STRUCTURAL ANALYSIS AND EVALUATION OF ACTUAL PC BRIDGE USING 950 keV/3.95 MeV X-BAND LINACS*

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Abstract

In Japan, bridges constructed during the strong economic growth era are facing an aging problem and advanced maintenance methods have become strongly required recently. To meet this demand, we develop the on-site inspection system using 950 keV/3.95 MeV X-band (9.3 GHz) linac X-ray sources. These systems can visualize in seconds the inner states of bridges, including cracks of concrete, location and state of tendons (wires) and other imperfections. At the on-site inspections, 950 keV linac exhibited sufficient performance. But, for thicker concrete, it is difficult to visualize the internal state by 950 keV linac. Therefore, we proceeded the installation of 3.95 MeV linac for on-site bridge inspection. In addition, for accurate evaluation, verification on the parallel motion CT technique and FEM analysis are in progress.

BACKGROUND AND OBJECTIVE

In Japan, many concrete bridges are facing aging problems. Potential deteriorations are periodically inspected visually. However, it is necessary to accurately detect imperfection inside concrete for accurate safety assessment. Currently, several inspection methods have been proposed for detecting deterioration of the main cable of the bridge. Transmitted X-ray inspection is one of the effective methods in respect of visualization of internal defects of bridge [1]. So far, low energy X-ray sources, which is up to 300 keV, have been used for on-site concrete structure inspection. However, the applicable thickness of 300 keV X-rays is limited to about 300 mm, and it takes long time to obtain a result even if it can be applied to over 300 mm thickness. Therefore, our research objective is to apply 950 keV/3.95 MeV linac for on-site bridge inspection, which makes it possible to inspect thicker concrete briefly.

Table 1: Parameters of Mobile Linac

Parameter	950 keV Linac	3.95 MeV Linac
RF Source	9.3 GHz Magnetron	9.3 GHz Magnetron
RF Power	300 kW	1.5 MW
Repetition	330 pps	200 pps
Beam Energy	950 keV	3.95 MeV
Electron Gun Voltage	20 kV	20 kV
Pulse Width	2.5 μs	4 μs

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950 keV/3.95 MeV Linac

950 keV and 3.95 MeV Linac parameters are shown in Table 1 [2]. The X-ray energy generated by the mobile linacs have a spectral distribution with maximum energy of 950 keV and 3.95 MeV, respectively. Both mobile linacs are composed of a high-frequency magnetron source and an accelerating tube part. Both are coupled by X-band flexible waveguide and mutual position is variable. Power supply and water cooling chiller are in stationary boxes. These setting ensures linac's portability and flexibility of X-ray irradiation direction. The weight of the 950 keV X-ray source is about 52 kg and magnetron is 45 kg. As for 3.95 MeV X-ray source, the X-ray source is 140 kg and the magnetron is 62 kg. The 950 keV X-ray source is effective for thin concrete which is 200 to 350 mm and X-ray protection chief qualification is required for operation. The 3.95 MeV X-ray source is effective for thicker concrete which is 350 to 740 mm. However, the 3.95 MeV X-ray source require the complex process for operation to follow the Japanese law. Now, we mainly use the 950 keV linac for on-site inspection and installation of 3.95 MeV is now on progress. We will use both linac separately in necessary cases in future.

ON-SITE BRIDGE INSPECTION

We applied our inspection system for on-site bridge inspection. The target bridge was a post-tensioned PC box girder bridge. This bridge aged over 40 years, and it will be dismantled in a few years. The purpose of inspection was detecting the corrosion of tendons which are main cables of bridge and play an important role in maintaining the safety of the bridge by introducing compressive stress to the concrete. The experiments using 950 keV linac were conducted to scan the bottom flange of the bridge. Figure 1 shows schematic view of the experiment. In the experiment, X-ray source was placed inside the box, webs and flanges of which can prevent X-ray from spreading

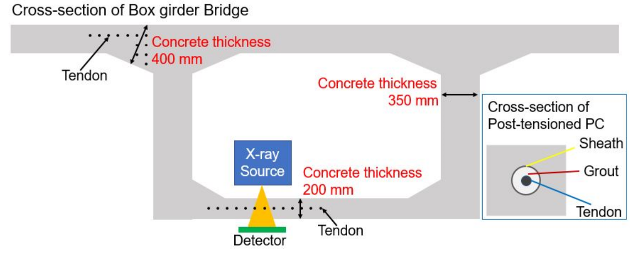

Figure 1: Schematic view of real bridge inspection.

