における問題を背景として，反応性骨材を使用してASR劣化を生じさせたPC桁を作製し，フライアッシュ混和有無のPC桁を対象とした曲げ破壊試験を行い，破壊に伴う挙動を比較することで，フライアッシュ混和による材料学的および力学的な効果を明らかにした．また，暴露期間中において，非破壊による動的な衝撃試験を行い，振動特性（振動数，振動モード）の変化を調べることで，ASR劣化過程におけるフライアッシュ混和による健全度の違いについて明らかにした．このように本学位申請論文のフライアッシュ混和に伴う構造物の健全度評価に関する研究成果は，今後の維持管理における点検，診断，評価において，有用な知見を明らかにした．また，早期劣化対策として注目されているフライアッシュコンクリートの普及に貢献した論文といえる．さらに，本学位申請者（HA MINH TUAN氏）は，国際会議4編の発表に加えて，国際ジャーナルに3編（うち2編はSCIE論文），国内査読付き論文に2編掲載された．以上を勘案して，博士（工学）に値するものと判定した．

4．審査結果　(1) 判　　定（いずれかに○印）　（合　格）・　不合格

(2) 授与学位　博　士（工学）