

Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte
Band: 81 (1999)

Artikel: Safety evaluation system of damaged structures and performance based design
Autor: Hosoda, Akira / Ishida, Tetsuya / Tsuchiya, Satoshi
DOI: <https://doi.org/10.5169/seals-61440>

Nutzungsbedingungen

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. [Mehr erfahren](#)

Conditions d'utilisation

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. [En savoir plus](#)

Terms of use

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. [Find out more](#)

Download PDF: 01.04.2026

ETH-Bibliothek Zürich, E-Periodica, <https://www.e-periodica.ch>



Safety Evaluation System of Damaged Structures and Performance Based Design

Akira HOSODA
Graduate Student
The University of Tokyo
Tokyo, JAPAN

Tetsuya ISHIDA
Graduate Student
The University of Tokyo
Tokyo, JAPAN

Satoshi TSUCHIYA
Graduate Student
The University of Tokyo
Tokyo, JAPAN

Summary

In the performance based design, it will be required to evaluate structural behaviors considering the deterioration of materials. We conducted an experiment to observe the effects of initial defects mainly due to environmental action upon structural behaviors. In our experiment, it was concluded that the main reason that affected the failure mode and ductility of RC beams was internal stress due to drying shrinkage. And then we proposed our future direction of establishing an analytical method to evaluate structural behaviors with material deterioration in time and space taken into account.

1. Introduction

The design systems of reinforced concrete structures are shifting to performance based design systems, which seems to be an international current. In the new systems, highly developed analytical methods are indispensable in order to check in a direct way whether the performances of structures surely satisfy required performances. Therefore, intensive researches have been done to develop analytical tools that can evaluate the structural performances of RC structures accurately. Conventionally, RC structures have been analyzed under realistic conditions that they are cured perfectly or material properties of them will never change. But it is apparent that in actual cases material properties of RC structures will change while they are in service just after construction, and that the performances of them will also change with time. Therefore, both structural and durability performances should be evaluated in an integrated way considering the changes of material properties in order to evaluate the lifetime performances of structures from birth to death. With this kind of tool, the performances of existing structures can be evaluated which seem to deteriorate compared to those of structures just after construction.

In this study, we discuss the necessity of evaluating the performances of structures with the deterioration of materials taken into account, and we suggest a future direction of establishing an evaluation tool for structures damaged mainly due to environmental action.

2. Damages of Structures due to Environmental Action

Real structures are destined to have internal stress introduced due to hydration heat, drying shrinkage, and autogenous shrinkage, and cracks might happen when the stress exceeds the

tensile strength of concrete. These initial defects in concrete cause the large deterioration of resistance to mass transport, and substances harmful to reinforcing bars penetrate easily toward them through cracks, then under severe environment conditions reinforcing bars might be corroded. Therefore, initial defects have been considered to be one of the factors promoting corrosion of reinforcing bars or harmful to serviceability and appearance of structures.

But, it has not been discussed so much that initial defects might affect structural performance directly. As the shear capacity of concrete structures is affected so much by axial stress due to external force, it is likely enough that the capacity and the deformation of structure members are affected by internal stress. And it also seems possible that concrete cracks and internal stress distributed in structures may affect crack propagation when external force is applied. Therefore, in this study we concentrate on discussing the effects of initial defects mainly due to environmental action at early ages upon the structural behaviors, particularly, shear capacity and ductility of RC structures. Not so many experiments have been done in terms of structural behaviors considering initial defects, so we conducted fundamental experiments mentioned in the next chapter.

3. Experimental Study

3.1 Purpose

As mentioned above, the purpose of this experiment is to observe shear capacity and ductility under the presence of initial defects due to environmental action. The experiment was planned under a supposition that two RC beams made of the same material and cured in different conditions might fail in different modes. Because, compared to flexure capacity which depends on rather reinforcement than concrete properties, shear capacity seems to change so much due to the effect of initial defects upon crack propagation. Then, RC beams with no stirrups were provided and all of them were designed so that the flexure capacity was smaller than the shear capacity. And we observed the effect of internal stress and cracks generated by changing curing conditions. And, we used not only normal concrete but expansive concrete for the specimens in order to observe the effects of expansive agents. Furthermore, mechanically damaged specimens were provided in order to compare mechanical damage with initial defects. Therefore, the experiment consisted of 2 series. Series A for the specimens of different kinds of curing conditions, and Series B for the specimens damaged mechanically. The experiment was conducted in Asian Institute of Technology, Bangkok, Thailand.

