SHM
Structural Health Monitoring

Fracture Monitoring System of Sewer Pipe with Composite Fracture Sensors Via the Internet

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Sewer pipeline breaks were reported after severe earthquakes like the great Hanshin-Awaji earthquake in 1995. Although sewer pipeline breakage is not an emergent problem, they may cause epidemic disasters if left unrepaired. However, it is extremely expensive to find damaged parts and very time consuming to visually inspect all sewer pipelines laid underground. This demands a low-cost fracture monitoring system for sewer pipelines. The present study proposes a new fracture monitoring system for sewer pipelines and explains its demonstration using a small sewer pipe. The fracture monitoring system adopts fracture sensors made of fabric glass and carbon black–epoxy composite materials; a small embeddable terminal is included that can be connected to the Internet. In the sensor, a carbon black sheet is sandwiched between a surface layer and a base layer: both are made from fabric glass–epoxy plies. A part of the glass fibre in the surface layer is cut perpendicular to the loading direction to make a crack starter. Direct current electric voltage is charged in the embedded carbon black sheet; then, an electric resistance is connected serially to the carbon black sheet. Electric voltage of the resistance is monitored using the embeddable tiny terminal through the Internet. When the fracture sensor is loaded, large deflection causes a crack in the crack starter; then, the crack breaks the carbon black layer. This causes electric disconnection, and electric voltage of the resistance drops to zero. This system is applied to a fracture monitoring of a sewer pipe. As a result, the system successfully monitored fracture through the Internet.

Keywords sewer pipe · fracture · monitor · composites · Internet · carbon black

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1 Introduction

Structural health monitoring is a notable technology to reduce maintenance costs for civil structures such as bridges, highways, gas pipelines, water pipelines and sewer pipelines. The structural health monitoring system comprises attached/embedded sensors and diagnostic systems. The system diagnoses integrity of target structures a short time after structural damage. Recently, structural health monitoring systems have been applied to many kinds of civil structures [1–12]. In a severe seismic disaster, multiple collapses or damage to buildings, bridges, tunnels, gas pipes, and water and sewer pipes would be reported at the same time; these faults would have to be repaired within a few days. Such inspection and restoration tasks are very difficult after severe earthquakes because most transportation facilities are also damaged or congested for evacuation. Even medium-sized earthquakes require very high expense of rapid visual inspection for entire structures.

Many researchers have proposed fibre-optic sensing for such structural health monitoring systems of civil structures [1,2,8,11]. Fibre optic sensors collect strain information of the target structure. Usually, the fibre optic sensor offers capability to collect strain information from multiple points using only a single fibre placed on a target structure from a long distance. The fibre optic sensor is also very robust against electro-magnetic noise. On the other hand, the fibre optic sensor has no redundancy. The fibre optic sensor looses its sensing function through breakage at a single point; the information that we can measure using the fibre optic sensor is limited to target structure strain and temperature.

A new approach for structural health monitoring using the Internet was proposed recently [9,12]. In this Internet system, the number of kinds of available sensors is unlimited; we can install conventional non-distributed sensors as distributed sensors by simply connecting these sensors to the Internet. The sensor network can be classified into sub-networks, so the system has high redundancy matching an existing PC network. Such advantages are very attractive for an actual structural health monitoring system. However, it requires a PC with a network card or a data logger having the Ethernet connector; such a device is too large and cumbersome for actual structural health monitoring. This causes a demand of development of an embeddable tiny terminal that is a bridge between conventional sensors and the Internet.

Sewer pipes are not severely damaged even by large earthquakes because sewer pipelines are usually laid underground. However, sewer pipelines have many junctions and manholes. These are points of structural discontinuity: most damage is reported at these discontinuity points [13]. Restoring damaged sewer pipelines is not urgent work, but neglecting damage may cause epidemic disasters. Visual inspection of entire sewer pipelines requires an extremely high cost and a long time. These factors demand development of a low-cost fracture-sensing system of sewer pipes for detecting damage within short time. Recently, optical fibre cables for the Internet are installed in sewage pipes in many Japanese cities; electric power is available in main sewer lines. This makes it possible to monitor sewer pipeline fractures using the Internet. Even without Internet resources, wireless LAN systems are appropriate for this objective if electric power is available.

A new tiny embeddable Internet terminal is developed in the present study; the terminal is then tested in various environments. It offers high reliability because it has no mechanical moving parts. Next, a new fracture sensor is developed using a carbon black composite sheet and fabric glass/epoxy layers. Using the tiny terminal and fracture sensors, a new monitoring system is proposed that enables monitoring of large deformation of a sewer pipe. The system is demonstrated for monitoring a small model sewer pipe.

