AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

Issue 39, March 2024

Contents

President Report

Tommy Chan

Professor in Civil Engineering, Queensland University of Technology

Dear All,

In February, the ANSHM Executive Committee had one EC meeting. In the meeting, we identified the importance of setting up the task force to apply for the Industrial Transformation Research Program (ITRP) grant to set up either an Industrial Transformation Training Centre (ITTC) or an Industrial Transformation Research Hub (ITRH) for ANSHM. Then, just in the last two weeks, we had two meetings held for this Task Force.

You may remember that we decided to go for an ITTC in the last Advisory Board Meeting. However, after analysing the data available for the ITTC and ITRH, we find that the success rate for the ITRH proposal is much higher than that for ITTC. Just taking the success rates of the last round of ITDP applications (ITDP 2024) as a comparison, it can be seen that the overall success rate for ITRH is 71.4%, and for ITTC, it is 34.8%.

Basically, both the ITRH and ITTC schemes encourage and support university-based researchers and industry to work together to address a range of priorities to transform Australian Industry. The intended outcome of the ITRP schemes is to increase Australia's research and innovation capacity to generate new knowledge and result in the development of new technologies, products and ideas, the creation of jobs, economic growth, and an enhanced quality of life in Australia. Both ITRH and ITTC provide funding for research on developing solutions relevant to the Industrial Transformation Priorities, and training for Higher Degree by Research (HDR) students and Postdoctoral fellows to benefit the industry partners. As the names imply, ITRH will focus more on research and development projects to create innovative and transformative solutions for industry, while ITTC will focus more on providing training for HDR students and Postdoctoral fellows for industries at developing researchers with capability in end-user research that is vital to Australia's future. In other words, ITRH will also provide training for the industries, and ITTC will also develop solutions relevant to the Industrial Transformation Priorities for the industry.

Having said that, specific requirements for each scheme differ from the other. For ITTC, each centre must fund at least 10 higher degree research students (ICHDRs) and 1 post-doctoral fellow (ICPD) using ARC payment rates, and each ICHDR must complete a placement equivalent to one year full-time with an Industry Partner over the funding period. For ITRH, if any of the Industry Partners has more than 100 employees, the total cash contribution must be at least 75% of the total funding requested from the ARC. Hence although the success rate for ITRH is higher, the total amount of cash contribution from the Industry Partners for an ITRH could also be much higher than that for an ITTC. As an example, if we ask for an amount of $5M from ARC, we should be able to have an amount of $3.75M of total cash contributions from our industry partners.

We consider that it is time to set up an ITRH or ITTC in Australia to support the development, maintenance and enhancement of Australia's building and construction industries through innovative research and technologies in the area of SHM. By monitoring the condition of structures, innovative SHM technologies and approaches will enhance public safety through early alerts of distress to reduce risks of failure and help engineers and asset managers make more informed decisions on scheduling and costs of maintenance and repairs. SHM can prolong the service life of ageing infrastructure and can also pinpoint design flaws in new infrastructure. Hence it will also help decarbonisation by extending the lives of ageing infrastructure and reducing the cases of cradle-to-grave infrastructures and leading to the new generation of cradle-to-cradle smart infrastructure. For infrastructure under construction, SHM methods improve safety and efficiency by verifying and adjusting design predictions during construction (e.g. differential ground settlement, differential axial shortening). SHM can also help verify design assumptions and provide data for future design, including the use of green materials and green technologies.

As discussed above, both the ITRH and ITTC schemes could help achieve the purposes and benefits to the Industry. ITRH and ITTC will provide training for the industry and develop solutions relevant to the Industrial Transformation Priorities for the industry. . The success rate is larger for ITRH, but it requires a larger amount of cash contribution from the industry. Hence, we decided not to make the decision to go for an ITRH or an ITTC yet, but for sure we will apply for the ITDP this year, and the amount of cash contribution that we could have from the industry will be the determining factor for us to decide to go for an ITRH or ITTC. The members from the industry and the universities of the ANSHM Advisory Board and Executive Committee will work together to make it a success. We will start the call for participation soon. We will keep updating you on this plan and we look forward to your participation.