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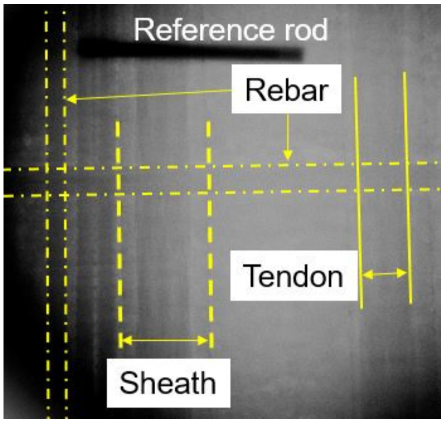

Figure 2: Visualized tendon, sheath and rebars in the bottom flange by X-ray.

Table 2: Assumed Reduction Rate of Cross Sectional Area of Tendon

Reduction rate of cross sectional area	Number of tendons
0 %	14
0 ~ 30 %	5
30 ~ 60 %	1
60 ~ 90 %	1
100 %	1

outside. In the examination, we irradiated X-ray downward and the IP (Imaging plate, made by Fuji Film) was placed on the opposite side of X-ray source. The linac was operated at a beam current of 120 mA and a repetition was 300 pps.

Figure 2 is one of the results in this experiment, and the tendons, sheaths and rebars were successfully visualized by X-ray. As a result, we succeeded in clearly imaging the internal concrete structure, and then assumed the reduced section areas as shown in Table 2 [3].

In general, the thicknesses of concrete to be inspected are often over 400 mm: for instance, web concrete is about 300 mm, connection of web and flange is about 400 mm in this experiment. It is considered difficult to obtain clear results on top flange by 950 keV X-ray source because of the thickness of the concrete. From this consideration, it is necessary to introduce 3.95 MeV linac for a wider range of on-site bridge inspection.

BENCHMARK EXPERIMENT OF 3.95 MeV LINAC

To confirm the feasibility of 3.95 MeV linac for on-site inspection, benchmark test is required by radiation regulatory body. In March 2017, we conducted the benchmark experiment at PWRI (Public Works Research Institute in Japan). In this experiment, the sectional part of a hollow slab cut from an actual bridge was examined by 3.95 MeV in the experimental field. Figure 3 shows the cut-out sample. The picture also shows three examination lines and inspection points in this examination. Point 1 line (P1) has approximately 400 mm, point 2 has 700 mm and point 3 has 800 mm thickness of concrete. Figure 4 shows

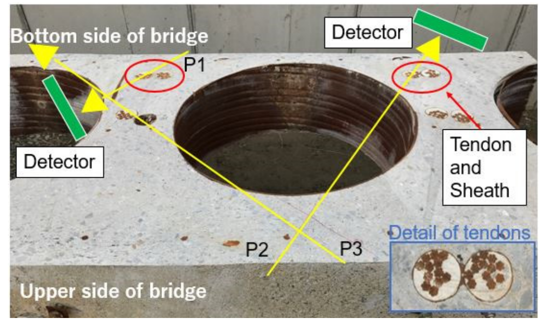

Figure 3: Cut-out sample and inspection points.

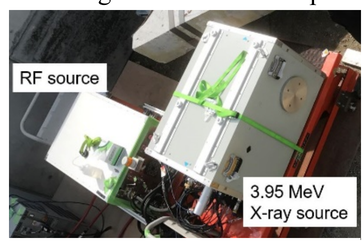

Figure 4: 3.95 MeV Linac.

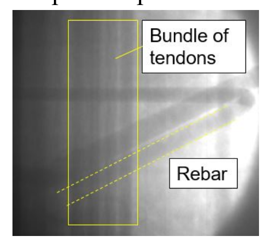

Figure 5: The result of P1.

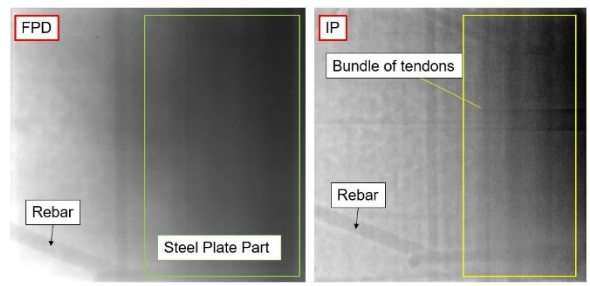

Figure 6: The inspection result of P2.

the 3.95 MeV X-ray source. In this experiment, 3.95 MeV linac was operated at a beam current of 100 mA and a repetition was 200 pps.

For point 1, a FPD (Flat panel detector, XRD1622 made by Perkin Elmer) was placed in a hollow of the bridge. As a result of inspection, the bundle of tendons and some rebars are visualized in 5 seconds (Fig. 5).

As for point 2 line where X-ray should penetrate the thicker concrete part, we used FPD and IP as detectors. At this inspection point, X-ray crosses two steel plates until the detector. Figure 6 shows the results given by FPD (left side) and IP (right side), respectively. In the result of FPD, several rebars are visualized, but the right part of this figure is blurred due to the steel plate. The integration time of FPD was 20 seconds. In the IP result, in addition to rebar, bundle of tendons is slightly visualized in 1 minute integration time.