2 Monitoring System

2.1 Schematic Image of the System

Figure 1 is a schematic image of a proposed new monitoring system. The proposed system comprises fracture sensors made from composites, tiny Internet terminals and the Internet. Composite fracture sensors are attached to target sewer

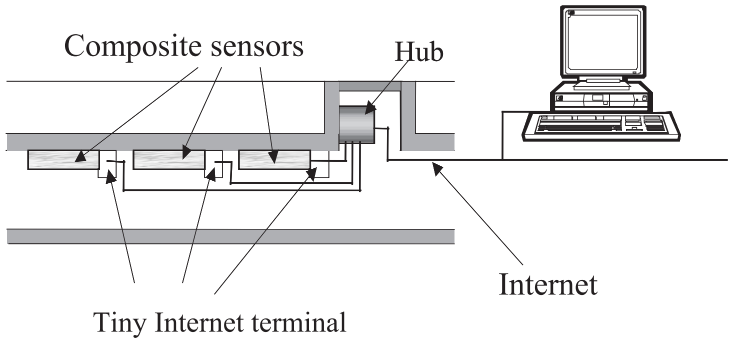


Figure 1 Schematic image of monitoring system.

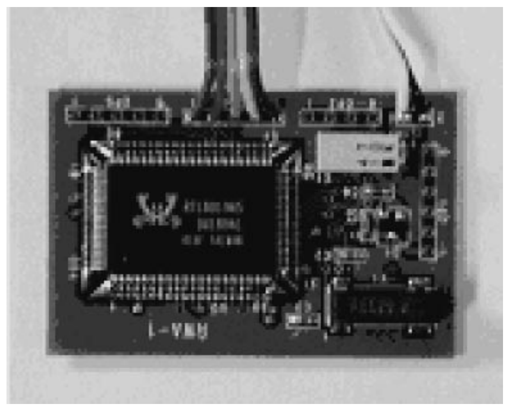


Figure 2 Configuration of developed tiny Internet terminal.

components. Sensors are connected to tiny Internet terminals; then, the terminals are embedded in composite sensors. The tiny terminals are connected to the Internet. A typical sewer pipe is a reinforced-concrete pipe with ductile steel rods; the pipe deforms severely before it fractures. Composite sensors have the ability to detect such severe sewage pipe deformation. Large deformation is monitored through the Internet using the tiny terminal. In fact, the terminal is very tiny and can be embedded into composite sensors. Electric power and Internet cables are available for main sewer pipes in many cities in Japan in the near future. Of course, wireless Ethernet systems can be applicable if conventional wired Ethernet is unavailable.

2.2 Tiny Internet Terminal

The terminal detects electric voltage output change with an analog/digital converter (A/D converter); it then sends fracture information using Web server through the Internet. The terminal has four A/D converter channels, so it detects four points in components. All IC parts are installed in a small double-side-mounted circuit board of $37 \times 47\,\mathrm{mm}^2$. This is a very small circuit board that can be embedded in composite structures. Figure 2 shows a photo image of the terminal. The terminal comprises a PIC IC numbered 16F877 and an Ethernet IC. This system has a 10-base-T connector. The system is connected to the Ethernet using this connector. When the terminal receives an access through the Ethernet to the Web port, 4-channel data of the A/D converters are sent using HTTP protocol. The converted measured data can be monitored through the Internet web as shown in Figure 3. The four figures listed in the rectangular table represent measured electric voltage results of 4 A/D converter channels. The figures show measured voltages from 0 to 5 V as integers

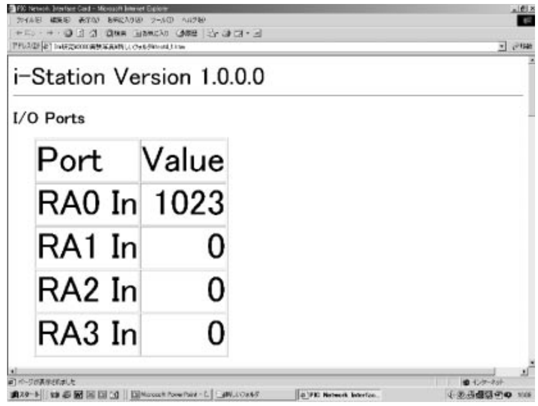


Figure 3 Display window of the measured results.

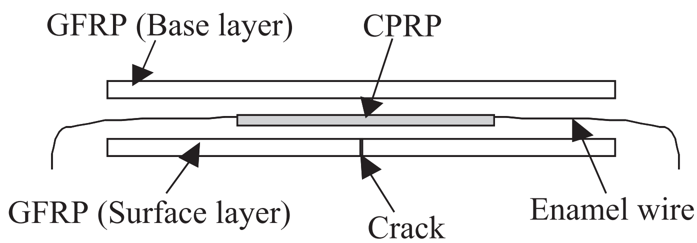


Figure 4 Schematic image of a fracture sensor.

between 0 and 1023. This means that the measured 3 V is shown as an integer of 613.

