Fracture Mechanics of Concrete Structures
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FRACTURE PROCESS AND MAINTENANCE OF CONCRETE STRUCTURES

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Abstract
In the study on the failure of structures, how actual failure begins, progresses and comes to an end must first be observed and grasped. Next, we have to recognize the failure mechanism. Finally, a generalized model of the failure process should be composed for the sake of the structural design and/or analysis.

Two different types of failure processes, that is, time-independent failure process and time-dependent deterioration process are discussed and several topics are presented on these processes. Characteristics of the failure process and ductility of RC and PC beams are discussed through load-deflection curves. The shape of stress-strain curves, especially at the post-peak portion, and their meaning in relation to beam failure are discussed. Mechanical behavior of ASR deteriorated and chloride corroded beams are shown as an example.
Key words: deterioration, ductility, concrete structure, failure process

1 Introduction

Concrete is one of the most important materials in 20 century along with steel and it will continue to be so in the next century. Almost all the concrete structures in Japan have been constructed during these 50 years after World War II, and many of them have deteriorated in the course of time. Concrete structures exhibit high durability when they are properly designed and constructed. But they show low performance when the level of design and/or construction is low.

The whole process concerning structures is to be shown as follows:

planning – designing – construction - maintenance

Basically, concrete structures are designed to satisfy the various required performances to the required level, such as serviceability, strength, ductility and other mechanical properties, durability, aesthetic aspect, economy, etc. Such performance design is fundamental in the design of the structures. However, for the sake of simplicity, only aspects of mechanical and durability performance are dealt with in this paper.

Maintenance of a structure is a matter that arises after the structure begins to be used. The expected life of infra-structures is much longer than that of ordinary engineering products, such as personal computers or cars. In addition, almost all the parts of the structures cannot be easily replaced, in general. Therefore, various unexpected problems will occur in the course of time which were not forseen at the time of design and construction. Recently, maintenance costs, as a result of deterioration of structures, are increasing year by year and will continue to increase in the future and the issue of maintenance will become more serious.

The terms "fracture" and "failure" seem to be very similar; but the former seems to relate rather to the material level while the latter to the structural level. The term "failure" will hereafter be used to mean the fracture of a structure in this paper. Several topics will be presented on the failure process and maintenance of concrete structures, in order to build up a more advanced system concerning concrete structures.

2 Failure process

In the study on the failure of structures, how actual failure begins, progresses and comes to an end must first be observed and grasped. Next, we have to recognize the failure mechanism. Finally, a generalized model of the failure process should be composed for the sake of the structural design and/or analysis.

Structures are not considered to move from a stable state to final collapse state instantaneously. The failure of structures may be defined as the process of how they change their performance and lose their required functions in the required levels. The process can be characterized by several points. These points should hopefully have a certain physical meaning, such as the yield point of mild steel. However, they do not necessarily have such a definite meaning, just like a nominal yield point of high strength steel. In the latter case, there should be some common understanding as to how the characterized point in the process should be defined.

The failure process of a concrete structure can be classified into two categories from the view point of a time sequence; one is a rather time-independent failure process and the other is highly time-dependent. An example of the former is when a structure is subjected to a strength-exceeding load, such as an earthquake load. In this case the failure process depends only on the state of the structure at the moment and does not directly depend on the history of the structure. In the latter case, deterioration of a structure over the course of time should be taken into consideration in the failure of the structure due to, for example, corrosion of reinforcement.

These two types of failure are interrelated in some cases and it may be difficult to discuss them separately. But in the former case, failure of a structure is closely related to the failure of its constituent materials and structural members; whereas in the latter case, what matters most is damage and deterioration of the structure itself.

Firstly, studies on the time-independent failure process of concrete structures will be presented.

