The Reliability of Model-Based NDT in Civil Engineering Using Vibration-Based Inspection Method Including Models Coupling Quality

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Abstract. The estimation of the probability of detection (POD) of certain damage in a structure by means of non-destructive testing is usually based on the statistical evaluation of experiments with a large number of test specimens. In civil engineering this approach is usually rather impractical due to the uniqueness and size of the considered systems. Therefore it is suggested to replace the large number of physical tests by numerical simulations what leads to the so-called model-assisted probability (MAPOD) of detection approach.

To identify global damage in civil engineering structures, the application of vibration-based methods has become popular in recent years. Several damage detection methods that are based on vibration measurements were developed in previous years. In this contribution the POD of damage in a civil engineering structure by means of vibration measurements is considered.

Vibration tests using different levels of damage severity as well as a variety of test setups, excitations and response measurements are simulated numerically. An important issue in this context is an appropriate modelling of the damage to be detected, such that the simulated signals are representative for signals that would be measured on a physical structure. The damage indicator applied here is related to the energy of the signal that is derived from structure response. The quality of the results is influenced by several aspects including the coupling of the different stages of analysis.

From the results the influence of the considered parts of the methodology is estimated such that an assessment of both the parts of the analyses and the global result is possible in terms of the POD.The contribution demonstrates the capability of combining numerical simulations and the methodologies to determine a POD for a certain damage that were developed for non-destructive testing. This implies also uncertainties and challenges. However, in situations where a large test series cannot be performed, such as for most civil engineering structures, the proposed methodology is a sensible approach.

Future work will be related to different kinds and locations of structural damage and alternative approaches for the evaluation of the probability of damage detection (POD).

Introduction

Non-destructive testing (NDT) has been used in different fields and for many purposes. Rummel and Matzkanin **[1]** presented the application of NDT for general industrial process control, general exchange in commerce and for maintenance purposes besides other fields. Recently, NDT has been an attractive subject in civil engineering research and applications. This arises from newly proposed requirements and updated standards to evaluate the quality of different structural properties and determine the continuing service of the structures beyond their lifetime warranty.

The Probability of damage Detection (POD) curves are used to check the reliability of the NDT. The analysis of statistical data to obtain the POD curves in both hit/miss and signal response methods is explained in details by **[2]** and **[3]**. Moreover, in 1999, the U.S Department of Defence published a handbook as inspection guidance for more reliable NDT. The handbook was updated in 2004 and 2009 **[4]**.

The disadvantage of using statistical methods is that calculating reliable POD curves needs a large number of specimens and experiments which can be costly and time consuming. Moreover, in most civil engineering applications such investigations are simply impossible due to the uniqueness of the systems.

The contribution of this work is to develop a model-based strategy with the advantages of the response surface approach to assess the reliability of the vibration-based inspection method in civil engineering structures. The developed method takes in account the quality of transferred damage data between the models. This is important in order to develop a correct objective function for damage detection. Moreover, the results are successfully validated with limited set of experimental data.

2. Methodology

2.1 Sensitivity Analysis

The approach is based on developing a regression model which simplifies the relationship between the response and the physical properties of the studied structure. Sensitivity analysis is performed in order to simplify the regression model by eliminating unnecessary terms. Since the interaction between parameters is considered, the Total-effect index sensitivity analysis which is proposed by **[5]** is used as follows:

$$\mathrm{S_{Ti}} = \frac{\mathrm{E(V(Y|X{\sim}Xi\ ))}}{\mathrm{V(Y)}}$$

The term $\mathrm{E(V(Y|X{\sim}Xi\ ))}$ is the expected amount of variance that would remain unexplained (residual variance) if $\mathrm{X_i}$ and only $\mathrm{X_i}$ was left free to vary over its uncertainty range, assuming all other variables had been determined.

