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Data-driven vision-based inspection for reinforced concrete beams and slabs: Quantitative damage and load estimation

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ABSTRACT

We show that computer-vision-based inspection can relate surface observations to quantitative damage and load level estimates in common reinforced concrete beams and slabs subjected to monotonic loading. This work is related to an earlier study focused on shear-critical beams and slabs (i.e., specimens lacking shear reinforcement), but here an expanded image database has been assembled to include specimens with both flexural and shear reinforcement such as would be found in practice. Using this expanded data set, a supervised machine learning algorithm builds cross-validated predictive models capable of estimating internal loads (i.e., shear and moment) and damage levels based on surface crack pattern images. The expanded data set contains a total of 127 specimens and 862 images captured in past studies across a range of load and damage levels. Textural and geometric attributes of surface crack patterns were used for feature engineering and tuning of predictive models. The expanded data set enables comparison of the estimation accuracy for shear-critical and shear-reinforced beams and slabs considered separately and in combined form. This includes the capability to categorize whether shear reinforcement is present or not. Estimation models based on surface observations for shear-reinforced elements are found to be comparable to those for shear-critical beams and slabs, with variability observed due to loading type range, member geometries, whether categorization is combined with regression, and the image feature sets used.

1. Introduction and motivation

Infrastructure inspection is an important task in various contexts, including structural condition monitoring, post-disaster damage assessment, and commissioning of new systems. The outcomes of such inspections include decisions regarding repairing or replacing damaged systems, predicting remaining useful life, evacuating building occupants, or opening new facilities to full public use. Research focused on augmenting existing inspection procedures with computer-vision-based tools has been underway in different contexts for many years. The work in this paper is part of series of studies focused specifically on characterizing the feasibility of quantitative estimation of load and damage levels based on images of surface crack patterns—that is, determining the degree to which computer vision techniques can successfully relate surface observations to quantitative load level estimates in structural components.

For any image-based method of this type to work, there must be visible (but not necessarily unique) correlations between observed behavior and the underlying mechanics of the structural systems in question. This is similar to the expectation for any instrumented system, be it an accelerometer on a bridge or a strain gauge on a beam. For cracks in concrete beams and slabs subjected to standard loadings, the characteristic crack patterns observed under increasing load are indeed reflective of the stresses and strains induced in the system, with apparent distinctions between, for example, shear and flexural failures, and with clear correlations between load levels and degree of cracking. The existence of such qualitative correlations between mechanical behavior and observable damage leads to the possibility this could be extended to the level of quantitative correlation using computer vision technology. As in any data-driven evaluation approach with major empirical components, sufficiently comprehensive data sets would be needed to bracket the parameter ranges arising in targeted applications, and extrapolation beyond the targeted applications would not be viable. Similarly, correlation accuracy and reliability could be improved by including additional structural information beyond that which could be measured directly in situ. Within these limitations, the results presented in this paper demonstrate that potentially useful quantitative correlations exist between crack pattern images and load and damage

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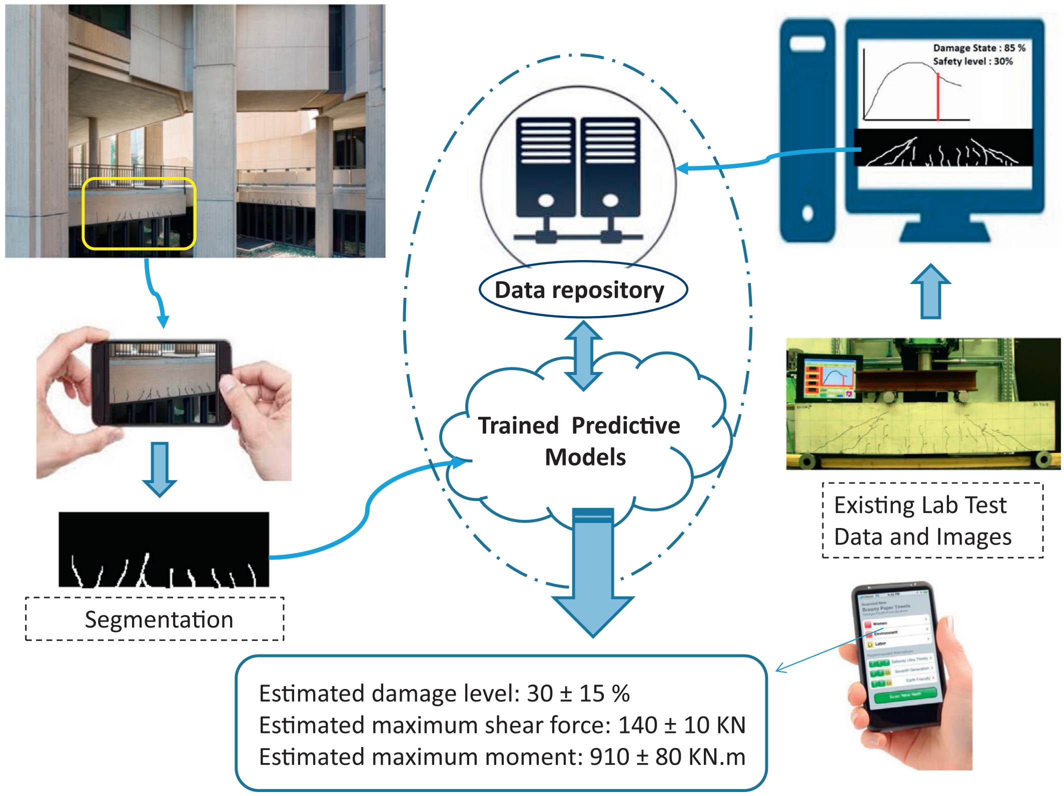

