DETERIORATION OF BONDED POST-TENSIONED CONCRETE BRIDGES AND RESEARCH TOPICS ON THE STRENGTH EVALUATION IN ISARC

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SUMMARY

Many bonded post-tensioned concrete bridges in the world have exhibited tendon corrosion and fractures caused by voids in ducts and ingress of water and chloride ions. For safety, strength evaluation of these bridges is required at the time of investigation, but limited information about corroded tendons can be lead to wrong direction or evaluation. The paper describes deterioration of post-tensioned concrete bridges and research topics related to strength evaluation method in ISARC, and discuss a strength evaluation method that considers tendon corrosion. Load test of post-tensioned concrete beams with corroded tendons will also be presented.

***Keywords**: Post-tensioned concrete bridge; strength evaluation; tendon corrosion; wire fracture; voids in duct; chloride ingress.*

INTRODUCTION

Post-tensioned concrete bridges have constructed with the efficiency of construction method for concrete structures with high strength of prestressing steel. Historically, prestressed concrete bridges had been considered as needing less maintenance than steel bridges, but after the collapses of a few precast post-tensioned concrete bridges in Europe, it was realized that post-tensioned system is believed to be at long-term risk. Many post-tensioned concrete bridges have exhibited corroded tendons and severe wire fractures caused by ingress of water and chloride ions into partially grouted ducts. Corroded tendons could be inspected only using invasive inspection due to the lack of reliable nondestructive techniques. The invasive inspection requires excavation of concrete and only exposed tendons among the total number of tendons can be inspected. In case of un-bonded tendons, because the condition of whole length of exposed tendons could be checked using screw driver test, invasive inspection can be applied without exact information of the location of corroded tendons. For bonded tendons, because only exposed tendons at the locations applied invasive inspection can be inspected, reliable information of the location of corroded tendons should be provided and confirmed

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prior to starting invasive inspection. However, unfortunately it is very difficult to find visual evidence of corroded tendons and in some locations almost impossible.

Within these limitations, reliable strength evaluation method should be developed to evaluate ultimate strength of post-tensioned concrete bridges with corroded tendons.

The paper describes deterioration of post-tensioned concrete bridges and research topics related to strength evaluation method in ISARC, and discuss strength evaluation method including tendon corrosion. Load test of post-tensioned concrete beams with corroded tendons will be presented also.

DETERIORATION OF POST-TENSIONED CONCRETE BRIDGES

Tendon Corrosion

Prestressed concrete have been used extensively in the construction of highway bridges. For many years these bridges were considered as being maintenance free. However, after the sudden collapses of the Ynys-y-Gwas Bridge in 1985 and the Malle Bridge in 1992, it was recognized that long-term risk exists in post-tensioned concrete bridges. Ingress of chloride at segmental joints is believed to have contributed to the pitting corrosion which led to the collapse of the Ynys-y-Gwas Bridge in the UK (Woodward et al. 1988). In case of the Malle Bridge in Belgium, corrosion of the post-tensioning through the hinged joint of the end tie-down member led to collapse without warning (Mathy et al. 1996). After the understanding of the long-term risk, special inspection has been undertaken in Europe. In many bridges voids in ducts were found frequently (Woodward, 1981) and in some bridges, unfortunately, serious corroded tendons were found, which led to replace the bridges (The concrete Society, 1996). Due to the uncertainty of the whole condition of the tendons and the lack of reliable evaluation method, bridge owners had no alternative to replacement for safety (Fricker et al. 2006).

Ingress of Chloride

Ingress of chloride into the partially grouted duct and anchorages is to be the most serious cause of deterioration of post-tensioned concrete bridges. Most of expansion joints are not completely watertight and hence de-icing salt can run down tendon anchorages at the ends of decks. Waterproofing membranes on bridge decks deteriorate with time and all are susceptible to damage during the course of resurfacing operations. Thus, de-icing salt is likely to find its way through the membranes. If the tendons are not properly grouted, they are never protected from chloride-induced corrosion. Most of prestressed concrete bridges in Korea are constructed using post-tensioning system and no proper watertight expansion joints. A number of tones of de-icing salt are spread on the bridges every cold weather. From these conditions, ingress of chloride may be expected without any reports of invasive inspection and the symptoms of chloride-induced corrosion. Recently Korea Highway Corporation has started to developing non-metallic sheath for precast concrete girders.