The terminal has high reliability because it has no mechanical parts. Moreover, since terminals are inexpensive, multiple terminals could be used for monitoring important components for system robustness. Some self-check functions could be installed for a production version of the terminal. Here, the terminal is trial version so such self-check functions are not installed.

2.3 Fracture Sensors Made from Composites

A fracture sensor made from composites developed here converts large deformation of a monitored sewer pipe into electric voltage change. This is an on–off type sensor. The fracture sensor comprises several layers, as shown in Figure 4.

Outer layers are all covered with electric insulator layers made from fabric glass–epoxy composites. A sheet of electric conductive carbon black composites is embedded inside the sensor. A base layer is adopted to maintain sufficient stiffness of the sensor. The base layer is attached to a sewer pipeline component. A surface layer is used as a crack starter to break electric conductivity of the middle carbon black sheet when the sensor deforms largely. All glass fibres perpendicular to the loading direction are cut at one place like a notch before curing, then mounted on the carbon black layer. Although the fibre-cut region is a slit, like a crack, before curing, epoxy resin fills the fibre-cut crack after layers are co-cured. This insulates the middle carbon black layer electrically from outside.

Surface layer glass fibres are cut like a slit and epoxy resin has very low strength; therefore, this component can be fractured easily with applied load. Fracture easily produces a crack and penetrates into the carbon black layer. Since strength of the carbon black layer is also very low, the crack grows towards the base layer and electric conductivity of the carbon black sheet is lost. Since the base layer has intact glass fibres, the crack stops at the interface between the base layer and the carbon black sheet.

Usually, sewer pipelines comprise of a concrete matrix and ductile steel rods. Many cracks are made in the concrete matrix when sewer pipelines are loaded, but ductile steel rods deform plastically. Sewer pipeline breakage follows, causing large residual deformation of sewer pipelines. If fracture sensors are mounted on sewer pipelines, large deformation causes fracture of surface layers of sensors. Consequently, disconnection of the carbon black sheet occurs. Electrical disconnection of the carbon black sheet due to crack growth remains after unloading due to large plastic deformation even after a severe earthquake. Therefore, we can detect large deformation after the earthquake.

Degradation due to chemical and environmental factors is identical to that of glass–epoxy composites because outer layers comprise glass–epoxy composites. We can obtain sufficient resistance by applying a chemically resistant resin like vinyl ester if more resistance against chemical factors such as acids is required.

Stress is not applied to the sensor when sensors are mounted on sewer pipelines. Therefore, this sensor is free from stress corrosion cracking. If sensors and terminals are perfectly embedded into glass–epoxy composites, fracture error signals will not occur due to fracture of these components except for malfunctions of the terminal.

3 Demonstration of a Tiny Internet Terminal

In actual monitored structures, the developed tiny terminal is embedded in fabric glass–epoxy composites to protect them from water and wastes flowing in sewage. Two types of tests under the modelled practical circumstances were performed to confirm utility of the tiny terminal in actual circumstances. Figure 5 shows the embedded tiny terminal in fabric glass–epoxy composites. Two types of tests performed here as demonstrations are as follows.

(a) Long-term test: The embedded tiny terminal was activated for a week; operation of the tiny terminal was checked with a PC connected through the Ethernet. Surface temperature was measured with a thermocouple at the same time.

(b) Operating temperature limit test: The embedded tiny terminal was connected to a PC through the Ethernet; this terminal was inserted into a chamber of an electric heating furnace. Temperature of the tiny terminal was increased from 30 to 100°C in 10°C steps in the chamber. A charge of 5 V was charged to one channel of the A/D converter. A PC prepared outside of the furnace through the Ethernet monitored output voltage.

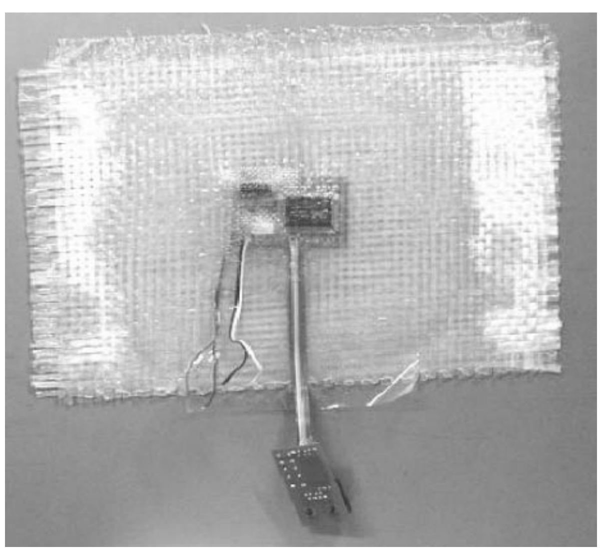


Figure 5 Embedded tiny terminal in glass–epoxy composites.