2.2 Model Updating

The results of the sensitivity analysis can be used to select the parameters that require more investigation in order to reduce their variations. There are different methods which can be used for model updating. In this work, Model updating was performed applying Bayes Theorem using the mean values of the measurements at each sensor. As a result, the statistical properties of the estimated parameters can be determined and used later for damage detection.

2.3 Damage Detection

Since the difference between updated model and measurements is not a good indicator for damage if the uncertainty is larger than the influence of damage, a new method is proposed in this work to develop a better indictor. The method is based on the influence of damage on the accuracy of the updated model. If including damage increasing the error in certain sensors then the following objective function should be used for those sensors:

$$\Delta_1 = \sum |y_d - y_{ur}|$$

If damage improves the accuracy then the following objective function should be used

$$\Delta_2 = \sum \frac{1}{|y_d - y_{ur}|}$$

The final objective function is

$$y = \Delta_1 \times \Delta_2$$

where: y_d is damaged structure response
y_{ur} is undamaged structure response estimated from the regression model which explains how the uncertainty and damage influences the response (coupling model).
y is the global damage indicator, Δ_1 is damage indictor for sensor group 1 and Δ_2 is damage indictor for sensor group 2

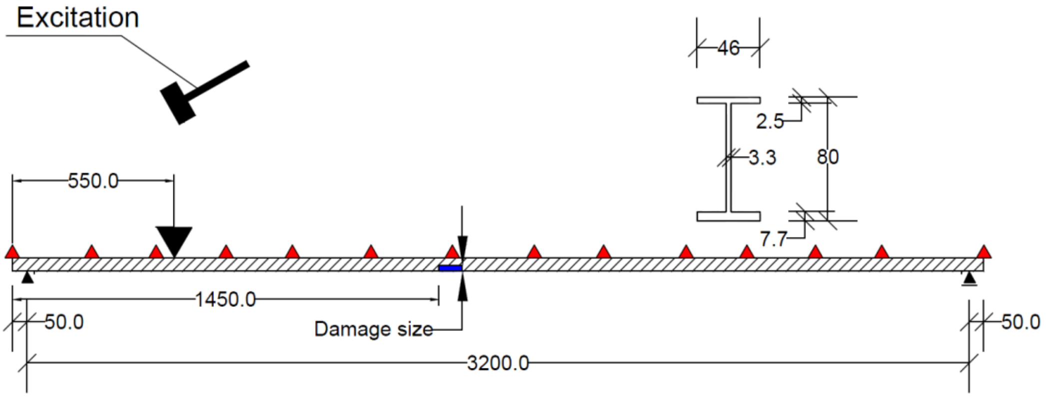
2.3.1 Coupling

By definition, coupling is the process to obtain a final global model by unidirectionally or bidirectionally transferring information within partial models. The coupling here is between the numerical partial model and experimental partial model. The global final model is the indictor y which is used to calculate the POD curves. Two issues qualify the quality of coupling. First, the relation between damage and the response at each considered sensor must be well-posed otherwise the sensor should be excluded. Second, the developed regression model must be able to transfer the behaviour of damage at each sensor correctly including the remained uncertainty. If these two conditions are not fully satisfied, the coupling is bad and damage will not be detected.

3. Numerical Model

3.1 Studied Structure

The vibration-based method is chosen as a non-destructive method to test a simply supported beam. The studied beam has a length of 3300 mm, a cross section of type IPE 80 and typical steel material properties (Pic.1.). The beam is simply supported at two positions which are 50 mm away from each end of the beam. The beam is modelled by using beam elements with 133 nodes. The distance between two nodes is 25 mm. Damage is simulated each time by reducing the thickness of the lower flange in length of 50 mm close to the middle of the beam. Damage variation is considered between 0% and 90% of the thickness of the lower flange.



Pic. 1. Studied example: simply supported beam

3.2 Signal Energy

The energy of the discrete acceleration signal $a(t)$ where $t_1 \leq t \leq t_2$ is calculated as

$$E = \sum_{t1}^{t2} a(t)^2$$

where: E is signal energy, t_1 is time point when the slop of the energy function starts to increase, and t_2 is the time point when the slop of the energy function starts to decrease.