Factors Affecting Strength Evaluation

Evaluation of deteriorated post-tensioned concrete bridge is needed to determine strength and safety at the time of investigation. If it is considered that there is no concern about any deterioration, flexural strength of prestressed concrete bridges may be obtained from Equation (1).

$$M_{n1} = A_p f_{ps}\left(d_p - \frac{a}{2}\right) + A_s f_y\left(d_s - \frac{a}{2}\right) \quad (1)$$

where, A_s : Area of nonprestressed tension reinforcement

A_p : Area of prestressing steel

a : Depth of equivalent rectangular stress block

d_s : Distance from compression face to centroid of nonprestressed tension reinforcement

d_p : Distance from compression face to centroid of prestressing tendons

f_{ps} : Average stress in prestressing steel at the time for which the normal resistence of member is required

f_y : Specified minimum yield strength of reinforcing bars

If corroded tendon is found, it is required to assess how much section has been lost from the tendon. If corroded tendons are assumed to show ductile behaviors, Equation (1) can be applied to calculate residual flexural strength. However, as mentioned earlier, chloride-induced corrosion is believed to have contributed to pitting corrosion which led to wire fracture. Different from reinforcing steel, prestress steel shows brittle behavior and hence, Equation (1) is not always applicable, especially in case of severe wire breakage. Due to the lack of enough technical information, consensus guidelines and code for such analyses have not been developed.

If deterioration of concrete at compression face is only found, Equation (2) can be applied to consider the loss of concrete section.

$$M_{n2} = 0.85 f_c' ab\left(d - \frac{a}{2}\right) \quad (2)$$

where, b : Width of compression face of member

d : Distance from compression face to centroid of tension reinforcement

f_c' : Specified compressive strength of concrete

In Korea deterioration of concrete bridge decks under waterproofing is frequently occurred due to the leakage of water and de-icing salt which led to the combined deterioration of chloride contamination and freezing & thawing action. This deterioration of concrete bridge decks will be discovered during a routine pavement resurfacing (Figure 1).

RESEARCH TOPICS ON STRENGTH EVALUATION IN ISARC

In 2004 Infra-Structure Assessment Research Center (ISARC) was established in Korea to perform a national project to develop new assessment codes and guidelines for concrete structures. As a member of concrete bridge group in ISARC, the authors are in charge of strength evaluation part of prestressed concrete bridges. Following research topics have been considered as being interested:

(1) Inspection guideline
(2) Evaluation guideline
(3) Non-destructive test: Acoustic monitoring and Radiography
(4) Load test; ultimate load test
(5) Proof load test
(6) Prestress measurement test

Inspection Guideline

For grouted post-tensioned concrete bridges, it is generally considered that detecting any visual evidence of tendon corrosion is very difficult and there are no cost-effective and practical non-destructive test methods available. Depending on budget plan, destructive inspection including exposing tendons or drilling holes and inspecting with endoscope can be applied. However, actually no-one wants invasive inspection if they have other solutions and after the inspection, actually only limited technical information can be obtained at local area. Prior to developing evaluation guidelines or code, severe tendon corrosion will lead to the conclusion of bridge replacement.

Considering many aspects of the circumstances of existing bridges in Korea, such as types of bridges (cast-in place construction or precast segmental construction), probability of sudden failure, years in public use, weather condition related to de-icing salt, details of expansion joints and anchorages, waterproofing, available non-destructive testing method, etc, inspection guideline should be prepared with a bright strategy for both of safety and management cost. It will need to investigate valuable technical information and guidelines in the world. Special inspection for samples of vulnerable bridges from de-icing salt will be helpful to understand grouting conditions and corrosion conditions of bridge stock in Korea.