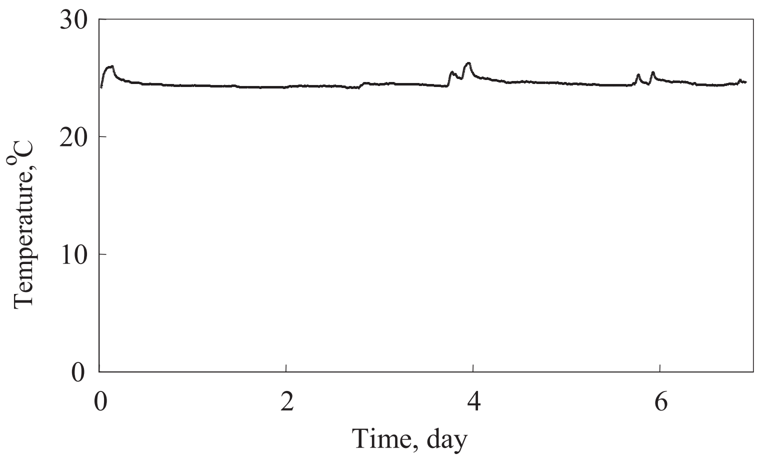


Figure 6 Surface temperature of the tiny terminal.

Figure 6 shows the measured temperature change for a week. In the figure, the abscissa is time (days), and the ordinate is measured temperature (Celsius) with a thermocouple. This figure shows that it has almost constant temperature for a week. Temperature of the terminal is kept constant even if it is embedded in fabric glass–epoxy composites because the tiny terminal has no moving parts.

In the operating temperature limit test, the tiny terminal operated exactly even at 100°C. This seemed sufficient for operation in a normal sewer. To check maximum operating temperature, the terminal was tested at 105°C; it did not operate at that temperature. This may be caused by poor connections at soldered joints at high temperature or by an error of IC at high temperature. Actual use would require that the tiny terminal be under 100°C.

These experimental results confirmed the tiny terminal to be applicable for fracture monitoring of sewer pipelines if embedded into fabric glass–epoxy composites.

4 Demonstration of Composite Fracture Sensors

4.1 Specimens and Experimental Method

First of all, we present a process method for fracture sensors shown in Figure 4. Mixing epoxy resin of room temperature curing and carbon black powder produced a carbon black sheet of 20% volume fraction. Mixed composite materials are pressed to obtain a thin sheet of 1-mm thickness; it is then cured at room temperature. An electric conductive sheet of 40-mm length is fabricated from the thin carbon black sheet.

A base layer is made from commercially available fabric glass–epoxy composites by stacking four prepreg plies. The carbon black sheet is placed on the middle of the base-layer surface. Surface layers of fabric glass–epoxy composites are stacked on the carbon black sheet. Before stacking surface layers, each prepreg sheet of surface layers is cut to half the size of the base layer. The fibre-cut prepreg is placed on the carbon black sheet to cover the entire base-layer surface.

Lay up of the fibre-cut surface layer yields a slit in surface layers. This fibre-cut slit is used as a crack starter to grow a crack into the carbon black sheet. Two electrodes made from copper foil of 200-μm thickness are mounted on the carbon black sheet; then lead wires are soldered to those electrodes. These layers are sandwiched with two aluminium plates. Then, they are cured under the condition of 130°C × 1.5 h in an electric heating furnace. Rectangular specimens of 1.5 mm × 20 mm × 110 mm are fabricated from the cured plate.

The specimen is mounted on an aluminium plate of 2 mm × 25 mm × 170 mm using four

M2-size bolts (see Figure 7) to simulate the situation of mounting the fracture sensor on target sewer structures. The specimen is then bent with 4-point bending jigs of 20 mm inner diameter and 160 mm outer diameter. Then, we perform a displacement control test: test speed is 1 mm/min. We record loading point displacement; we measure specimen strain on the base-layer surface using a conventional strain gage in each test.

Electric resistance of 120 Ω is serially connected to the lead wire connected to the carbon sheet. Electric voltage of 1.5 V is charged to the circuit comprising that resistance and the carbon sheet. Electric voltage charged to the electric resistance is measured as shown in Figure 8. The serially connected electric resistance of 120 Ω is used to obtain 0 V when the carbon sheet is broken.

