論 文 の 内 容 の 要 旨

論文題目　Development of in Situ Quantitative Bridge Inspection System with Portable 950keV/3.95MeV Linac X-ray Sources
(950keV/3.95MeV可搬型X線源を用いたその場定量化橋梁検査システム開発)

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1. Introduction

Techniques to inspect inner structure are highly demanded for aging bridges suffering degradation problems due to long years' service. Quantitative NDE system for bridge is under development in this research to realize in situ inspection with portable 950kwV/3.95MeV X-band linac as beam source. The research scope focuses on early prevention of deterioration phenomenon of corrosion or crack in inner steel rebar and wire as well as steel components. Specific inspection methods are proposed for inspection of reinforced steel rebar thinning problem, prestressed steel wire cluster soundness problem and corrosion of steel component problem. The method can provide credible quantitative reference for analysis by the beam bending theory to further verify the mechanical character and degradation performance.

For the RC rebar with diameter around 10~25cm, the thinning is evaluated through X-ray radiography. Since 2~3% thinning rate would be very critical for RC bridge and collapse may be induced under such situation, inspection accuracy of 1~3mm is expected. The RC rebar is single steel rebar and it can be easily confirmed by radiography. The quantitative analysis of rebar diameter reduction can be realized by deducing from prior information or other methods.

PC wire is very difficult to be discriminated clearly from simple radiography image, because more than 10 wires are overlapped in each cluster. Computed tomography (CT) is a very effective solution to provide detail information in sectional slice of object.

Although the diameter of PC wires is around 7mm, PC bridge is much more robust than RC bridge and it can still sustain under thinning rate of 7~10%. Resolution of CT image is expected to be 1mm. Simulation and experiment was carried out to study CT application in PC wire inspection. Because the bridge is large scale structure, it's impossible to acquire the full scanning data. Incomplete and truncated projection would happen during inspection for bridge and such situation would bring about artifacts in the sectional image. Advanced algorithms are studied and compared in this research with both simulation and experimental validation.

For the steel components, corrosion will be distinguished by dual-energy CT analysis. The rusty layer or the rust rate of steel rebar or wire would be verified in the analysis. Relative program was developed and experiment was implemented and discussed.

2. Radiography for RC Structure Inspection

In situ NDE experiment is implemented for RC rebar inspection using radiography imaging. Pillars of a berth pier constructed 40 years ago were detected in field by 950keV Linac and Imaging Plate (IP) of FUJIFILM. According to the transmission image, the inner steel rebar can be confirmed and the diameter is deduced based on reference sample and prior information. Totally 3 positions was inspected and the general reduction rate of cross-section area is estimated to be around 7%~14.5%. Based on the inspection result, comprehensive evaluation is assessed by mechanical analysis. Final maintenance plan was established that the structure is still robust and only water proof is necessary in several fixed positions. Consequently, instead of preliminary estimates to repair the whole structure, budget is saved substantially.

For realization of quantitative evaluation on general case that prior information is inaccessible, one solution is proposed with analyzing radiography images at different geometry. For example, 3mm diameter rod inside 40mm thickness polyethylene material is irradiated in test experiment. The distance between source and detector varies from 100mm to 40mm. Analyzing the diameter in these two images, the real diameter can be calculated and the error is just 3.2667%. The accuracy could be further improved by rising image resolution, enhancing boundary in the image by tomosynthesis and so on.

3. Computed Tomography for PC Structure Inspection

Similar field work of NDE experiment for PC structure was conducted. Based on this experience, computer tomography is proposed focusing on degradation part.

Sectional images can be reconstructed with projection data obtained to detect interior details. Further structural analysis is possible to estimate the mechanical characters of bridge with 3D model built from CT sectional images. A small concrete sample is test with 950keV Lianc and analysis is successfully realized including sectional image reconstruction, 3D modeling and mechanical analysis. The system is further improved by collimator to suppress scattered X-ray noise.

With consideration of partial projection conditions, possible solution is proposed based on relative simulation and experiment work. Artifacts caused by incomplete projection problem of limited angle range or sparse view can be reduced by Simultaneous Algebraic Reconstruction Technique with Total Vibration (SART-TV) algorithm. Furthermore, truncated projection data can still reconstruct region of interest effectively with Differentiated Back Projection with Hilbert Transform (DBPH) algorithm.

4. Dual-energy CT Analysis for Corrosion Evaluation

Assessment of steel components corrosion can be estimated through deducing material components of atomic number and density from dual-energy CT analysis. CT image denotes how strongly the media attenuates beam light. For specific material, attenuation coefficient is determined under given spectral source and detector characteristics. In other words, mass density ρ and atomic number Z of absorber can be deduced with attenuation coefficient under different energy level. Simulation was calculated by developed program using the sample of concrete including one steel rod with erosion coating with thickness of half its radius. The estimation process uses standard data table provided by NIST to get the relationship with material attenuation ability and energy level. Two artificial energy spectrums of low and high energy level and detector efficiency is simulated by EGS5 program based on the model, which adopts 3.95MeV X-ray linac as beam source, and line sensor with thin detector and thick detector sensitive for low and high transmittance respectively. Results are estimated from CT images to give the atomic number Z and density ρ of media. For steel rod with erosion coating, Fe and Fe2O3 can be identified apparently. The error of Z value is within 0.2-1.3 and error of density is within 0.3g/cm^3.

Relative experiment was done using seriously eroded iron component cut from bridge. Dual-energy condition was created by using iron plate filter or not. Energy spectrums and detector efficiency are simulated by EGS5 program. The estimated atomic number shows large error from the standard value for several reasons. The main reason is the used simulation result is actually different from real data during experiment condition. Besides, the Linac operation was interrupted several times due to

unstable factors, which increases error in CT reconstruction. The scattered X-ray noise also contributes to the error. Moreover, the attenuation ability of Fe and Fe2O3 are too close under the using energy level. In order to solve the above problems, collimator or proper noise reduction software should be adopted to suppress scattered X-ray noise. Other improvement such as compensation algorithm is also considered. Additionally, since it is very difficult to probe accurate information about real spectrum, calibration before estimation is proposed using information by attaching reference sample with known material to the object.

5. Conclusion

The main work of this research is concentrated on in situ quantitative NDE technique development for internal structure of degradation bridge with portable 950keV/3.95MeV Linac X-ray beam source. In situ NDE experiment is successfully implemented for RC rebar inspection using radiography imaging. For realization of quantitative evaluation, methods are proposed with analyzing radiography images and image enhancement by tomosynthesis. In situ NDE experiment for PC structure is also conducted and based on this experience, CT is proposed with consideration of partial projection conditions. Possible solution is proposed based on relative simulation and experiment work. As for corrosion evaluation, program is developed adopting dual-energy analysis with CT image. Experiment method is discussed as well. The mentioned inspection results would provide meaningful information for further evaluations referring to mechanical analysis and civil work criterions.