The Honourable Steven Miles, in his speech in early February (Premier's Speech - Homes for Queenslanders - Ministerial Media Statements), 2 months since he became Queensland's new premier, mentioned about Queensland's Big Build, which was announced by QLD Treasurer, Cameron Dick announced in June 2023, confirming it won't be affected by his new government. The Big Build is a capital program for the next four years, forecast to cost $89 billion, which is the largest ever undertaken by a Queensland Government. The Premier considers

"…133,000 people moved here from interstate since 2020. That's the largest movement of people within Australia to Queensland since the 1990s… and since international borders reopened, 115,000 people have moved here from overseas… the biggest movement since ABS records began… All these people need access - not just to housing - but to hospitals, roads, energy infrastructure, transport and schools…Queensland is in the biggest decade of infrastructure delivery in our history – Queensland's Big Build… That's why we're delivering Queensland's Big Build … and it will deliver the largest infrastructure program in Queensland's history.

Once again, it can be seen that the government has no reservations about the investment of Physical Infrastructure, and yet not much in Soft Infrastructure, which I defined as those like training, education, research and development for the effective operation, maintenance and management of the infrastructure. I hope this situation will be changed soon.

Below are the updates for the month.

First Executive Committee Meeting in 2024

Our 1st Executive Committee Meeting in 2024 was held on 6 Feb 2024. Based on the tasks identified during the discussions in the last Advisory Board Meeting (ABM) on 23 November 2023 and the last Annual General Meeting (AGM) on 24 November 2023, we have reviewed and allocated the EC members' roles and duties for the year 2024 as follows.

i) Review of current tasks of EC Members:

- Prof Tommy Chan (President): Tommy will continue to lead and chair the Executive Committee and the Advisory Board to work on the tasks identified during the discussions in the last ABM and the last AGM on 25 November 2023 and plan for ANSHM to achieve the ANSHM Aims and Objectives.

- Prof Jianchun Li of UTS (ANSHM Who's Who): Jianchun will continue working on the Who is Who and research collaborations.

- Dr Andy Nguyen of USQ (External Affair Coordinator and Acting Newsletter Editor): Andy will continue working on the ANSHM external affairs. He would like to create a task force to increase the connection and linkage between academics and industry. He also wants to offer more opportunities for young researchers. He will also be the Acting Editor of ANSHM Newsletter while Mehri is on her special maternal leave.

- Prof Alex Ng of U of Adelaide (Membership Officer): Alex will continue to be ANSHM Membership Officer to look after all the membership matters of ANSHM and based on the membership information applications and other information available, he will create and manage the ANSHM membership database.

- Associate Prof Colin Caprani of Monash U (SHM Specification Development): Colin will continue working with Ulrkie and John on the preparation of the SHM specifications/guidelines. He will also assist Alex in creating and managing the ANSHM membership database.

- Prof Hong Guan of Griffith U (ANSHM Website Manager): Hong will continue to be the ANSHM Website Manager to manage, update and upgrade the ANSHM website upgrade. She will also assist with the organization of a special ANSHM session in EASEC-18 together with Jun and Tommy.

- Mr John Vazey of EngAnalysis (Industry Coordinator): John will continue to work on the role and seek assistance from other academics and industry members to assist him in carrying out the role. He will also work with other EC members to have more members from the industry contribute to the organisation and participate in various ANSHM activities.

- Associate Prof Lei Hou (Web forum & Social Media Coordinator): Lei will lead the organisation of the upcoming ANSHM workshop. He will also continue working on the ANSHM web forum, organize more web forums, and promote ANSHM through Facebook, LinkedIn, and YouTube channels. He will also work with Alex on reviewing the ANSHM Rules on membership matters.

- Prof Jun Li of Curtin U (Newsletter Editor and ANSHM Who's Who): Jun will continue to work on the newsletter management and editing. He will also work with Jianchun for the preparation of ANSHM Who's Who. He will also organise a special ANSHM session in EASEC-18.

- Dr Mehrisadat Makki Alamdari of UNSW (ANSHM Newsletter Editor): When Mehri returns from her special maternal leave in August 2024, she will continue to work on the role together with the other two ANSHM Newsletter Editors, Richard and Jun. She will also work on Technical Notes with Xinqun.

