学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　　博士（工学）　　氏名　苗　鵬勇

学 位 論 文 題 名

Prediction-based maintenance of existing structures considering multi-influential factors
(複数の劣化要因を考慮した予測モデルに基づく既存構造物の維持管理)

Existing structures must be sufficiently managed to balance social, economic, and environmental requirements, and the maintenance of such structures has become a major social concern. Among all the maintenance approaches, prediction-based maintenance is an increasingly popular method to keep the structure sound. Progress has been made in adopting preventive measures, but performing prediction-based maintenance remains challenging because of the following four points: (1) prediction-based maintenance depends heavily on the accurate prediction of deterioration. For existing structures, deterioration is affected by various factors such as chloride, material, and traffic load. However, the relationships between factors and deterioration are neither explicitly determined, nor the relative effect of each factor on deterioration is well understood; (2) cracks are of particular importance for the safety of structures. Although crack images were collected from onsite inspection, quantifying the cracks requires considerable time and effort; (3) in previous inspection, a large amount of inspection information including cracks was collected, but intuitive management of the information is not easy; and (4) a general civil structure is a complicated system, i.e., its deterioration situation, the propagation of cracks, and other damages should be comprehensively considered when performing the prediction-based maintenance.

Four types of bridges (PC, RC, RC-PC hybrid, and steel bridges) were considered in this study among civil structures. Onsite inspection databases for these types of existing bridges collected by engineers during regular inspections include abundant information on structural conditions, thus providing the possibility of using the database for formulating prediction models. The inspection database in this study includes twelve potentially influencing factors and three deterioration grades, grade 1 being the sound situation and grade 3 indicates the requirement of early intervention. In addition, crack images of concrete components were collected from onsite inspection and indoor experiment. These images can be used to build models to quantify cracks effectively.

Firstly, this study explored the feasibility of using the neural network to establish deterioration prediction models. Appropriate neural network architectures can be trained using the inspection database to predict deterioration situations. If the network parameters are appropriately designed, the network would show satisfactory forecasting performance. One of the best-known neural networks is the Multilayer Perceptron (MLP), consisting of an input layer, one or several hidden layers, and an output layer. The Recurrent Neural Network (RNN) is another type of neural network specialized in learning time-related patterns from time-series data. Among the RNNs, Long Short-Term Memory (LSTM) is most widely used, and therefore, was applied in this study.

Testing the MLP and LSTM models on an inspection database of 3,368 bridges indicated that the LSTM model achieved the accuracy of exceeding 80 %, i.e., outperformed the MLP model of 65 %. For four types of bridges, the LSTM showed the equivalent performance. In addition, the prediction ability of the LSTM for bridges in coastal regions was slightly superior to those outside of coastal regions. The LSTM showed no significant differences in accuracy between different deck areas.

Secondly, the Shapely value method and the Sobol indices method were applied to the LSTM to determine the contribution of each factor on deterioration by calculating the relative importance of each factor. The analysis preliminarily determined the five most important factors affecting the deterioration. They were years in service, traffic volume, deck area, chloride, and lowest temperature. In addition, the analysis revealed that the structure type was another significant reason to induce deterioration. The results also showed significant differences in deterioration between coastal and non-coastal regions, which were caused by airborne salt.

Thirdly, a commonly used probabilistic method-Markov Chain (MC), was proposed using the aforementioned inspection database. Then, the MC model was compared with LSTM in terms of bridge degradation path. Specifically, the MC and the LSTM models were compared from four aspects: the mean deterioration paths, the deterioration paths of different types of bridges, the deterioration path of a specific bridge, and the influence of each factor on deterioration paths.

The results indicated no significant differences between these two models, except that the LSTM usually predicts deterioration occurring two years earlier than the MC. Both the MC and LSTM models predicted that the PC and steel bridges were more durable than RC and RC-PC hybrid bridges. The factors affecting the deterioration path were the same as those found by the Shapely value and the Sobol indices methods.

Fourthly, the onsite and indoor collected images were employed to a Convolutional Neural Network (CNN) and a developed application for crack detection and quantification. Specifically, four commonly used CNNs were tested, and GoogLeNet was determined for this study. Then, the transfer learning and fully training of GoogLeNet were further tested on the testing dataset and a public dataset.

The results showed that the transfer learning GoogLeNet has relatively balanced performances on these two datasets, with an accuracy of 96.69 % and 88.39 %, respectively. A new sliding window technique (neighborhood scanning) was proposed and almost equivalent to the previous dual scanning method. A method for calculating crack widths was presented. The average relative error of this method was 14.58 % (0.05 mm), i.e., much smaller than the previous method having 36.37 % (i.e., 0.14 mm) error. An application was then developed to integrate the proposed methods and other techniques (such as edge detectors, boundary tracking, and threshold segmentation) to segment, quantify, and analyze cracks. Verifications on 23 untrained raw images (eleven with 10240 × 2048 pixels, twelve with 2592 × 4608 pixels) showed that: (1) the developed crack identification model and a previous pixel-level segmentation model required an average of 9.48 s and 10.35 s; and (2) these two models showed an 80.40 % and a 78.64 % average Intersection over Union (IoU). Therefore, the proposed crack identification model is a cost-effective solution for detecting and analyzing cracks on concrete surfaces.

Lastly, Building Information Modeling (BIM) was studied for five bridges as examples to integrate the deterioration prediction models and the crack identification model to form a collaborated BIM platform. In this platform, the crack identification model extracted the crack pixels and located them to the corresponding components; the deterioration prediction model determined the deterioration situations and reasons. This platform can intuitively visualize each component's crack damage, can determine the remaining life of each bridge, and can analyze external factors affecting the deterioration. In conclusion, this platform can act as a supplementary tool to help the engineer comprehensively evaluate the bridges' situations and formulate corresponding intervention strategies.