3.2 Specimens

The dimensions of all the specimens are shown in the Fig.1. For Series A, 3 types of curing conditions were provided. One was water curing from 4 days after casting until just before testing, and another was water curing only for 7 days from 4 days after casting, and the other was being put in experiment room from 1 day after casting. Two kinds of concrete were used, that is, normal concrete and expansive concrete. Two specimens were provided for each material and each curing condition. Mix proportions of the specimens are shown in Table.1.

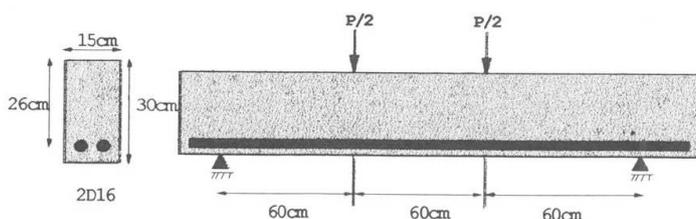


Fig.1 Geometry of the beams and Loading System



Table.1 Mix proportion

	Water [kg/m ³]	Cement [kg/m ³]	Expansive Agent [kg/m ³]	Fine Aggregate [kg/m ³]	Coarse Aggregate [kg/m ³]	Superplasticizer [% by weight of cement]
Normal Concrete	176	375	0	805	948	0.25(%)
Expansive Concrete	176	337.5	37.5	805	948	0.275(%)

3.3 Loading System

Before testing, the compressive strength and the yielding stress of reinforcing bars were measured. Then the flexure capacity was calculated by JSCE code [1] formulation and the shear capacity was also calculated according to Okamura-Higai equation [2] shown as eq (1),

$$f_v = f_{v0} \left(0.75 + \frac{1.4}{a/d} \right) (1 + \beta_p + \beta_d) \quad (1)$$

$$f_{v0} = 0.94(f_c')^{1/3}$$

$$\beta_p = \sqrt{100p} - 1$$

$$p = A_s / (bd)$$

$$\beta_d = \sqrt[4]{1/d} - 1$$

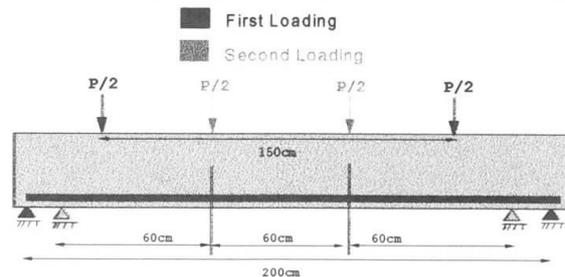


Fig.2 Loading System for Series B

where, f_v : shear stress when diagonal shear crack happens [kgf/cm²], f_c' : compressive strength [kgf/cm²], a : shear span [m], d : effective depth [m], b : width [m], A_s : total area of reinforcing bars [m²].

According to the calculated results of flexure and shear capacity, the loading system was decided as shown in Fig.1.

The loading system applied for Series B was shown in the Fig.2. Bending cracks were supposed to be introduced in the first loading with wide loading span, and after unloading, the beams were subjected to the same loading system as the one in Fig.1.

3.4 Summary of the results

The summary of the results of Series A is given in Table.2. Shear and Flexure capacity calculated with measured compressive strength and yielding stress of reinforcing bar are also given in Table.2. Unfortunately, some of the cylinder specimens for compression test were not tested properly, so the measured values of them were excluded here.