- Prof Richard Yang of UWS (Technical Workshop Coordinator and Newsletter Editor): Richard will continue to be part of the editorial team. He is also happy to organise other training/technical workshops.

- Prof Tuan Ngo of U of Melbourne (Research Collaboration): Tuan will work with the Research Collaborating Task Force committee to promote research collaboration within ANSHM.

- Dr Ulrike Dackermann of UNSW (Workshop Coordinator and SHM Specification Development): Ulrike D will continue to be the workshop coordinator and assist Lei in organising the 16th ANSHM Workshop this year. She will prepare ANSHM Workshop

Sponsorship Guidelines and update the Hosting Guidelines for ANSHM Workshops, and she will also contribute to the ANSHM Specifications.

- Associate Prof Xinqun Zhu of UTS (Technical Note Coordinator and Technical Workshop Coordinator): Xinqun will work on the Special Issue in CSHM together with Jianchun and Tommy, and technical workshops and technical notes.

ii) Allocation of Officers in Charge for New Tasks Identified

- Prof Tommy Chan will be taking the lead of the Task Force on preparing the submission of the ARC Industrial Transformation Research Program Application in the establishment of an ANSHM ARC Industry Transformation Training Centre/Research Hub. The Task Force team consists of:
    - Tommy Chan
    - Tuan Ngo
    - Hung Guan
    - Jianchun Li
    - Alex Ng
    - Jun Li
    - Colin Caprani

- Regarding data collection for SHM Research, as suggested in the AGM, Andy will investigate this topic further and provide an update.

16th ANSHM Workshop

Associate Prof Lei Hou is taking the lead to organise the 16th ANSHM Workshop hosted by RMIT. His first task is to identify the best dates for the workshop to ensure many of us will be available to attend. He has sent a spreadsheet to ask the EC members to indicate their availabilities alerting us about avoiding the key dates of some important events, e.g. EASEC-18 (13-15 Nov 2024), and 1st International Conference on Engineering Structures (ICES2024), which is scheduled on November 8-10, 2024. Besides, the ITRP application was due on 14 Dec 2022 and 29 Nov 2023. As we will apply the ITDP this year, as mentioned above, it would be good to void the workshop to be close to the ITDP submission deadline. Therefore, it would be better if we could have it on or before 20 Nov 2024. Once the EC identified the options for the possible dates, Lei will approach the Advisory Board members to indicate their preferences on the dates.

Core Membership Renewal

Alex sent a message to the Core Members of ANSHM checking if they are interested in renewing their annual Core Membership. Please refer to https://www.anshm.org.au/rules-of-the-association for the details of the role of Core Member. Please respond to his message if you have not done so. Please note that you will still be an ANSHM member representative of your organisation even if you do not renew the Core Membership. For queries on ANSHM membership, please contact Prof Alex Ng (alex.ng@adelaide.edu.au).

Special Issue in Journal of Civil Structural Health Monitoring (CSHM)

As mentioned, we will prepare a special issue in the Journal of Civil Structural Health Monitoring for the papers generated from the 12th to 14th ANSHM Workshop. I am pleased to let you know that our proposal for the special issue has been approved by the Editor-in-Chief of the Journal, Prof Farhad Ansari. Many thanks for the effort of Associate Prof Xinqun Zhu. The journal will be edited by Associate Prof Xinqun Zhu, Prof Jianchun Li and myself. We have received 15 titles for the papers to be included in the special issue and it is expected 10 to 12 papers will be accepted and published in the Journal. Although the papers are by invitation, the publisher requires all special issues to be advertised publicly. Please refer to the link https://link.springer.com/journal/13349/updates/26758416 regarding the details of this special issue.

Submission Guidelines

Submission Status: Open | *Submission deadline:* ***31 October 2024***

All papers must be prepared in accordance with the Instructions for Authors at: https://link.springer.com/journal/13349/submission-guidelines. Articles for this special issue should be submitted via the journal submission system Editorial Manager. During the submission process you will be asked whether you are submitting to a special issue, please select "***Recent Developments in Digital Transformation and Intelligent Infrastructure in Australia for Structural Health Monitoring***" from the dropdown menu.