In practical application, several types of fracture sensors for detection of fracture are required at different deformation levels. This control of fracture strain is performed by means of changing slit depth of surface layers in the present study. Let us assume that a crack starter slit in a surface layer is a crack even though it is filled with epoxy resin. This assumption makes it possible to obtain different types of sensors that break at different deformation levels by means of changing surface layer thickness (changing crack length). Thick surface layers mean that the specimen has a long initial crack. This is inferred to have small fracture strain. Four types of surface layers are tested here to confirm this. The four types have one, two, three and four plies as surface layers, respectively. Four-point bending

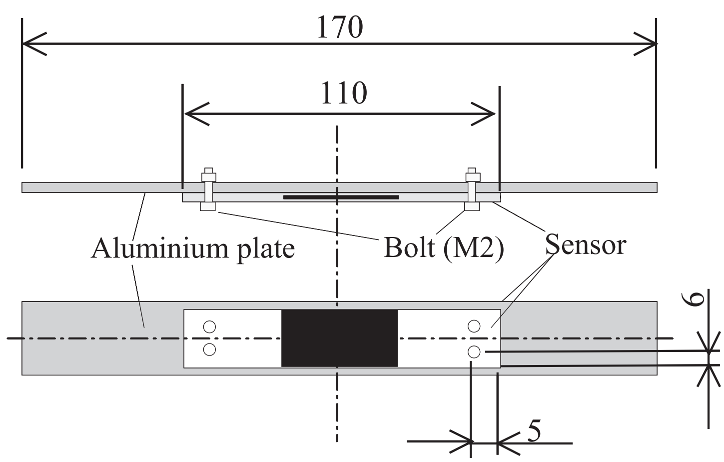


Figure 7 Composite sensor with aluminium plate for 4-point bending test.

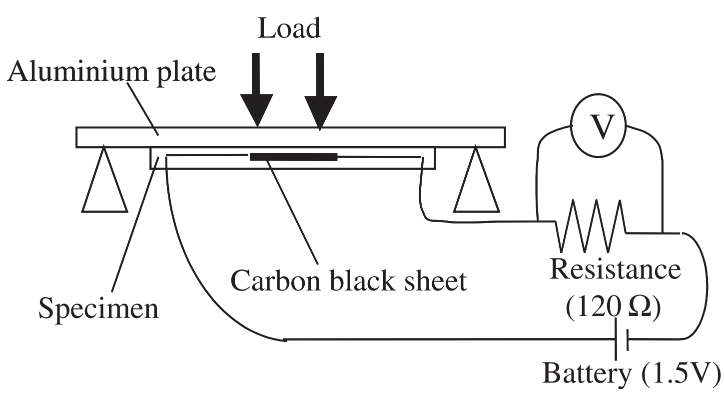


Figure 8 Experimental setup.

tests are performed and fracture strains are measured using these specimens.

4.2 Results and Discussion

Typical measured results of the four types of specimens (one–four plies) are shown in Figure 9(a)–(d). The abscissa is loading point displacement. The ordinate is measured strain of the specimen surface of the base layer and measured voltage of electric resistance of 120 Ω. The thin solid curves show applied strain; thick solid curves show measured voltage data. Each initial voltage value before fracture differs because each specimen has different initial electric resistance. In Figure 9(a), showing a one-ply surface layer, a crack originates from the crack starter of the fibre-cut layer at approximately 4.5 mm displacement; it grows into a carbon black sheet. Loading decreases with crack growth. The crack breaks the electric current in the carbon black sheet; simultaneously, measured voltage drops to zero. Measured load does not drop to zero. This is because the base layer has still integrity and stiffness. Similarly, in all specimen types, measured electric voltage drops to zero after crack generation. Observed images of all types of specimens of side surfaces are shown in Figure 10(a)–(d). As Figure 10 shows, perfect bonding between the surface layer and the carbon black sheet is observed in all specimen types. This indicates that electric voltage drop is caused by crack growth from the crack starter.

The relationship between measured fracture strain and surface-layer thickness is plotted in Figure 11. In this figure, the abscissa is a logarithmic plot of measured surface-layer thickness; the ordinate is a logarithmic plot of measured strain at fracture. All solid symbols show measured results for all specimen types. As mentioned before, we consider surface-layer thickness as crack length (*a*), even though the