3 Failure process of concrete structural members

Concrete structures are composed of structural members. The members are classified into two kinds: one-dimensional line members and multi-dimensional plane members. When discussing the failure process of a concrete structure, generally, failure processes of the composed members are dealt with, instead of the structure itself, because of the easy clarification and simple treatment of their behavior. Yet, it is still complex and difficult to grasp the failure process and to realize the mechanism for the plane members. The difficulty in predicting a failure process lies largely in the bi-furcation problem in the process.

In this study, the failure process of reinforced concrete (RC) flexural members is mainly dealt with. The failure process of a simply loaded RC beam is schematically represented by a load-deflection (or bending moment versus curvature of a section) diagram. Figure 1 shows the load-deflection diagram of an under-reinforced RC beam.

The diagram can be generally characterized by a cracking point, yield starting point, strength failure (maximum strength) point, yield ending point, rupture point, etc. At the yield ending point of tensile reinforcing bars, yielding stops and then stress and strain in the tensile reinforcing bars begin to decrease, though deflection of the beam is still increasing. After the yield ending point, the load of RC beams decreases suddenly.

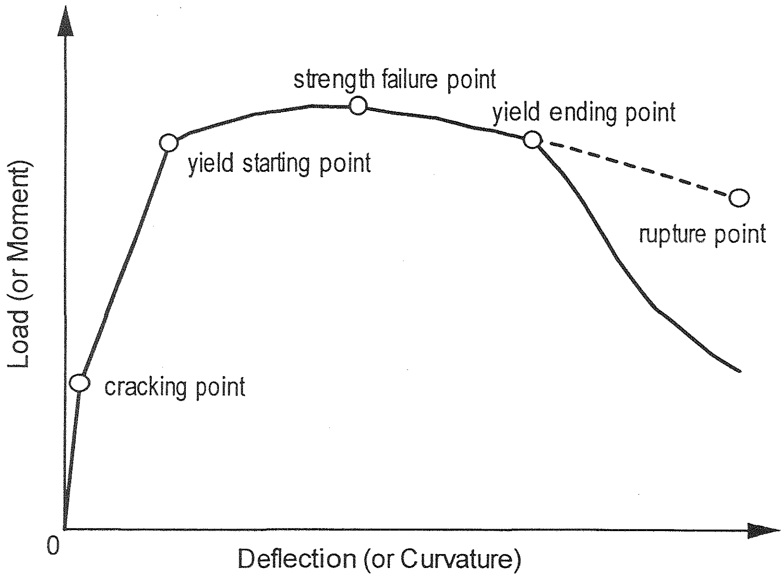

Fig. 1. Schematic failure process of RC beams

The failure process also ends by the rupture of tensile reinforcement when the tensile reinforcement ratio or the difference of tension and compression reinforcement is too small. Since most of the absorbed energy of RC beams in bending dissipates in tensile reinforcing bars by the yielding, the yield ending point as well as the yield starting point are considered to be suitable points for the ductility evaluation of RC beams.

Ductility is one of the outstanding features of an RC beam and it can be defined as the plastic deformation capacity of the beam, from the yield starting point to the yield ending point. From this point of view, the so-called "balanced reinforcement ratio" seems incorrect if the word balance contains a favorable nuance. It corresponds to the reinforcement ratio that the yield ending point coincides with the yield starting point. Therefore, the term "limiting reinforcement ratio of no plastic deformation" is more suitable than "balanced reinforcement". Plastic deformation cannot be expected there.

Figure 2 shows the load deflection curves of singly reinforced concrete beams with three tensile reinforcement ratios p (Koyanagi, Rokugo et al, 1982). Ductility became smaller when p increased and in the case of p=7% no ductility could be seen. Figure 3 also shows the load deflection curves of doubly reinforced concrete beams with three compressive reinforcement ratios p' where p was kept constant (Koyanagi, Rokugo et al, 1983a). Deflection at the yield ending point and ductility increased