Please note that although the submission deadline is 31 October 2024, the authors are strongly recommended to submit your paper accordingly when it is ready. The Editor-in-Chief will allocate your paper for us to allocate reviewers. We will invite the relevant experts within ANSHM to review the paper. Please accept the invitation when we invite you to review and many thanks in advance.

ANSHM Website

Our website is maintained by Prof Hong Guan and her assistant, Dr Huizhong Xue. At the moment, the team is working with Alex, our Membership Officer, to modify our online ANSHM membership application form so that more valid information can be collected for the Executive Committee to decide on approving the membership application as well as identifying those ANSHM members who are keen to contribute to the association. They are also exploring how the web entries for membership applications be automatically converted to some database format so that all the application data can be easily stored, maintained and retrieved. They are also continuously updating the site information, e.g. updating the lists for “Current Projects” and “Completed Projects”. Many thanks for the hard work of the team.

ANSHM Symposium at EASEC-18

As mentioned before, we will organise an ANSHM Symposium at the Eighteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-18), 13–15 November 2024 at the Shangri-La Chiang Mai, Thailand, with the topic, Australian Network of Structural Health Monitoring (ANSHM) mini-symposium: Emerging techniques for structural health monitoring of civil infrastructure.
The details of the ANSHM Symposium can be located via the conference website (https://easec18.org/callforsymposia) and the online submission system. If you are interested in submitting a paper for this ANSHM Symposium, please choose the correct symposium as stated above. You can submit your full paper of about 4-6 pages (including references) via https://easec18.org/paperandabstractsubmission. Click the corresponding links for the instructions for full paper submission and the full paper template. Please note that the deadline for Full Paper submission is **15th March 2024**.

In the following sections, we will have two articles from our members. The first article is from QUT researchers introducing a novel Modal Kinetic Energy (MKE) based damage identification procedure, which can be performed robustly either with or without mass variations, making a breakthrough in damage detection as most of the conventional vibration-based damage identification methods assume mass is unchanged between two health states of the structure. The second article is from Curtin

University researchers presenting the development and application of a decision tree-based ensemble technique, an extremely randomised tree (ERT), as a multi-output regression model in structural damage quantification of civil engineering structures.

With kind regards,

Tommy Chan

President, ANSHM

www.ANSHM.org.au

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Research profile | Research publications | Google Scholar citations

Damage Assessment for Truss Structures with Mass Variations using Modal Kinetic Energy

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Abstract

Most of the conventional vibration-based damage identification methods assume mass is unchanged between two health states of the structure. These methods are usually unable to quantify damage accurately in mass change situations. This article presents a novel Modal Kinetic Energy (MKE) based damage identification procedure, which can be performed robustly with or without mass variations. A correlation-based damage identification procedure is proposed with the help of a Genetic Algorithm (GA) optimisation tool after deriving a new sensitivity parameter. The damage extent is then computed using the changes in natural frequency and mass. Finally, a desktop study is conducted on a simply supported two-dimensional truss structure to verify the performance of the proposed approach in locating and quantifying damage under various pre-determined damage conditions in combination with mass change and noise. The results show that the proposed method is competent in locating and quantifying damage in mass change and noisy environments.

Introduction

A well-developed, safe, and reliable infrastructure is the backbone of any healthy nation. While investing in new infrastructure projects, it is equally important to maintain the existing infrastructure systems to avoid structural failures due to ageing and extreme loading. Vibration-based damage identification (VBDI) methods have been advancing rapidly due to their adroitness in accurately predicting damage. This is because the vibration characteristics such as natural frequency, modal damping and mode shape have close correlations with physical properties (e.g., stiffness, mass and damping). Hence, the change in physical properties due to damage can be represented by the changes in these vibration parameters [1].

Natural frequency is one of the earliest and most common parameters used for damage identification. Messina et al. [2] proposed a correlation coefficient called the Multiple Damage Location Assurance Criterion (MDLAC) and used it as an objective function to predict the location and severity of damage at single or multiple locations from the changes in natural frequencies. Inspired by this approach, Shi et al. [3] employed a few mode shapes in a sensitivity-based correlation method for identifying single and multiple damages. A similar MDLAC approach using modal strain energy change (MSEC) as an objective function and Genetic Algorithm (GA) as a computational tool was proposed by Wang [4] and successfully identified and quantified damage in a lab-scale truss structure.