Evaluation Guideline

Evaluation of deteriorated post-tensioned concrete bridges is not new one, but will be the most complicated task for structural engineers. Because of the uncertainties of whole conditions of corroded tendons, it is almost impossible to calculate residual flexural strength exactly. However, if reliable information is collected and categorized in the world, at least it is believed that post-tensioned concrete bridges could be controlled and managed during in use successfully without sudden collapse. Many aspects of design code based on strength design concept are not always applicable for strength evaluation of deteriorated post-tensioned concrete bridges especially severe wire breakage. For example, because current design code does not consider longitudinal and transverse moment redistribution, any defects at local area can be influenced on the strength of whole bridge system. Therefore, strength evaluation method should be based on ultimate limit state of bridges and fortunately, in Korea, a national project for developing new design code, which is based on limit state design concept, is still running and will be helpful to develop evaluation guideline.

First of all, it will be needed to categorize the possibility of sudden collapse for concrete bridge types and to simulate possible failure mode and probability of failure for each type of bridges (Lindsell et al. 1993; Fjeldheim et al. 1996; Webster et al. 1999). If we consider the variation of bridge categories, details of evaluation procedure or techniques can be changed and hence, we can manage post-tensioned concrete bridge stock with safety and cost effective. In case of high-risky bridges, more sophisticated techniques will cooperate to make sure the safety.

Second, a consensus guideline is essential to determine the effective tendon area among corroded tendons in a duct. There are many variables within a structure and between structures. Such variables should be included as follow: details of tendons, volume of voids or grouting condition in a duct, location of voids, contents of water and chloride ions, amount of corrosion products, surface condition of corroded wires, and limitations of special inspection. Considering the tolerances of variables, consensus guideline should be formed an opinion by structural engineer.

Non-destructive Test

Five possibilities have been available to detect fracture of prestressed wires as follow:

(1) Visual inspection after opening the concrete;
(2) Application of the radiography;
(3) Application of the magnetic methods;
(4) Application of the ultrasonic tests; and
(5) Acoustic emission

Visual inspection

Visual inspection methods have traditionally required the excavation of the concrete in order to expose a sample of the total number of tendons. This results in many openings in the concrete structures to allow a reasonable test sample and the potential of damage to sound cables by jackhammer removals. The main disadvantage of the visual inspection in a short opening in the concrete is its local nature: the conditions of the exposed tendons may not represent of the structure’s post-tension system as a whole (Halsell et al. 1996). In addition this destructive examination the opening needs to be repaired and the repair could become the starting point for a corrosive attack.

Endoscopes can be used to inspect areas, which are inaccessible to the naked eye. These instruments consist of a bundle of optical fibers through which light is transmitted to illuminate the area of interest. The image is then transmitted back to the eye either through a lens system or other fibers. Both rigid and flexible endoscopes are available and cameras can be attached to enable photographs to be taken. Applications include inspecting behind bearings and looking in ducts in post-tensioned concrete. For the latter application 25mm diameter holes are drilled into ducts. If voids are found further measurements can then be made to determine their volume.

Radiography

Radiography can be used for locating and detecting voids and corrosion in ducts in post-tensioned concrete (Guinez et al. 1991), but there are many limitations to its use. The fracture is not detectable with the radiography if it is covered by other steel wires and the resolution is not sufficiently good to determine tendon condition. It is very expensive to carry out. As concrete is a shielding material against x-rays, the method needs high x-ray energy, long exposure time, and focusing to small areas (Woodward et al. 1996; Bligh et al. 1994). Finally ionizing radiation presents a dangerous health hazard and stringent safety precautions are required.