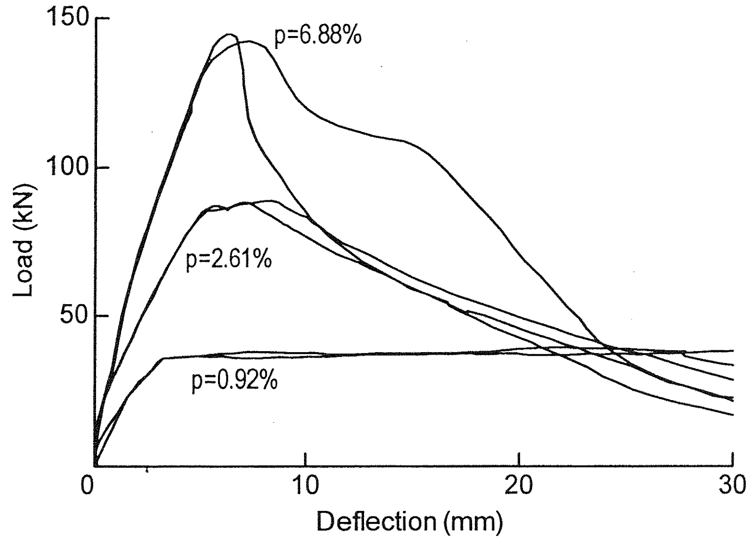

Fig. 2. Load-deflection curves of singly reinforced concrete beams

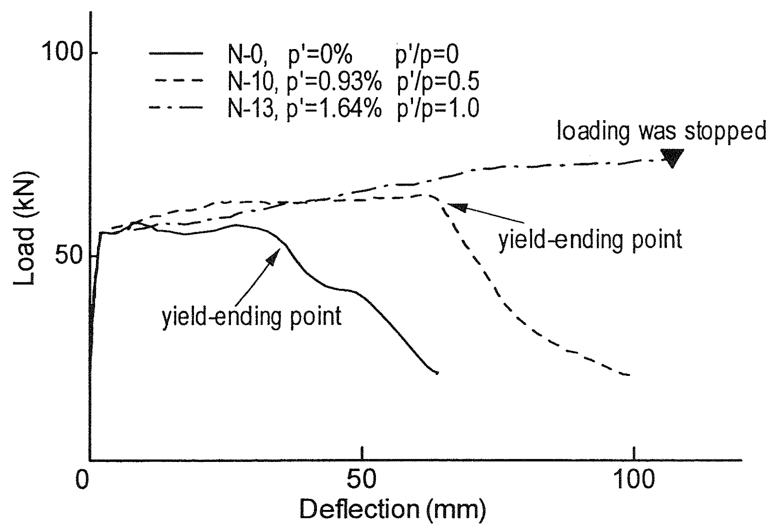

Fig. 3. Load-deflection curves of doubly RC beams

when p' increased. After the yield ending point, the load carrying capacity decreased suddenly.

It is said that the shape of stress-strain relation of concrete is not so important for under-reinforced beams because it scarcely affects the RC beam strength and it becomes important only in the case of over reinforced beams where no yielding of bars occurs. It is true when the discussion is limited only to the strength of section failure. However, even for the under-reinforced beams, stress-strain relation of concrete becomes very important when we deal not only with deformation property of RC beams but also strength property of beams without definite yield of reinforcement. In addition, it becomes very important when we deal not with section failure but with structural failure of RC beams.

A number of valuable investigations have been done on the fracture process of concrete and almost all of them were done under the tensile stress state. Actually, concrete is utilized mainly as a compression member in structures. However, the compression fracture process is clarified only in a certain limited range. Crack initiation process and some growing process of micro-cracking in concrete under compression have been fairly clarified and the works are described in elsewhere(van Mier, 1997). However, it is difficult to trace the fracture process completely especially in the final stage even for the case of simple cylindrical specimens. Bifurcation and localization of deformation should be solved.