Since it was possible to measure the impulse excitation, the signal energy was normalized with the excitation energy.

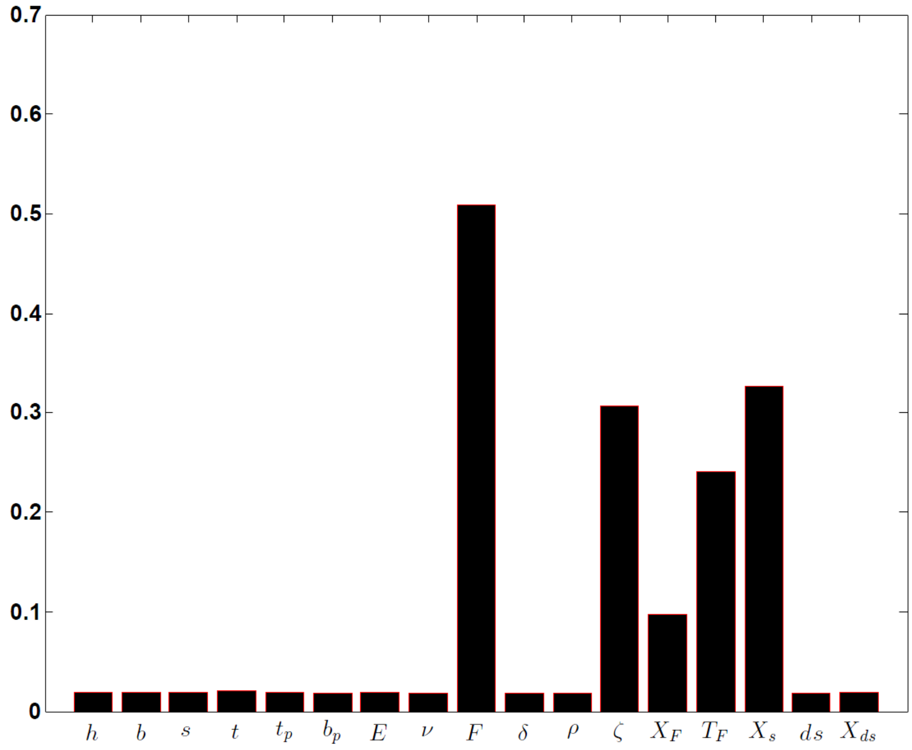
$$E = \sum_{t1}^{t2} a(t)^2 \Big/ \sum_{t1}^{t2} F(t)^2$$

3.3 Sensitivity Analysis

The regression model developed based on 10000 times test simulation was employed to estimate the crucial parameters by using sensitivity analysis. The uncertainties of 17 parameters including geometry, material property, excitation (impulse), and white noise were considered. The results show that only the uncertainty of 5 parameters is strongly influencing the response. They are the amplitude, the duration, and the location of the impulse, damping, and the position sensor (Pic.2.).

3.4 Model Verification

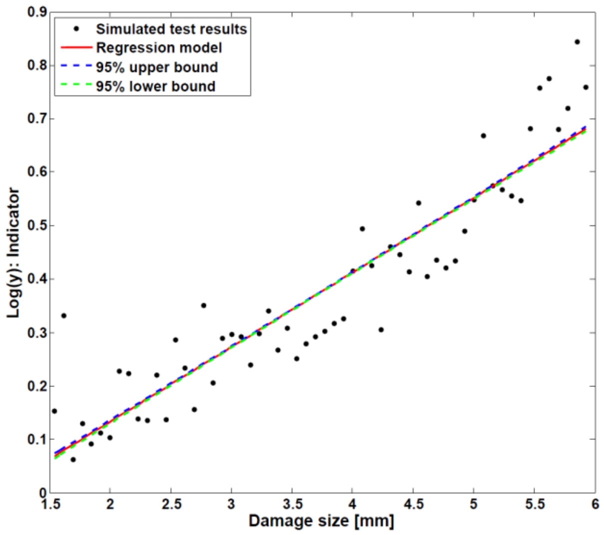
In this level, the regression model was developed using 2000 simulated tests including only the uncertainty of the important parameters. All other parameters were fixed to their initial values and damage considered 0%. The results show that the regression model is able to represent the response of the structure even including damage. The relative error is less than 1% when damage is 0% and almost 2.5% when damage is 90%.