Magnetic methods

The disturbance of a magnetic field in the vicinity of flaws in prestressing steel forms the basis of a technique. Magnetic method can be used for detecting wire fractures. Tendons can typically be tested along their whole length. The characteristic magnetic flux leakage field can be detected even if the fractures wire is screened by other wires or by metal sheathing. However, distinguishing between these defects and other causes of disturbance, such as pieces of tie wire embedded in concrete, presents problems. This method has been applied to detect wire fractures of prestressed parking decks or bridge decks (Scheel et al. 2003). However, it is not yet applicable to detect wire fractures which occur in large concrete cover of the tendon.

Ultrasonic methods

Ultrasonic techniques can be used for detecting fractures in post-tensioning tendons. A transducer is coupled to the end of individual wires or strands and pulse is injected. If there is loss of section or fracture of a wire, energy is reflected and detected by transducer. There is considerable loss of energy into surrounding material, so the technique can only detect fractures occurring within a few meters of the end of a tendon (Woodward et al. 1996). Another disadvantage of the technique is that it requires access to the anchorage.

Acoustic emission

Acoustic Emission techniques can be used to detect wire fractures in post-tensioned concrete structures. A wire failure releases a substantial quantity of energy. This energy dissipated through the structure in the form of sound waves, which can be detected by acoustic sensors. The different arrival times of the sound waves at several sensors allow the calculation of the location of the fracture. This method has been applied to detect wire fractures of prestressed parking decks or cable stayed bridges (Halsell et al. 1996). The AE technique requires a permanent data acquisition system with a sufficiently high-sampling rate. This technique does not provide any information on failures that occurred before its implementation. Currently this technique has been tried to post-tensioned concrete bridges (Cullington et al. 1999; Youn et al. 2004; Fricker et al. 2006).

Load Test

Research works for severely deteriorated post-tensioned concrete beams have not been extensively conducted and thus, more experimental tests are strongly required to investigate ductility and ultimate flexural strength. As an example, load test presents briefly in the paper.

Proof Load Test

In general proof load test is not considered for concrete bridges just because of the possibility of damage during test. However, when considering its powerful tool, it is not easy to exclude proof load test, which gives a simple confirmation of minimal load-carrying capacity (Bakht et al. 1990). In case of high-risky post-tensioned concrete bridges, this tool can be applied for checking both of minimal load-carrying capacity and minimal prestress. It will need to fully investigate possible behavior of bridge considered before the test and should be conducted by bridge experts. Guideline for proof load test will be developed considering about load condition in Korea.

Prestress Measurement Test

If it can be assumed that there is no tendon corrosion, prestress mainly affects the serviceability of post-tensioned concrete bridges. But as mentioned many times, loss of prestress can be caused by tendon corrosion. Different from cast-in place concrete construction, loss of prestress in precast segmental construction has an effect on fatigue life of prestressing tendon. If prestress is measured several locations including critical position along the axis of bridge, it is considered that technical information about tendon corrosion can be drawn from test results.

LOAD TEST OF POST-TENSIONED CONCRETE BEAMS WITH CORODED TENDON

Test Specimens

Ultimate load tests have been performed to show the effects of prestress and tendon corrosion on the flexural strength of post-tensioned concrete beams. Five test specimens were fabricated in laboratory with the variations of (1) the prestress of tendons and (2) the loss of tendon area (Figure 2, Table 1, and Table 2). The initial prestress introduced were measured using by electrical strain gages which are mounted on the surface of steel wires. For the specimens of PC-2 and PC-3, small area of tendons at the center of the beam were exposed by using $\phi 25$ mm drill and using accelerated corrosion equipment, tendon was corroded intentionally to reduce the tendon area. For PC-2, three wires were exposed after drilling and for two weeks 10 volts were applied at the wires. In case of PC-3, two wires were exposed and for three weeks the naked wires were corroding with same volts.

Measuring the loss of tendon area of PC-2 and PC-3 was not simple only by visual inspection and hence, based on the visual inspection, loss of tendon area of PC-2 was assumed to 10% of initial area and for PC-3, because two wires were disappeared, loss of tendon area was assumed nearly 30% (Figure 3). The specimen C-1 of reinforced concrete beam was fabricated to simulate 100 percentage loss of tendon for reference.