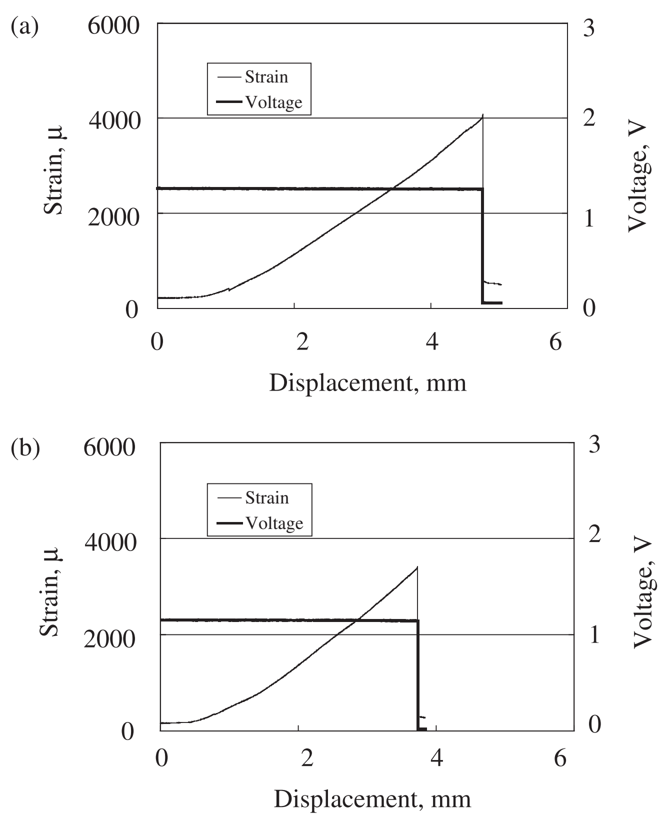


Figure 9 Experimental results of 4-point bending test: (a) Number of surface plies is 1; (b) number of surface plies is 2; (c) number of surface plies is 3; and (d) number of surface plies is 4.

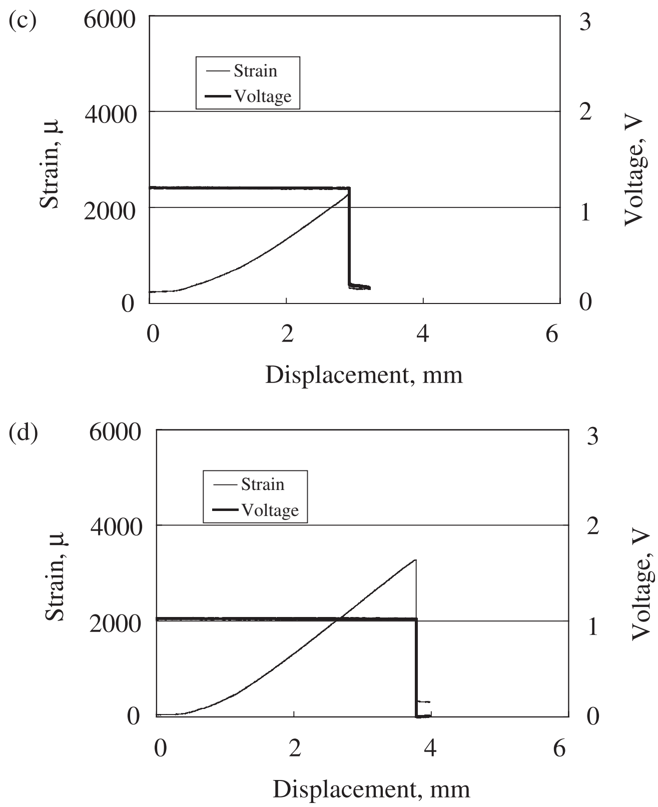


Figure 9 Continued.

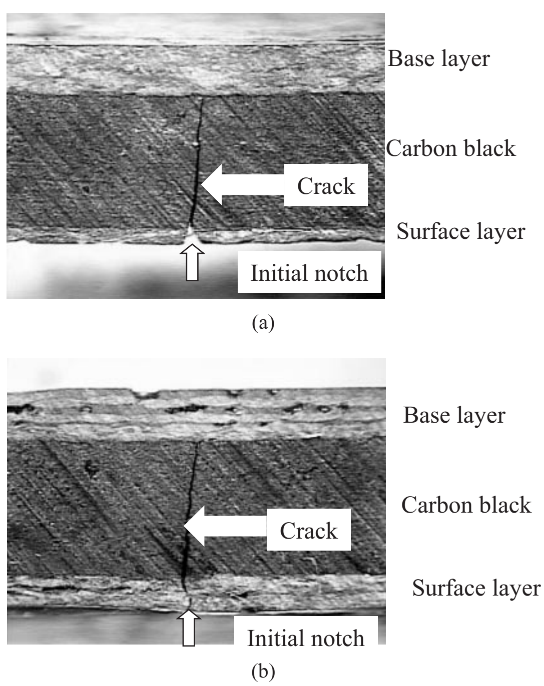
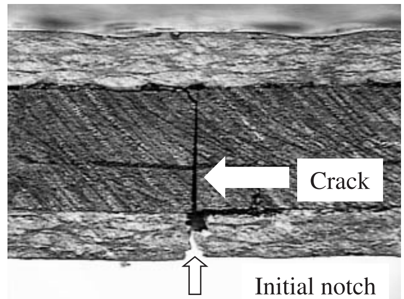
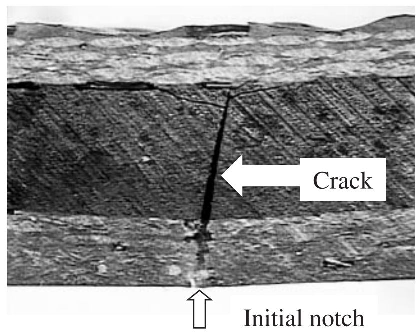