Damage can alter the total energy distribution in a structure since the law of conservation of energy is applicable to the damaged structure. Hence, like the change in MSE, the change in Modal Kinetic Energy (MKE) can also be employed for damage identification. As a product of a mass matrix and square of mode shape vector, MKE has been widely used to identify the optimal location of sensors for enhancing the accuracy of the damage identification process [5]. However, this parameter has received little attention to use as a damage-sensitive feature till recently. An MKE-based approach was first proposed by Fritzen and Bohle [6] and successfully used to locate damage in the Z24 Bridge with the help of the GA and Sequential Quadratic Programming (SQP) algorithm. Meng and Lin [7] used the MKE change ratio with a unit location matrix in lieu of a mass matrix of elements to locate perturbation. A closed-form expression for damage identification is proposed by Shahri and Ghorbani-Tanha [8] using a modal kinetic energy change ratio (MKECR).

Researchers usually assume that the mass change between damaged and undamaged states of a structure is negligible and simulate perturbation in lab-scale structures either by introducing saw cuts [8] or by replacing removed sections to mimic damage as external mass [9] to minimise mass variation. However, in the real world, the state of mass at the damaged structure might differ from that of the healthy structure. For example, imposed loads on buildings or pipe loads on petrochemical pipe racks at two health states may be different. The change in mass influences the modal properties and adversely alters the accuracy of damage identification results if not addressed adequately. Unlike other damage-sensitive parameters, MKE can incorporate mass variation between two different structure states more efficiently due to its inherent correlation with a mass matrix. This study presents a new MKE-based damage identification approach considering mass variation. A desktop study is conducted to confirm the efficiency of the proposed approach under various test conditions.

Damage Identification Method using Modal Kinetic Energy

A new parameter, the modified MKE residual (M-MKER) vector, is used in this study as a damage-sensitive feature. It can be calculated from the measured natural frequencies and mode shapes as follows:

$$^{KE} = \frac{\lambda_i^d}{\lambda_i}\{\phi_i^d\}^T[M]_j^d\{\phi_i^d\} - \{\phi_i\}^T[M]_j\{\phi_i\} - \{\phi_i\}^T[\Delta M]_j\{\phi_i\} - \frac{\Delta\lambda_i}{\lambda_i}\{\phi_i\}^T[M]_j\{\phi_i\}$$
$$- \sum_{j=1}^{L} 2\lambda_i\{\phi_i\}^T[M]_j\left\{\sum_{r=1}^{n}\frac{\{\phi_r\}^T[\Delta M]_j\{\phi_i\}}{\lambda_r-\lambda_i}\{\phi_r\}\right\}\sum_{j=1}^{L}\{\phi_i\}^T[M]_j\left\{\left(\{\phi_i\}^T[\Delta M]_j\{\phi_i\}\right)\{\phi_i\}\right\} \quad (1)$$

where $[M]_j$ and $[K]_j$ are the mass and stiffness matrices of element *j*; L is the total number of elements; λ_i and $\{\phi_i\}$ are the eigenvalue (square of natural frequency multiplied by 2π) and mode shape in the i^{th} mode, respectively; $\Delta\lambda_i$ is the change in eigenvalue of the i^{th} mode due to damage; and the change in mass of the j^{th} element between the undamaged and damaged states is represented by; the superscript "*d*" represents the damaged state. It is worth noting that the change in mass is not necessarily due to damage but can also be due to the variation in external mass at the damaged state. The change in mass due to damage is usually negligible, especially in the early stage of damage.