Load-deformation curves of mortar (M) and plain concrete (P) prism specimens under compressive loading both with three kinds of height width ratios (h/w), where cross sectional area was the same, are shown in Fig. 4 (Koyanagi, Rokugo et al, 1983b). The peak loads were almost the same but the deformations at the peak load were nearly proportional to the specimen height for mortar and for concrete. Figure 5 represents the stress-strain curves derived from the same test results described above. The stress-strain curves before the peak stress coincide with each other, whereas the shape of the curve after strength failure (in the post peak region) is remarkably influenced by the height/width ratio (h/w) of the specimen for both mortar and concrete. The post-peak curves become steeper as the h/w increases. A snap-back phenomenon is clearly observed in the case of mortar specimen with h/w of 6. The shape of the curve in the post-peak region largely depends on the specimen height and it relates to the failure length of the specimen. The reason for this can be explained by the fracture energy concept (Rokugo & Koyanagi, 1992).

The conditions in a flexural compression zone in RC beams are somewhat different from those in the uni-axial compression tests as stated above, because strain gradient more or less exists in the case of bending. However, the similar length-dependent fracture phenomena in the post-peak region of concrete possibly exists for bending failure of RC beams in the compression zone. If this inference is true, the length and zone of failure in the longitudinal direction of the beam axis must be taken into consideration for more advanced structural failure analysis of RC beams instead of conventional section failure analysis. The shape of the stress-strain curve of concrete in compression should be also re-examined .