Static Load Test

Static load controlled by displacement method is applied at the center of the test specimens and deflection, strains, and cracking behaviors are monitored until failure. AE sensors are attached at the ends of test beams of PC-2 and PC-3. Test beams of PC-1, PC-4, and C-1 are failed with ductile flexural mode. Cracking behaviors such as crack spacing and crack widths are shown as expected before. However, PC-2 and PC-3 which contained corroded tendons are failed by flexure with occurring several wire fractures (Figure 4 and Figure 5) and width of cracks at near the location of corroded tendon is shown much wider than that at other locations.

Figure 6 represents load - deflection curve for PC-3 and four times of wire fractures can be found in the figure. At the times of wire fractures, high sound could be heard by ears and acoustic signals were detected by AE sensors as shown in Figure 7.

Ultimate Flexural Strength

Test results of ultimate flexural strength are summarized in Table 2. As calculated before static tests, both of the loss of prestress and the loss of tendon area are influenced on the ultimate flexural strength of the test beams. In cases of PC-2 and PC-3, the test results of ultimate flexural strength were smaller than the expected values as shown in Table 2. For PC-2, ultimate flexural strength is similar to the calculated value assumed with 30% loss of tendon area. For PC-3, the calculated value assumed with 60% loss of tendon area is very close to the test results.

From the comparison, it is considered that estimation of flexural strength of prestressed concrete beams with corroded tendons is very difficult just based on the loss of tendon area obtained by visual inspection. If endoscope is used to inspect corroded wires, loss of tendon area has to be estimated from only one-side view. Therefore, reliable data can be obtained only by exposing corroded tendons. However, because corroded wires are likely to fracture, it is very hard to determine the effective tendon area which can be guaranteed to show fully ductile behaviors (Figure 8). To overcome these limitations, experimental works about the behaviors of corroded wires are required extensively and thus, proper method or guideline to estimate the effective tendon area can be proposed.

CONCLUTIONS

A brief description of the deterioration of bonded post-tensioned concrete bridges and research topics on the strength evaluation in ISARC. In addition, load test results of post-tensioned concrete beams with corroded tendons are presented also. Because of the uncertainty of the condition of tendons, strength evaluation of deteriorated post-tensioned concrete bridges is very complicated task for structural engineers. Within these limitations, reliable strength evaluation method or consensus guidelines for post-tensioned concrete bridges with corroded tendons should be developed and ISARC will be helpful to perform this task and to cooperate with foreign research teams.

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Table 1 Material properties of test specimens

Materials	Properties
Concrete	28 days compressive strength fck = 31.0 MPa
Reinforcing bar	D13, yield strength fy = 400 MPa
Prestress tendon	SWPC7B diameter ϕ12.7mm Ultimate tensile load = 18,700kgf load assumed at 0.2% permanent elongation = 15,900kgf

Table 2 Ultimate flexural strength of test specimens

Test specimen	Test parameters		Initial prestress (0.7 f_{pu} =100%)	Ultimate load (kN)	Ultimate flexural strength (kN．m)	
					Tests	Calculated
PC-1	**prestress loss**	**0.95** f_{pu}	**5%**	**67.5**	**45.56**	**44.63**
PC-4		**0.3** f_{pu}	**78%**	**82.5**	**55.68**	**51.48**
C-1	**loss of tendon area**	**1.0** A_p	**0%**	**46.0**	**31.05**	**24.88**
PC-2		**0.1** A_p	**60%**	**66.1**	**44.55**	**48.36 (43.75*)**
PC-3		**0.3** A_p	**76%**	**58.9**	**39.76**	**46.304 (37.14**)**

Note: * calculated value with the assumption of 30% loss of tendon area
** calculated value with the assumption of 60% loss of tendon area

(a)

(b)

(c)

(d)

(e)