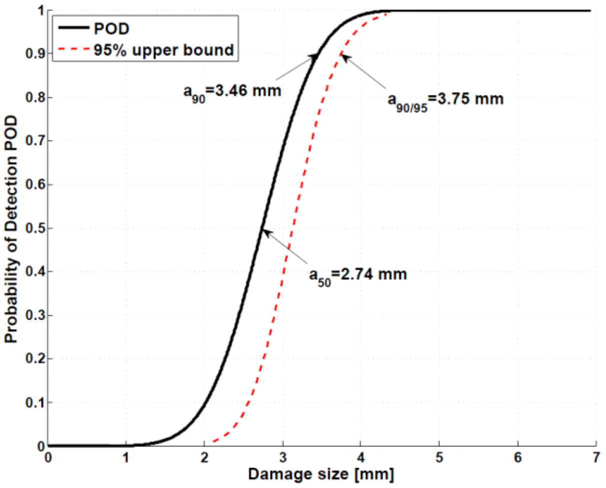
Pic. 2. The results of sensitivity analysis

3.4 Probability of Detection

Since the relation between the damage size and the indicator shows nonlinear behaviour, some of the data at large damage level where the probability of detection is expected to be 100% was excluded to reduce the nonlinearity (Pic.3.). Damage size vs. log(y) was chosen for calculating POD curve. Depending on the noise analysis approach proposed in [4] the threshold value was chosen the 95% upper confidence bound of the noise so the probability of false alarm is 5%. The approach considers that zero slope means there is no relationship between the response and the size of the damage associated with it. It is assumed that noise is normally distributed. Depending on those assumptions POD curve was calculated (Pic.4.).



Pic. 3. Log(y) *vs* damage size showing the indicator scatter and its linear regression model



Pic. 4. POD curve estimating using numerical model of the studied example

4. Experimental Model

4.1 Test Setup

In order to perform a non-destructive test, the beam is backed up with plates of size $150 \times 46 \times 2.5\,\mathrm{mm}^3$). Damage was simulated in the laboratory by removing a plate at the place of damage (Pic.5.). The plate replaced at the beam so the mass of the beam remains constant. 16 accelerometers were used. 10 tests were performed in each system: undamaged and damaged system. A force sensor was used to measure the excitation.

4.2 Model Updating

After calculating the energy of the signals for each test and for each sensor, they are normalized with the energy of the excitation signals. Then the mean value was estimated at each considered sensor. The regression model that was verified by the numerical model was used to estimate the important parameters of the physical test. They are the amplitude and the duration of the impulse and the damping of the system. The position of the excitation and sensor locations are known. The results show that there is about 20% relative error which is too large compared to the influence of damage. However, the behaviour of the response along the beam is represented by the updated model.