Fig. 1. Conceptual image-based inspection framework. Existing laboratory tests are used to train an estimation model that correlates the surface image of the structure to known load and damage levels. The predictive model could then in principle be used in field applications such that captured photos could lead to statistical damage estimates.

levels for monotonically-loaded, simply-supported beams and one-way slabs.

Fig. 1 illustrates conceptually how such capabilities potentially could be used in a typical field inspection scenario requiring damage and condition assessment. For the conceptual application shown, a cellphone is used to capture an image of a damaged structural component, and the image is then processed such that the crack pattern is highlighted and extracted (segmented). The segmented crack pattern images are evaluated using a damage estimation model that has been trained and cross-validated on a large data set drawn from experimental studies in which images have been captured at known load levels for similar structural systems or components. The captured image thus could be converted into an estimate of the load or damage level (expressed in terms of percentage capacity and absolute shear and moment values in the figure, including confidence intervals), which could then guide further decision-making. The key question in making such a system functional concerns the degree to which purely external imaging of structural members can be used to make quantitative estimates of the load levels associated with visible damage, and that is the overall context motivating the present work.

This present study adapts the computer-vision-based inspection approach from an earlier study focused on reinforced concrete beams and slabs without shear reinforcement [9], to the case of beams and slabs with standard shear reinforcement. As in the earlier study, the estimation scenario is based on surface crack pattern images such as one would be able to obtain in field applications like the conceptual scenario in Fig. 1. In particular, only externally visible data are assumed available (i.e., quantities like shear reinforcement spacing, concrete compressive strength, etc., are taken as unknown). For the present paper, additional image data sets were collected from seven previously published experimental laboratory studies, which provided an additional 304 crack pattern images captured from 43 RC beams and slab specimens across a range of load and damage levels. These additional data augmented the 558 images from 84 specimens used in the prior study, giving a combined data set suitable for the study of prediction across a wide range of failure modes. As before, the images captured correspond to known load levels (supervised learning) recorded during the testing, and the ultimate capacity of each specimen was also determined during the tests, which makes it possible to correlate image features to load levels, both absolute and relative to ultimate capacity (e.g., current moment over failure moment, M/M_{failure}).

Our previous study [9] demonstrated the basic feasibility of estimating quantitative damage and load levels based on surface image data, and considered fundamental issues arising in the development and evaluation of such models. This included studying the effects of different image standardization techniques and machine learning algorithms on estimation accuracy, identifying appropriate cross-validation approaches consistent with field application scenarios, and developing effective image feature sets. In addition, a suite of error measures was assembled to provide a consistent means for comparing estimation accuracy between different models. The results of this previous study have thus guided the present work in terms of selection of algorithms, image feature sets, image standardization, cross-validation techniques, and error assessment metrics.

The inclusion of shear reinforcement in beams and slabs results in flexural-shear and flexural failure modes, which gives rise to different crack patterns than those observed in shear critical cases. It is thus necessary to develop additional trained and calibrated models for data sets containing these classes of failures, but the overall framework is similar to that used before: images are transformed into a standard format based on uniform-width, segmented binary crack images; geometric image features are extracted for each image and fed into a machine learning process combining systematic identification of training and testing sets to support cross validation; and the estimation accuracy