Figure 1 View of deterioration of concrete bridge deck

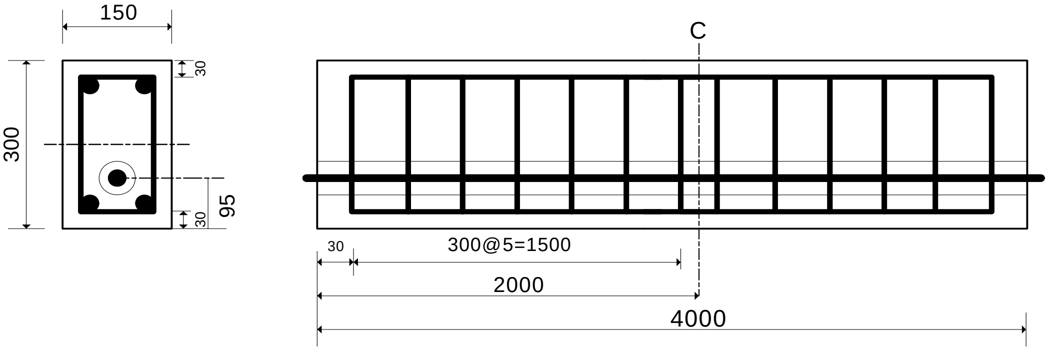
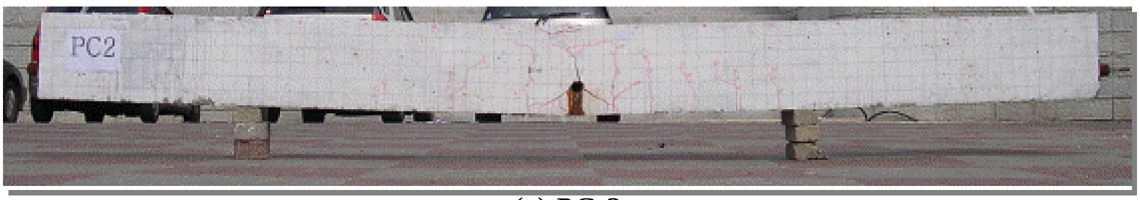