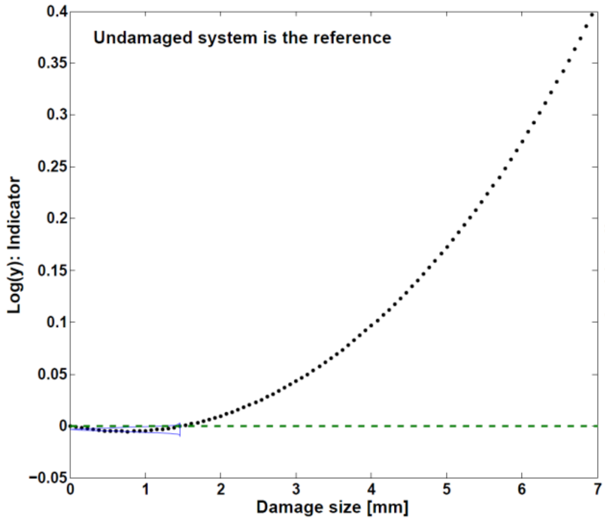
4.3 Probability of Detection

Two set of tests are not enough to build the POD curve. However, these tests can be used as reference data and the data of damaged system can be generated with the regression model which contains the information about damage at each sensor and the remained uncertainty after updating process (coupling model). Before that the agreement between the physical test data and numerical test data should be proved. The agreement is confirmed since the global minimum given by the regression model is inside the noise range when data extracted from undamaged system is used and close to damage size 2.5 mm when data extracted from damaged system is used (Pic.6. and Pic.7.). Therefore, the updated numerical model and experimental data had been used to estimate the POD curves (Pic.8. and Pic.9.). However, the indicator shows nonlinear behaviour and the noise feature is not clear. Therefore, the confidence bounds should be used carefully. The POD curve extracted from damaged system experiments can be normalized to zero damage by subtracting 2.5 mm.

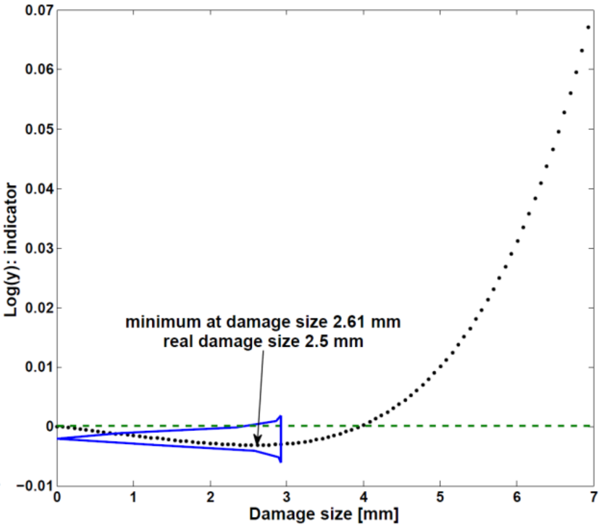
5. Model Validation

Comparing the POD curve extracted from numerical data only and those extracted from the combination of experimental and numerical data (Pic.10.), obviously that numerical model provides more conservative results in this example. Consequently it is reasonable to adapt the numerical POD curve. However, more research is required to choose the best model.

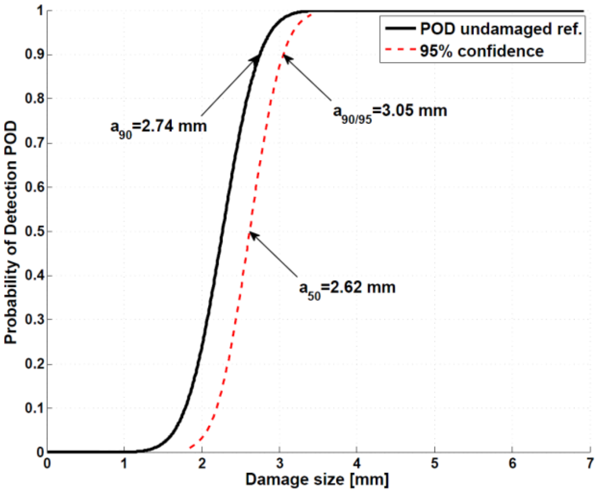
Pic. 5. Physical model showing the deploying of the sensors and damage model