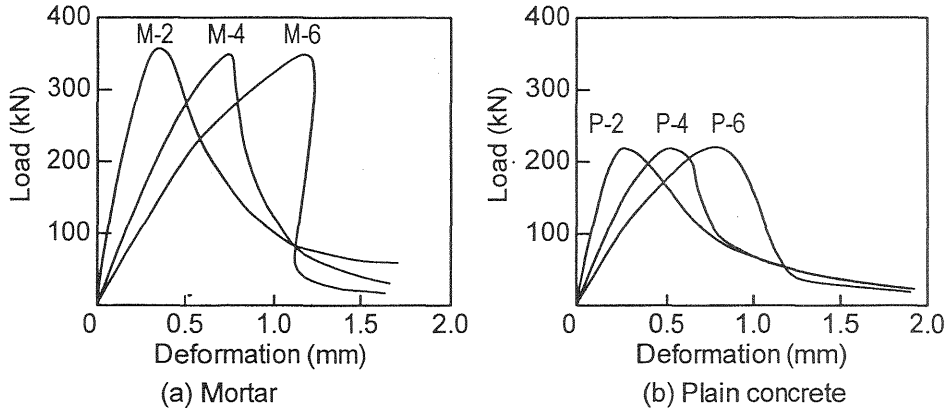

Fig. 4. Observed compressive load-deformation curve of prism specimen

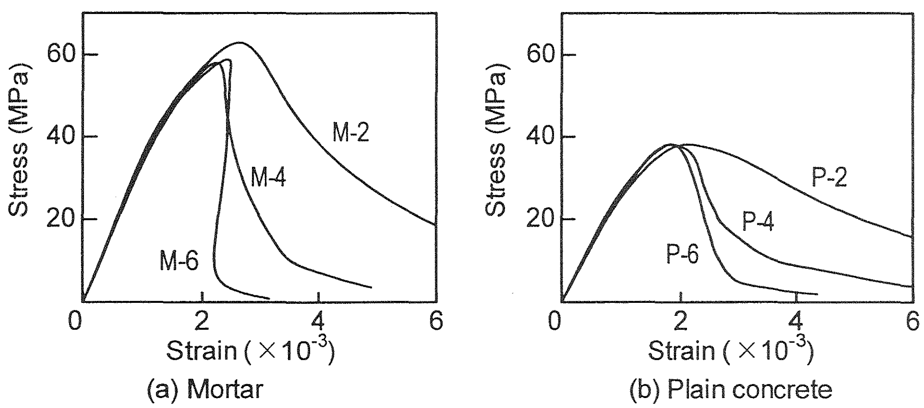

Fig. 5. Calculated compressive stress-strain relation

In the case of pre-stressed concrete (PC) beams, reinforcing steel does not exhibit a definite yield phenomenon. Figure 6 shows a typical load-deflection curve of a post-tensioned T-sectioned PC beam with a total length of 24.8m and height of 1.2m. Deflection of the beam increases with the increase in load and after many cracks occurred, the beam reaches the strength failure point. At this point, concrete crushes in the upper flange of the beam and crushing failure immediately propagates to the web portion because load bearing area for pre-stressing force in the flange decreases rapidly and the area is transferred to the relatively small web portion. T-sectioned PC beams show neither constant load nor softening portion in load-deflection diagram just like beams with a rectangular section and RC beams show. Even when reinforcing steel lies in the yielding zone, ultimate crushing failure occurs in an ascending portion of the diagram.

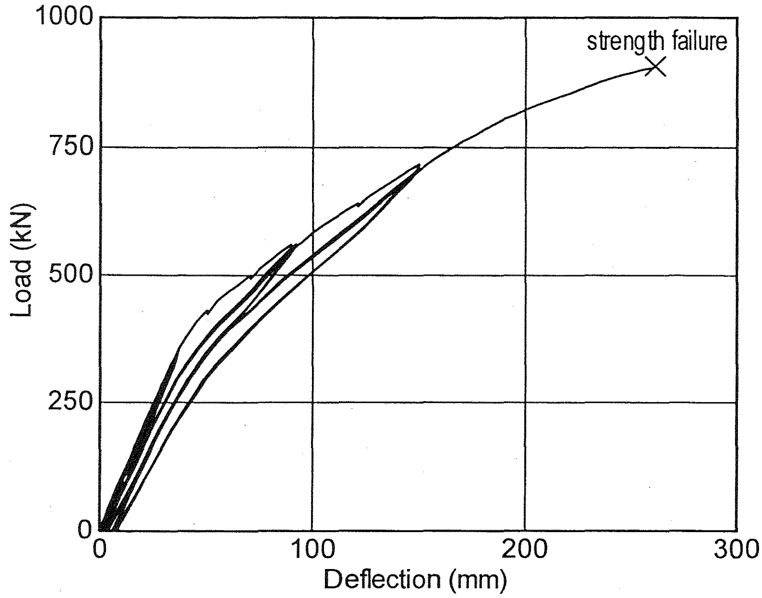

Fig. 6. Load-deflection curve of T-section PC beam

Ultimate compressive strains observed in the test of PC beams were 0.002 for the T-beam section. The value is smaller than that proposed for rectangular sectioned beams and agrees with the proposal of Rusch (1960).

Mechanical properties of PC beams are considered to be very close to RC beams from the standpoint of structural design, however, PC beams show quite different features from that of the latter from the viewpoint of the fracture process concept.

4 Deterioration process of concrete structures

Commonly, various deterioration or damage occurs over time in concrete structures, especially those exposed to an aggressive environment. When we deal with the matter of time-dependent failure process of concrete structures, the process is called deterioration process, in general. As stated before for time-independent failure process, in the first place, we have to observe and grasp the actual deterioration phenomena. Next, we have to recognize the mechanism of deterioration. And then, a generalized model of the deterioration process should be composed. When we deal with the deterioration process, information on the time-dependent procession of deterioration becomes also very important.

The deterioration of concrete structures mainly relates to the performance of structural strength, durability, function and appearance.

For structural aspect, there are two categories of damage. One relates mainly to the damage of the reinforcement of structural member, and the other relates to the damage of concrete. Typical "damage action" that directly influences the structural strength includes corrosion and fatigue. The damage actions which seem to indirectly influence the structural strength are ASR, abrasion, carbonation, sulphate attack, freezing and thawing, chemical degradation, etc. Deterioration and its speed of progress are influenced largely by climate, location, and surrounding of the structure.