Figure 2 Details of post-tensioned concrete beam

(a) PC-2 (b) PC-3

Figure 3 View of corroded wires before static load tests



(a) PC-2

(b) PC-3

Figure 4 View of tested beams of PC-2 and PC-3

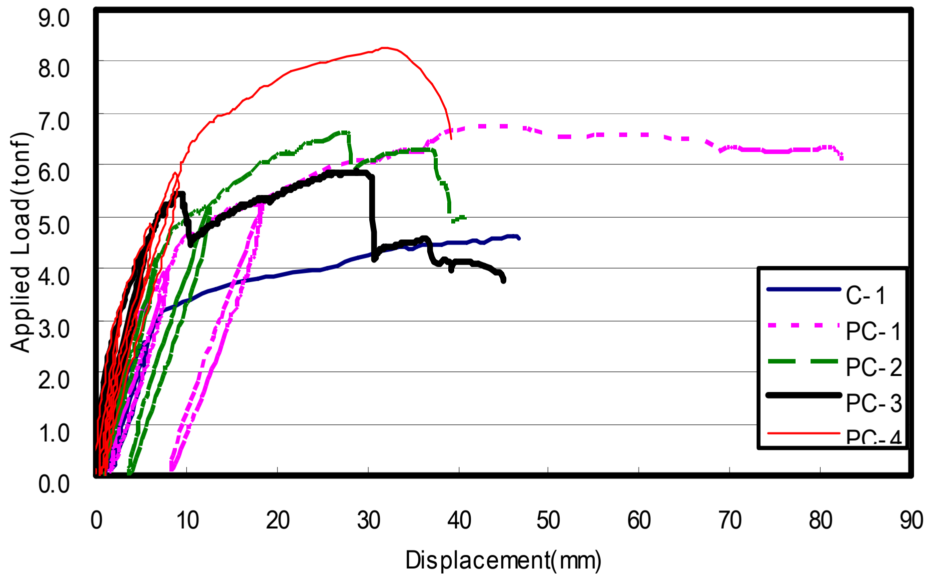


Figure 5 Relationship between load and deflection of test beams

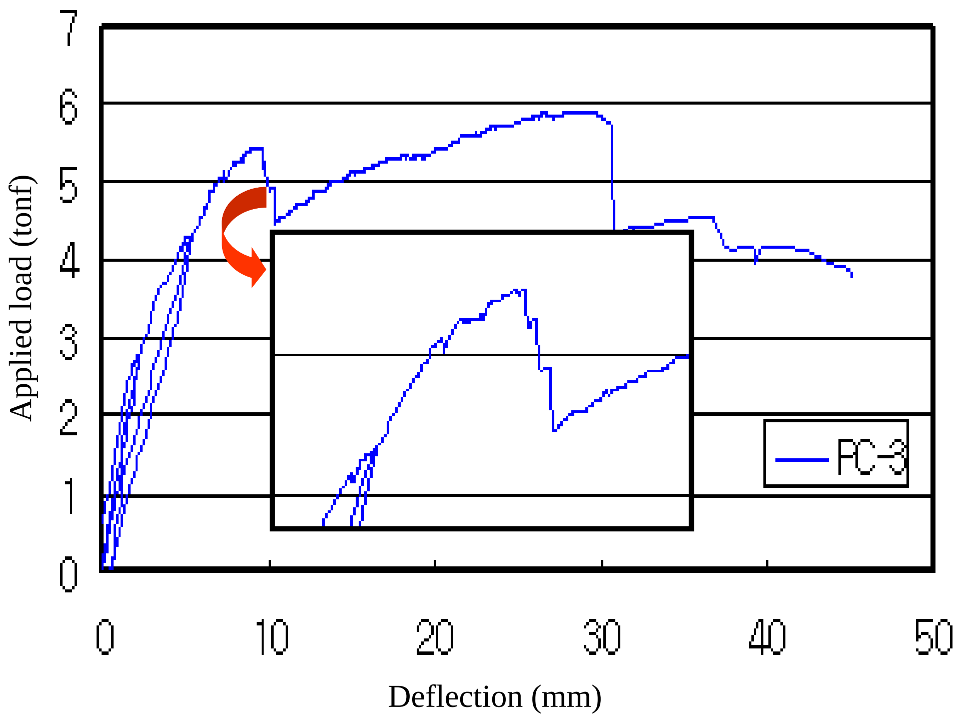


Figure 6 Close view of the load-deflection curve for PC-3

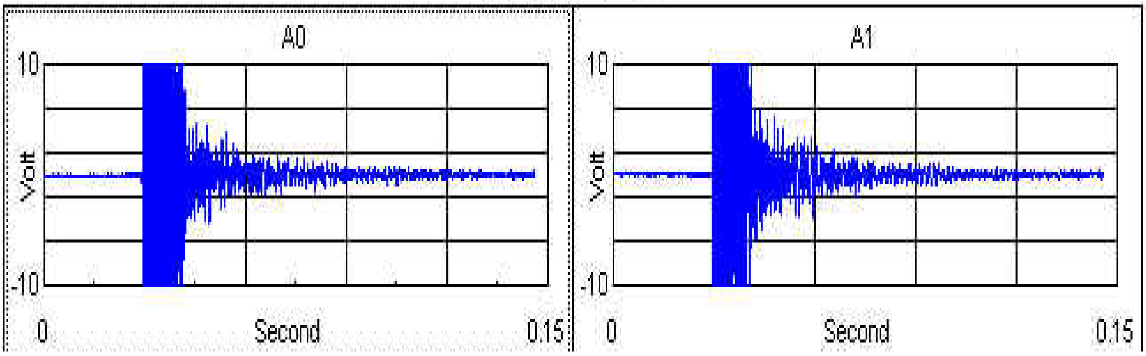


Figure 7 Acoustic signals at the first wire fracture in PC-3

(a) PC-2 (b) PC-3

Figure 8 View of corroded wires after static tests