Table.2 Experimental Results (Series A)

	Age at testing	f_c' (kgf/cm ²)	Shear Span (cm)	Curing (days)	Ultimate Load (tf)	Yielding Load (tf)	Failure Mode	Shear Capacity (tf)	Flexure Capacity (tf)
1NC 7+ 1.	27	453	60	23	10.61	9.7	flexure	10.77	9.75
1NC 7+ 2	29		60	25	10.58	9.8	flexure		
1NC 7 1	27		60	7	10.15	9.57	shear		
1NC 7 2	28		60	7	10.87	10.41	shear after yielding		
1NC 0 1	26	411	75	0	8.03	7.38	flexure	9.81	7.77
1NC 0 2	28		60	0	9.51		shear		
1NCEA 7+ 1	27	509	60	23	10.84	9.9	flexure	11.2	9.8
1NCEA 7+ 2									
1NCEA 7 1	27	375	60	7	10.41		shear (strange)	10.11	9.67
1NCEA 7 2	27	464	60	7	11.15	9.81	flexure	10.86	9.76
1NCEA 0 1	26	301	60	0	10.95	10.03	shear after yielding	9.4	9.55
1NCEA 0 2	28	374	60	0	10.24	9.78	shear after yielding	10.1	9.67

The specimens were named according to the following rules. The first *I* means Series A. *NC* means normal concrete. *NCEA* means expansive concrete. *7+* means all-time water curing. *7* means water curing for seven days. *0* means no water curing. *1* or *2* at the last mean the identification of specimens in the same condition.

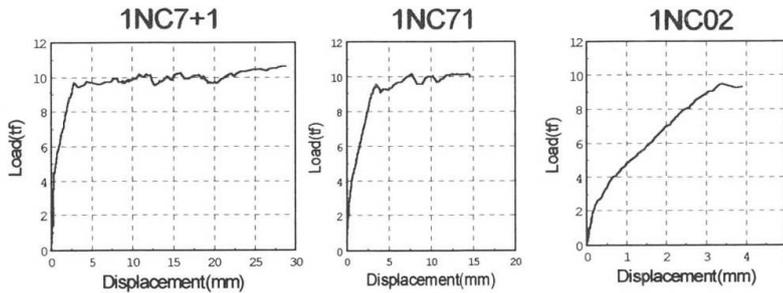


Fig.3 Load-Displacement Relationship at the center of the span (Normal Concrete)

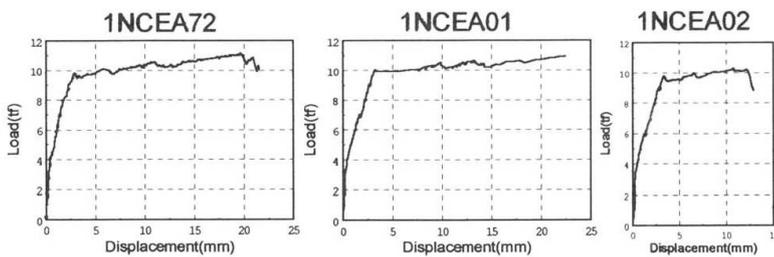


Fig.4 Load-Displacement Relationship at the center of the span (Expansive Concrete)

did not show so much difference. And we should pay attention to the results of expansive concrete. When we replaced 10% of cement with expansive agents, ductility of all beams were improved so much as shown in Fig.4 though the compressive strength was almost the same as that of normal concrete.

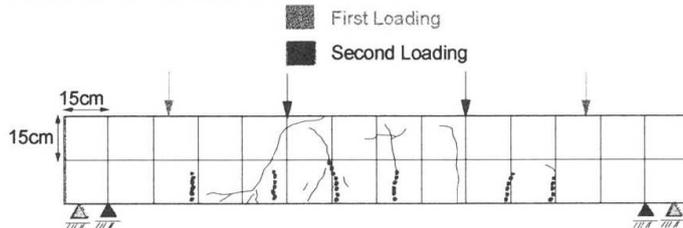


Fig.5 Crack Pattern of Series B (Normal Concrete, Water Curing)

The crack pattern of normal concrete beam in Series B is shown in Fig.5. At first loading 6 cracks were introduced with almost uniform crack spacing in as wide span as possible. After unloading, the beam was subjected to the same loading as Series A. Not so much difference was seen between normal concrete of Series A and that of B in terms of ultimate strength and ductility.