Various defects are generated in the structure by the damage actions. One typical visual defect is cracking and the cracking is considered to be one of the most suitable parameters in evaluating the state of deterioration. Cracks can be evaluated quantitatively through their length, width, direction, area and/or volumetric density, etc. Deflection under loading and vibration characteristics also seem to be effective parameters in evaluating the mechanical state of the structure. The state of the structure, that is, the degree of deterioration, should be evaluated using these state parameters, yet, it seems insufficient from our present knowledge to evaluate where the structure lies in the deterioration process clearly.

5 Deterioration process and maintenance of concrete structures

Maintenance of a structure is a matter after the structure started to be used as stated above. How long can we foresee in the future? Various unexpected problems will happen in the course of time, which were not expected at the time of design and construction. Changes happen not only on a hardware side, such as the change in the magnitude of standard design load, but also software side, such as social background surrounding the structure. In the late 1970s, chloride corrosion and ASR issues in concrete structures arose and people paid great attention to the durability problem. Maintenance of concrete structures is performed by maintaining its required performance level throughout the entire length of its use. The procedure of maintenance is as follows;

Initial inspection – Determination of maintenance category –
Deterioration prediction – Inspection – Assessment and judgement –
Repair and strengthening

In order to make appropriate maintenance of concrete structures, knowledge on the failure and deterioration process of the concrete structure is extremely important. Deterioration processes vary from one concrete structure to another according to extrinsic factors such as environmental condition and kind of damage action, as well as intrinsic factors such as type of structure, design and construction conditions. There are many kinds of deterioration processes of structural

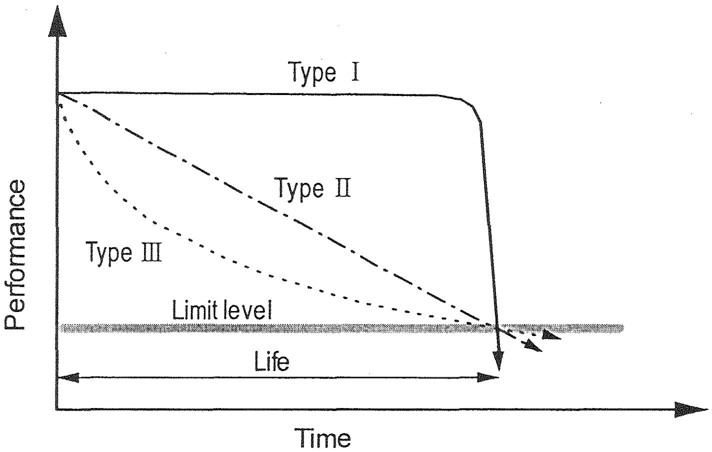

Fig. 7. Schematic deterioration process of structural performance

performances. Schematic deterioration processes with different types are represented in Fig. 7. One of the most important performances is a mechanical property of structure and it is taken as a representative of performance, hereafter.

In making the deterioration prediction of a structure, the deterioration mechanism of the structure must correctly be inferred and the prediction should be made according to the mechanism, such as chloride induced deterioration, carbonation, freezing and thawing, alkali-aggregate reaction, chemical erosion, fatigue, abrasion, etc. The deterioration is not necessarily caused by only one mechanism. Composite effects caused by several factors are also taken into account.

Inspection of structures can be classified to initial, daily, periodical and extraordinary inspections, according to the purpose and interval of the inspection. Development of effective NDT methods which can represent the degree of deterioration directly and precisely are strongly needed. State parameters, especially crack parameters, are effectively adopted. Yet, several catastrophic failures happened where almost no damage was found during the inspection. This type of failure occurs mainly due to the break of reinforcement, caused by either corrosion or fatigue. In this case, in general, various kinds of difficulties existed to detect damage in the structure because the structural system is so complex. It is one of the most important items that the structure should be designed so as to easily allow inspection and the degree of deterioration can be easily found.