Figure 10 Cracks in composite sensors: (a) Number of surface plies is 1; (b) number of surface plies is 2; (c) number of surface plies is 3; (d) number of surface plies is 4.



(c)



(d)

Figure 10 Continued.

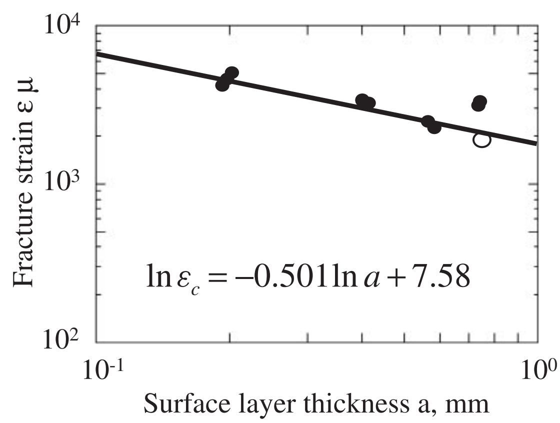


Figure 11 Relationship between fracture strain and surface thickness.

fibre-cut slit is filled with epoxy resin. Fracture strain ε_c can be estimated from the relation between applied stress σ and a stress intensity factor $K = \sigma\sqrt{\pi a}$ as

$$\varepsilon_c \propto \frac{1}{\sqrt{a}} \tag{1}$$

This means that inclination of the double logarithmic scale plots must equal −0.5. The solid line in Figure 11 shows results for the regressed line except for results of four plies. Inclination is −0.501; results show that fracture strain can be controlled through change of surface-layer thickness.

Results of fracture strain of four plies, however, show higher fracture strains than the predicted value. Additional experiments were performed to investigate the reason. A bending test of the specimen with a four-ply surface layer was performed, but the test was terminated at predicted fracture strain level of 1500 μ before fracture. After that, the specimen was unloaded and cut to investigate the internal damage. We observed debonding between the base layer and the carbon black sheet as shown in Figure 12. This debonding is inferred to have caused stress redistribution, and it is inferred to have caused higher fracture strain than the predicted value.

Base layer thickness is four plies. With an increased number of plies of the surface layer, the neutral axis of bending stress moves from the base layer to the carbon black sheet. Stress at the interface between the base layer and the carbon black sheet increases with movement of the neutral axis. Since the elastic modulus of the carbon black sheet differs greatly from that of fabric glass–epoxy composites, increased stress at the interface causes increased local shear stress at the interface. Shear stress causes debonding between the base layer and the carbon black sheet with an increased number of surface layers. An additional experiment was performed to confirm this effect. The test used a thicker base-layer specimen with an eight-ply base layer and a four-ply surface layer. Figure 12 shows that result as an open circle symbol. Results show good agreement with the predicted line. This indicates that surface-layer thickness must be less than base-layer thickness to control fracture strain using Equation (1). As predicted by Equation (1), a thicker surface layer is required with increasing base-layer thickness to obtain a smaller fracture surface.

5 Application of Monitoring System

The proposed system is applied to practical sewer-pipe-fracture monitoring as a demonstration. A sewer pipe of steel rod reinforced-concrete (200 mm outer diameter, 170 mm inner diameter, and 400 mm length) is prepared for demonstration. The developed composite fracture sensor and the tiny terminal embedded in fabric glass–epoxy composites are attached inside the sewage pipe as shown in Figure 13. The terminal is connected to a PC through the Ethernet with a 10-base-T cable. In actual fracture of a sewer pipeline, most fracture occurs at discontinuity points as mentioned before. In the present study, however, the sewer pipe bending test is used as a demonstration. The sewer pipe is loaded using a three-point bending test of 300 mm span length as shown in Figure 14. In this test, 5 V is charged to electric resistance instead of 1.5 V.

The pipe initially deforms linearly up to 2 mm of loading point displacement. Through displacement, many cracks were made in the matrix concrete. The sewer pipe fractured gradually due to high toughness of steel rods up to displacement of 25 mm; output voltage of the web indicator showed 0 V after large deformation (loading point displacement = 25 mm).