On the point 3 line, the internal structure was not clearly visualized. From these result, it is considered that the 3.95 MeV X-ray source is applicable to concrete up to 700 mm thick. However, if obstacle such as steel plate of hollow slabs is included, a long integration time is required for detector to visualize the internal structure.

From this result, however, safety of X-ray inspection executed in the field was confirmed, which enables the permission from the regulatory authority to conduct on-site bridge inspection by 3.95 MeV X-ray source.

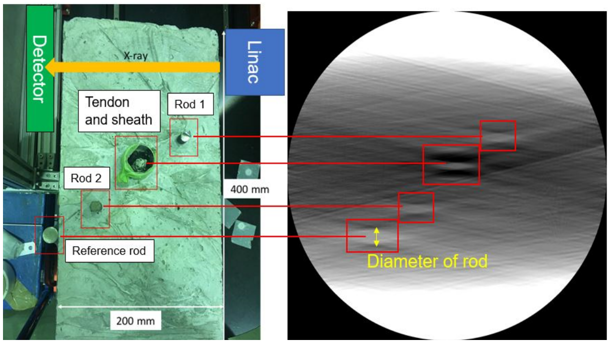

Figure 7: Target sample and reconstructed image.

ANALYSIS AND EVALUATION PROCESS

Parallel Motion CT

For evaluation of tendon's corrosion, cross-sectional image is highly required and CT reconstruction technique may open up the possibility to obtain the sectional image. However, it is not practical or impossible to conduct 360 degree rotated CT because rotation is limited. Therefore, we intend to apply the parallel motion CT which can reconstruct the cross-sectional image without rotating the X-ray source and detector [4]. Demonstration of parallel motion CT was conducted by R. Yano, and 950 keV linac was used to radiate X-ray as a cone beam with an angle of 30 degree. In this experiment, target concrete sample has 2 iron rods and a tendon located in the sheath. The thickness of concrete is 200 mm. Figure 7 shows the image reconstructed by parallel motion CT. Due to the limited angle geometry, reconstruction artifacts arise especially in beam direction. However, positional relationship and the diameter are reconstructed. This parallel motion CT technique requires only translational movement and does not need to rotate the X-ray source. Thus, the parallel motion CT is much promising for on-site bridge inspection.

Structural Analysis using FEM

Evaluation of cross-sectional reduction of tendon is estimated by the result of X-ray Inspection. This deterioration has a significant influence on the structural safety of the bridge. Therefore, by conducting the structural analysis using finite element method (FEM), the residual bearing capacity of the entire bridge is evaluated from the result of the X-ray inspection. Calculation software named DuCOM-COM3 is used for the FEM program [5]. Figure 8 shows the example of FEM model of bridge. In this software, physical properties of concrete are entered in 3-D meshes and tendon's physical properties and diameter are inputted in 2-D element. Figure 9 shows the strain distribution calculated by the FEM analysis where the physical parameters and boundary condition were properly considered on the basis of on-site inspection result listed in Table 2. The stress and strain distribution on cross section was calculated, confirming 60 μ increase of strain at the bottom part. Through this analysis, the decrease of tendon's sectional area much affect the bearing capacity and X-ray inspection can contribute to structural safety evaluation.

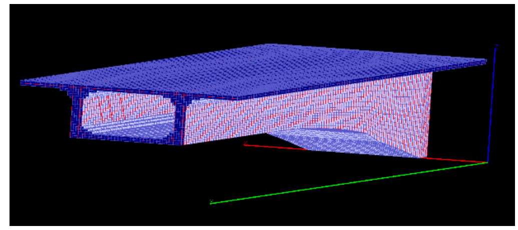

Figure 8: The mesh model of FEM.

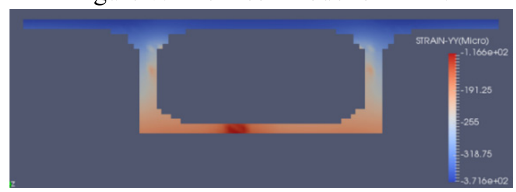

Figure 9: The example of strain distribution analysis.

CONCLUSION

We succeeded in visualizing the internal structure of bridge in on-site inspection using 950 keV linac. For thick concrete inspection, we conducted the benchmark experiment of 3.95 MeV linac. The 3.95 MeV linac succeeded in visualization of internal structure of 700 mm thickness of concrete and it can be applied for on-site bridge inspection in this year. As a post processing of X-ray inspection result, parallel motion CT exhibits high reconstruction performance. It was also suggested that this reconstruction method can be applied to bridge inspection by scanning the bridge using parallel motion stage. It is possible to perform FEM analysis using the result of X-ray inspection and contribute to the safety evaluation of entire bridge.

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