Assessment and judgement is performed according to the obtained results of the inspections. It is important to know whether the results of the inspections correspond to the predicted deterioration process as well as whether they exceed the limit for repair and strengthening. If they correspond to the predicted process, further prediction of future development of deterioration should be made. If they do not, another deterioration mechanism and/or velocity of deterioration should be considered. The interval of further inspection and the deterioration limit for repair and strengthening should be determined according to the type of the deterioration process curve. Recently, methods for repair and strengthening have developed remarkably. The subject is extremely interesting but it is outside the scope of this paper at this moment.

There is also an important matter concerning assessment and judgement, that is, how the structural performance is kept in relation to the degree of deterioration of the concerning structure (or the member). Several examples are shown in the following.

In the case of ASR, concrete deteriorates and many cracks occur in concrete because of the expansion of silica gel. Figure 8 represents static load-deflection curves of RC beams deteriorated severely by ASR, where the first letter means the kind of concrete (N: normal, A: ASR deteriorated) and the second letter means the amount of reinforcement (S: 0.9, L: 1.7%) (Koyanagi et al, 1996). We could not observe marked differences of the structural behavior between deteriorated and sound beams under static loading. The structural behavior seems to rather increase owing to the induced chemical pre-stress, generated by the arrest of ASR expansion through reinforcement. When the amount of reinforcement ratio becomes too small, a risk of breaking reinforcement may arise because ASR expansion may exceed the elongation capacity of the reinforcement.

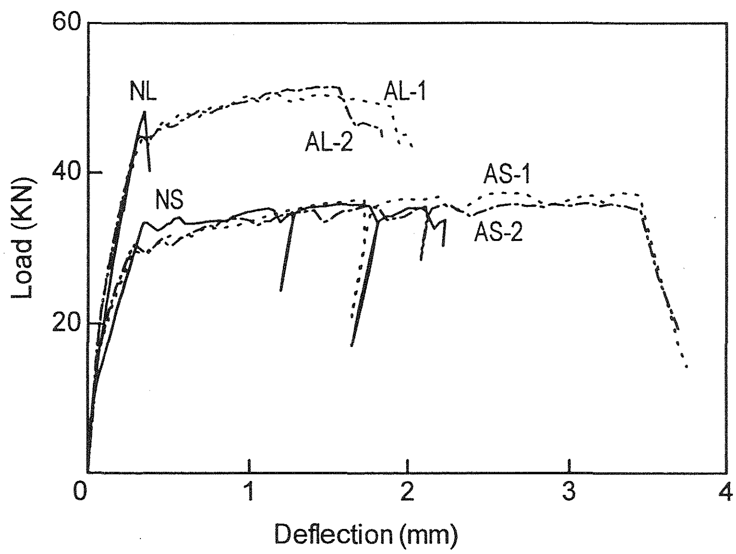

Fig. 8. Load-deflection curves of ASR deteriorated beams

In the case of chloride corrosion, corrosion products cause longitudinal cracks in cover concrete along reinforcing steel and the bond between steel and concrete decreases. However, mechanical behavior of chloride corroded RC beams under static and incremental reversed cyclic loading at certain deflections ($\pm\delta y$, $\pm 2\delta y$, $\pm 3\delta y$ · ·) is comparable to that under sound ones. When beams suffered thirty cyclic reversal loadings at each constant deflection, the difference becomes apparent as shown in Fig. 9 (Okada et al, 1988).

Electrolytic corrosion test has been made instead of chloride corrosion test because corrosion rate is very small in the former. Load deflection curves of deteriorated RC beams with rectangular hooks under static loading in different degrees of corrosion are shown in Fig. 10 (Lee et al, 1995). When the corrosion content becomes large, mechanical behavior of the beams is influenced by the corrosion. But when the corrosion