So far, it is not appropriate to decide a deformation limit of sewer pipes due to lack of experimental data of various types of sewer pipes. The deformation limit for detection could be different for various sewer pipeline system components. However, the proposed method is easy

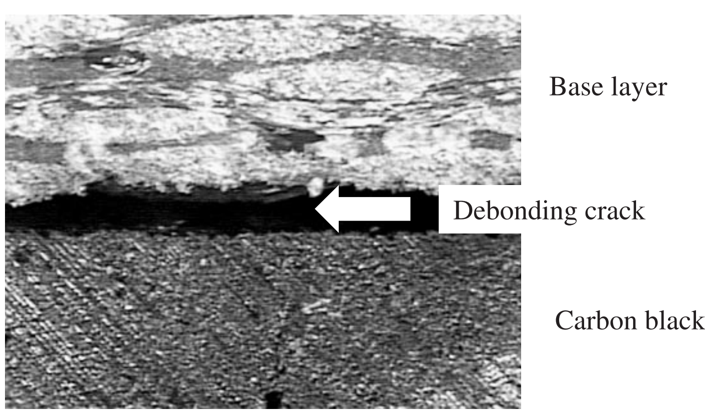


Figure 12 Debonding between carbon sheet and glass composites.

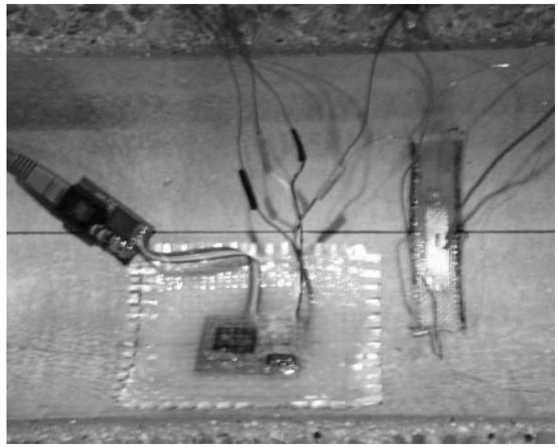


Figure 13 Schematic setup of sensor and connected terminal in sewer pipe.

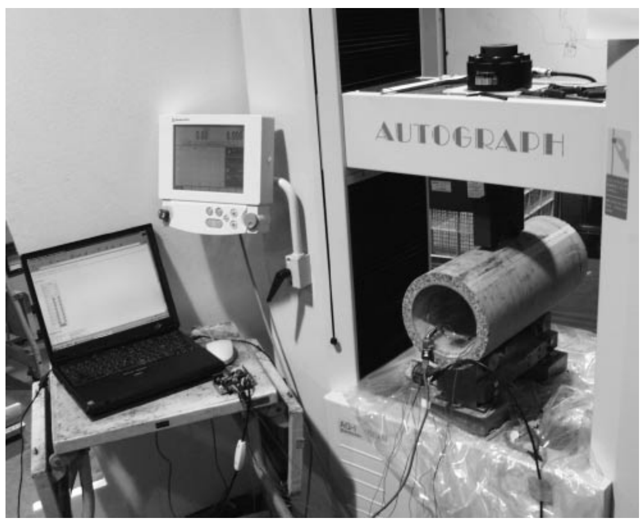


Figure 14 Experimental setup of demonstration test of fracture monitoring of sewer pipe.

to apply because fracture strain of the sensor can be varied to suit different tasks. Sensor size can be changed easily and sensors can be easily connected serially to cover an entire area for even a large sewer pipeline component. Total cost of the present system is low because all parts adopted here are commercially available. Unfortunately, the tiny terminal is only a trial version. We cannot determine the exact cost performance of the system yet. Of course, fracture detection in sewer pipelines comprising myriad components requires further research. The present study indicates that the proposed system has the capability of monitoring fracture at low cost without using expensive instruments.

6 Conclusions

In the present study, a new fracture monitor system after seismic damages using the Internet is proposed for large structural components. The system is applied to a sewer pipe as a demonstration. Obtained results include the following.

1. We proposed a new fracture monitoring system using the Internet: a tiny terminal and a fracture sensor embedded into an electric conductive sheet.
2. The tiny Internet terminal was developed; several demonstration tests showed that the terminal was applicable to actual environment.

3. The fracture sensor was developed using fabric glass–epoxy composites and a carbon black sheet. In the surface layer, the glass fibre was cut to make a crack starter before curing.

4. Fracture strain was shown to be controllable by changing surface-layer thickness. However, the surface layer should be less than the base-layer thickness.

5. The system was demonstrated using a sewer pipe fracture test.

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