3.5 Discussions

Each couple of specimen on the same curing condition showed almost the same results except only 1NCEA71, so we are sure that on the whole the experiment was conducted accurately. 1NCEA71 showed very brittle shear failure, which was completely different from 1NCEA72 that failed in flexure after enough deformation. Therefore we broke 1NCEA71 and checked the inside of it, but could not find any clear cause.

Concerning 1NC7+1, the shear capacity obtained from equation (1) was about 1.11 times larger than the flexure capacity obtained from JSCE code. It was clear that on these conditions, failure mode and ductility changed so much according to curing conditions. There seems to be many reasons for it, such as difference of compressive strength, internal stress, and cracking due



to internal stress. Judging from the amount of powder used in this experiment, rather drying shrinkage than autogenous shrinkage was dominant. And the compressive strength of 1NC01 was not much smaller than 1NC7+1. Therefore it can be guessed that main reasons for changing of failure mode and ductility were internal stress and cracks.

In general, expansive agent replaced with part of cement compensate drying shrinkage, and large amount of expansive agent introduces chemical prestress in concrete. In this experiment, compressive strengths of normal concrete and expansive concrete were almost the same, so it seems reasonable that structural performances of expansive concrete were greatly improved because there were no internal tensile stress and cracks.

In Series B, cracks introduced mechanically did not affect the failure mode and ductility. Comparison between the results of Series A and those of Series B indicates that dominant reason for changing of structural performances is not cracking but internal stress distributed inside the specimen.

In actual RC structures shear reinforcement is arranged, therefore internal stress will hardly affect the capacity of them. But it is likely that the effects of internal stress should be considered in terms of ductility.

4. Analytical Evaluation Method (Our Future Direction)

As we have mentioned in the introduction, the performance based design obligates quantitative assessment of required performances by means of transparent and objective science. Therefore, a 3D finite element computer code named COM3 for structural dynamics has been developed at the University of Tokyo for dynamic as well as static ultimate limit states. It can simulate structural behaviors expressed by displacement, deformation, stresses and macro-defects of materials in view of continuum plasticity, fracturing and cracking. Smearred crack modeling for reinforced concrete has been developed in the past decade at the University of Tokyo. The constitutive law can handle multi-directional cracking in 3D space by decomposing stress bearing mechanism into orthogonal 2D sub-planes on which 2D in-plane constitutive model of reinforced or plain concrete is applied [3][4].