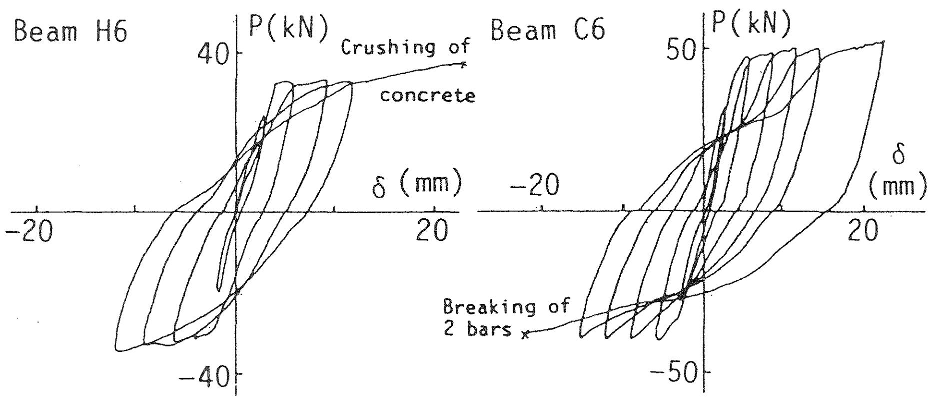

Fig. 9. Load-deflection curves of chloride corroded beams

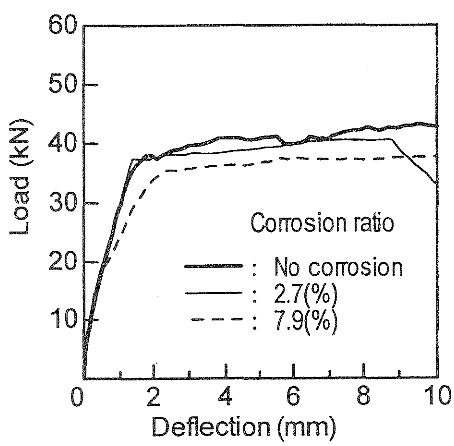

Fig. 10. Load-deflection curves of electrolytic corroded beams

content is small, no difference can be seen between corroded and sound beams.

In the case of reinforcement corrosion, decrement of the strength of a structural member is not so evident. But catastrophic collapse will occur abruptly when the reinforcement breaks and the deterioration process is expressed as the Type I curve as shown in Fig. 7.

In the case of fatigue of bridge deck deterioration, cracks extend in slab concrete in various directions with the increase of repeated heavy traffic and a portion of the slab falls down finally. Moving wheel loading tests have been performed in order to simulate the deterioration process. Water in concrete remarkably affects the fatigue strength of a bridge deck slab (Matsui, 1987). Judging from observed steel strain, bridge deck slabs fails without yielding of reinforcement under repeated heavy traffic load.

Application of fracture mechanics seems to be most appropriate in the analysis of fatigue failure process.

6 Conclusion

Concrete structures play a very important role in society as infra-structure but they are destined to deteriorate in the course of time. From the view point of maintaining global circumstances and effective utilization of limited resources, it is urgent to make the life of structures as long as possible. What is important to realize this purpose is to analyze deterioration process under various damage actions and perform appropriate maintenance in response to each case. Failure processes of structures are not yet completely clarified, but in my view, they can be classified into two categories, time-independent and time-dependent.

As to the time-independent failure processes, the present stage of study remains in the level of structural member but it should evolve into the level of whole structure, the structure itself in which, analysis and re-organization of fracture process with the concept of fracture mechanics as well as bi-furcation will be indespensable.

Collapse of structures gives great damage to society. A considerable number of concrete structures are supposed to have completely collupsed or nearly collapsed so far but there is only very limited number of them have been reported. There are several reasons for that. One reason is because it is a dishonor. Another reason lies in the attitude of mass media which tend to make sensational, short-sighted and hasty pursuit about who should take responsibility. This prevents people concerned from making reports of such collapse.

If these reports are properly made, they will provide very precious information for composing advanced system of design and maintenance. Especially, some phenomena come to appear only under the long lapse of time and it is impossible to fortell such phenomena at the initial stage of designing structures. Treatment of such information, which is very valuable from the engineering point of view, should be liberated from the pursuit of legal responsibility and made public and freely discussed on the engineering base. Therefore, I strongly wish a social situation will be prepared enabling such free discussions.

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