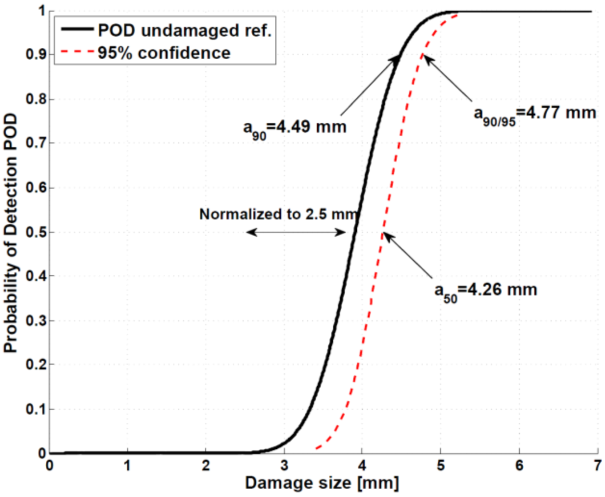
Pic. 6. Log(y) *vs* damage size showing that the minimum value of the indicator is inside the considered noise range when the physical undamaged system is used as a reference



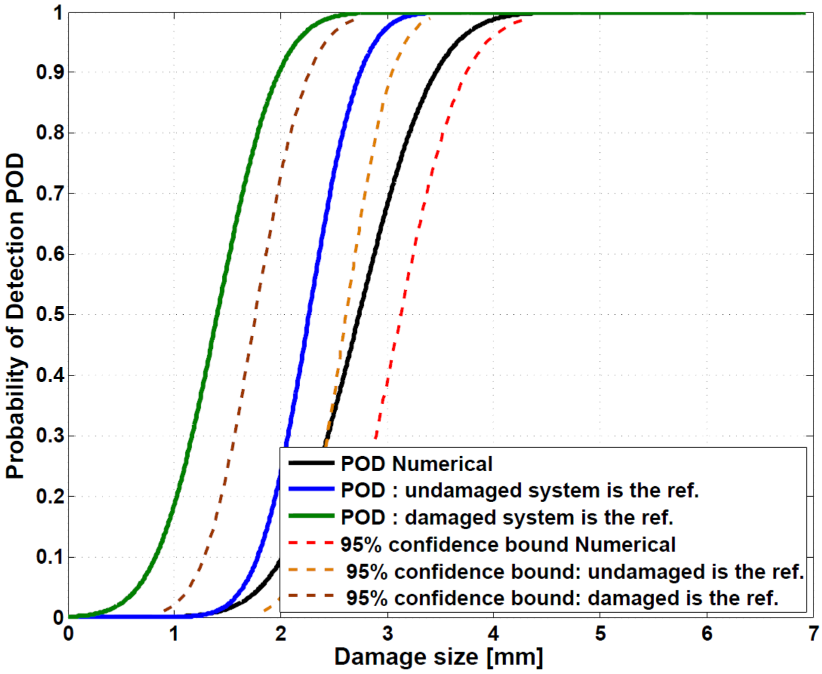
Pic. 7. Log(y) *vs* damage size showing that the minimum value of the indicator is close to the physical damage when the physical damaged system is used as a reference



Pic. 8. POD curve estimating using updated regression model and undamaged system data of the studied example



Pic. 9. POD curve estimating using updated regression model and damaged system data of the studied example



Pic. 10. Comparing POD curves showing that numerical model is providing more conservative results in case of the studied example

6. Conclusion and Outlook

The results show that it is possible to develop POD curves for civil engineering structures using the proposed method and validate them with limited set of experiments. The reliability of the inspection method is influenced by the quality of developed numerical model, the response of each chosen sensor due to damage, the regression model which transfer damage data from the numerical model to build the objective function (coupling quality), the agreement between the results of the numerical model and experimental model, and the quality of the measurements (controlled test)

Future work will be related to different kinds and locations of structural damage and alternative approaches for the evaluation of the probability of damage detection (POD) including the design of the experiments. Moreover, the method will be applied to the reference objects investigated by GRK1462 research group.

References

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[5] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana and S. Tarantola, Global Sensitivity Analysis. The Primer, England: John Wiley & Sons Ltd, 2008.