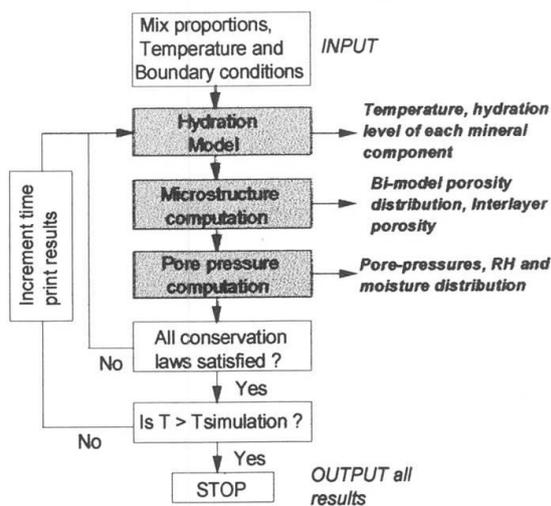


Fig.5 Framework of DuCOM thermo-physics

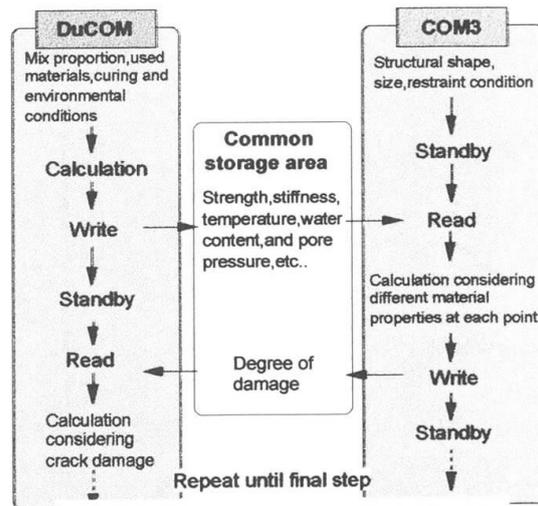


Fig.6 Parallel Processing of DuCOM and COM3

In COM3, the change of material properties with time is not taken into account. Therefore, when we try to simulate the experimental results in this study, we cannot trace the phenomena

faithfully but we have to depend on some simplified methods, that is to say, adjusting tensile strength or applying axial force in tension or compression. The structures with simple reinforcing arrangement used in this study could be analyzed with those simplified methods. But it is likely that real structures with shear reinforcement and with much more complicated shape have to be analyzed considering different material properties from part to part and internal stress distributed inside the structures.

Independent of COM3, a computational tool has been developed to trace properties of concrete for arbitrary materials, mix proportions, curing conditions, and dimensions. The hydration of cement in concrete volume, moisture migration, and micro-pore structural formation exhibit strong mutual inter-link. 3D finite element analysis program named DuCOM for simulating these transient phenomena in space and time has been developed at the University of Tokyo. The framework of DuCOM is shown in Fig.5 and the details were presented in literatures [5][6][7][8].

Furthermore, by solving two systems in parallel, that is, COM3 and DuCOM, we already have a unified approach of mechanics which governs stress and strain fields and thermo-hygro physics [8]. Parallel processing of DuCOM and COM3 is shown in Fig.6. With this kind of tool, we can evaluate the structural behaviors in time and space considering the development or deterioration of constitutive materials of structures. Though we are now in an immature stage, in the near future it will be possible to deal with problems like the experiment in this study or more complicated matters.

5. Conclusions

In the performance based design, it will be required to evaluate structural performances with the change of material properties with time taken into account. In this study, in order to observe the effects of damages due to environmental action upon structural behaviors, 2 series of experiments were conducted. From the results, it was concluded that in some conditions structural behaviors such as failure mode and ductility are affected by curing conditions. Internal stress mainly due to drying shrinkage was considered to be the main reason that caused the change of structural behaviors. In order to deal with this kind of problem, that is, structural behaviors with the change of material properties, we proposed our future direction of establishing analytical evaluation method, that is, a unified approach of mechanics which governs stress and strain fields and thermo-hygro physics.

6. References

1. Japan Society of Civil Engineering (1986) Standard Specification for Design and Construction of Concrete Structures, Part1(Design)
2. Okamura.H (1978) Limit State Design Method of RC Structures, Kyoritsu-Shuppan, Tokyo. (in Japanese)
3. Maekawa.K, Irawan.P and Okamura.H (1997) Path-dependent three-dimensional constitutive laws of reinforced concrete - formation and experimental verifications, Structural Engineering and Mechanics, Vol.5, No.6, pp.743-754.
4. Okamura.H and Maekawa.K (1991) Nonlinear Analysis and Constitutive Models of Reinforced Concrete, Gihodo, Tokyo.
5. Kishi.T and Maekawa.K (1996) Multi-component model for hydration heating of portland cement, Concrete Library of JSCE, No.28, pp.97-115.
6. Chaube.R.P and Maekawa.K (1994) A study of the moisture transport process in concrete as a composite material, Proc. of the JCI, Vol.16, No.1, pp.895-900.
7. Ishida.T., Chaube.R.P and Maekawa.K (1996) Modeling of pore water content in concrete under generic drying wetting conditions, Proc. of the JCI, Vol.18, No.1, pp.717-722.
8. Maekawa.K and Ishida.T (1998) Unification of Thermo-Physics of Materials and Mechanics of Structures - Toward a Life Span Simulator of Structural Concrete - , International Workshop on Concrete Technology for a Sustainable Development in the 21st. Century , Norway