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Safety Evaluation System of Damaged Structures and Performance Based Design

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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.

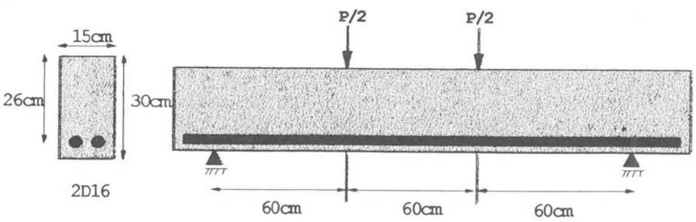

***Fig.1** Geometry of the beams and Loading System*

***Table.1** Mix proportion*

	Water [kg/m3]	Cement [kg/m3]	Expansive Agent [kg/m3]	Fine Aggregate [kg/m3]	Coarse Aggregate [kg/m3]	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),

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

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

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

$$p = A_s/(bd)$$

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

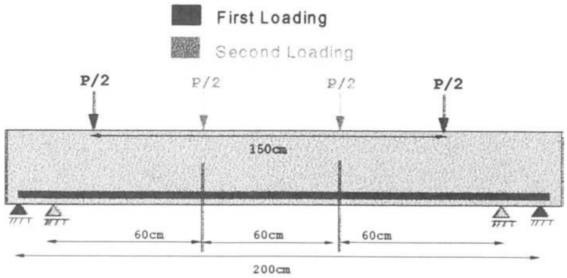

***Fig.2** Loading System for Series B*

where, f_v : shear stress when diagonal shear crack happens [kgf/cm^2], f_c' : compressive strength [kgf/cm^2], a : shear span [m], d : effective depth [m], b : width [m], A_s : total area of reinforcing bars [m^2].

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	fc'(kgf/cm2)	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 *1* 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.

1NC01 was tested first of all to decide the loading system. Therefore, only 1NC01 was tested under different loading system. Looking over the results of normal concrete, it can be said that failure mode may change according to curing conditions. As can be seen in Fig.3, normal concrete specimens under 3 types of curing conditions have completely different ductility. Of course it might be to some extent due to the difference of compressive strength. But the measured compressive strength 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.

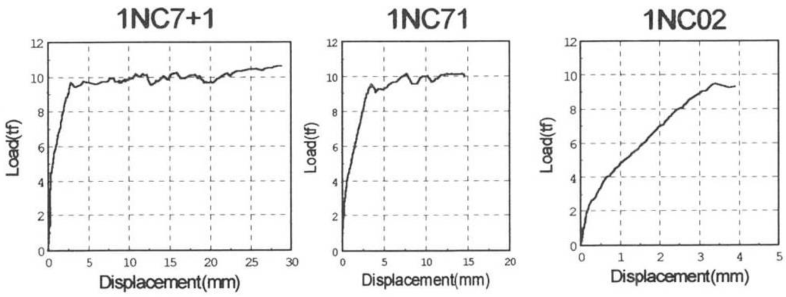

Fig.3 *Load-Displacement Relationship at the center of the span (Normal Concrete)*

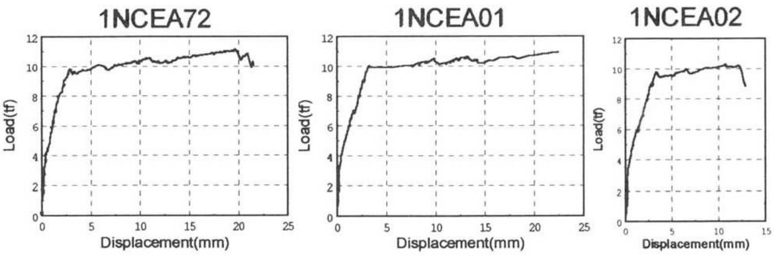

Fig.4 *Load-Displacement Relationship at the center of the span (Expansive Concrete)*

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.

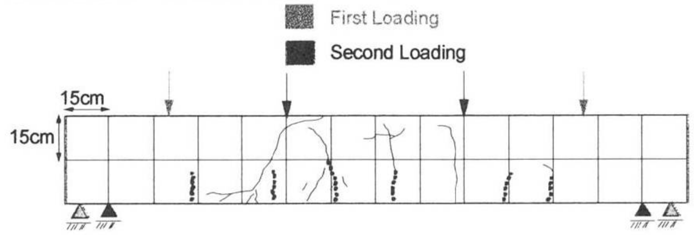

Fig.5 *Crack Pattern of Series B (Normal Concrete, Water Curing)*

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. Smeared 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].

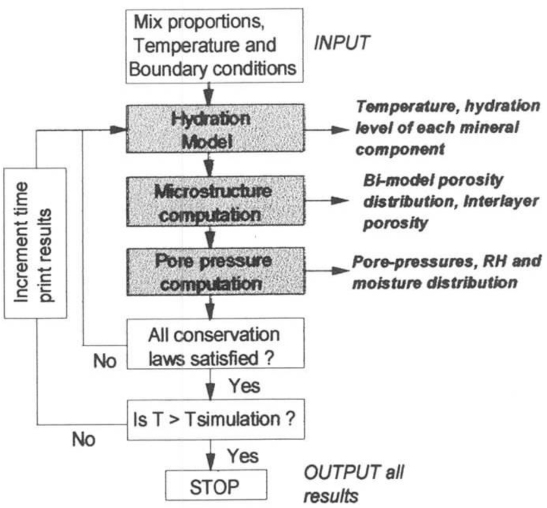

Fig.5 Framework of DuCOM thermo-physics

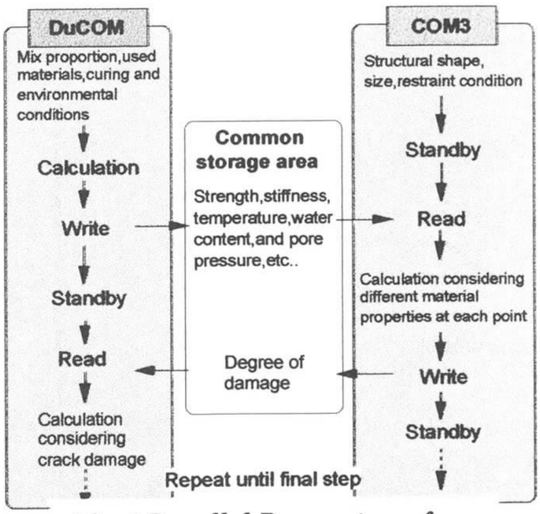

Fig.6 Parallel Processing of DuCOM and COM3

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.

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