The sensitivity of M-MKER due to damage can be estimated from the following expression:

$$S_{i,j,p}^{MKE} = -2\{\phi_i\}^T[M]_j^d\left\{\sum_{r=1}^{n}\frac{\{\phi_r\}^T[K]_p\{\phi_i\}}{\lambda_r-\lambda_i-\lambda_i\{\phi_r\}^T[\Delta M]\{\phi_r\}}\{\phi_r\}\right\} \quad (2)$$

To solve the damage problem, the Multiple Damage Location Assurance Criterion (MDLAC) [1] is modified to represent the correlation between the measured and analytical M-MKER as follows:

$$MDLAC^{MKE} = \frac{\left|\{R^{MKE}\}^T\{\Re^{MKE}(\{\bar{\alpha}\})\}\right|^2}{\left(\{R^{MKE}\}^T\{R^{MKE}\}\right)\left(\{\Re^{MKE}(\{\bar{\alpha}\})\}^T\{\Re^{MKE}(\{\bar{\alpha}\})\}\right)} \quad (3)$$

where $\{R^{MKE}\}$ is the experimental M-MKER vector calculated by Eq. (1), and $\{\Re^{MKE}(\{\bar{\alpha}\})\}$ is the analytical counterpart, which can be estimated for a particular damage vector $\{\bar{\alpha}\}$ using the sensitivity obtained from Eq. (2). Using MDLAC as the objective function, GA is employed to find the optimal damage vector $\{\bar{\alpha}\}$, which represents the damage location and correlative (unscaled) damage extent. The actual damage extent can be estimated by multiplying the correlative damage extent with the damage scaling coefficient, *C*. For each mode, the damage scaling coefficient can be obtained as follows:

$$C_i.\sum_{j=1}^{L} F_{i,j}^{s}.\bar{\alpha}_j = \frac{\lambda_i^d\{\phi_i\}^{d^T}[\Delta M]\{\phi_i\}^d + \Delta\lambda_i}{\lambda_i} \quad (4)$$

where C_i is the damage scaling coefficient in the i^{th} mode of vibration; where $F_{i,j}^{s} = \frac{\{\phi_i\}^T[K]_j\{\phi_i\}}{\{\phi_i\}^T[K]\{\phi_i\}}$ is the fraction of modal energy of the j^{th} member in the i^{th} mode. The errors associated with noise and other uncertainties can be minimised by computing the mean value of the damage scaling coefficient obtained from each mode. Accordingly, the damage scaling coefficient, *C* can be expressed as: $C = 1/\mathrm{n}\sum_{i=1}^{n} C_i$. Please refer to Joseph et al. [10] for more details on the M-MKER method.

Numerical Verification for a Truss Structure

To confirm the efficiency of the proposed method, a 2-D simply supported truss structure of uniform cross-section is simulated, as shown in Fig. 1. The effective span of the truss is 12 m. The structure consists of 15 elements and nine nodes with 15 degrees of freedom (DOFs). Mechanical properties of the truss model are as follows: modulus of elasticity, E = 200 GPa; area of cross-section of members, A = 0.003072 m^2; and mass density, ρ = 7850kg/m^3. The structure is modelled and analysed using the STRAND7 finite element software package.

Various damage scenarios considered to authenticate the proposed damage identification approach are shown in Table 1. The Young's modulus of the damaged elements is reduced by a predetermined percentage to simulate damage. Mass change between the damaged and baseline states is replicated by altering the density of specific elements.

The physical properties are derived from the undamaged structure. The modal properties, such as frequencies and mode shapes, are extracted from damaged and undamaged models. Four modes are used for the identification of damage in this truss model. The damage prediction results for the simulated damage scenarios without considering noise are shown in Figs. 2-4.

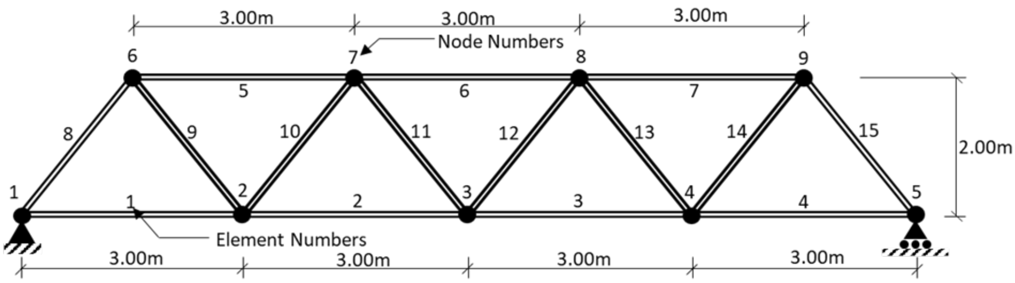


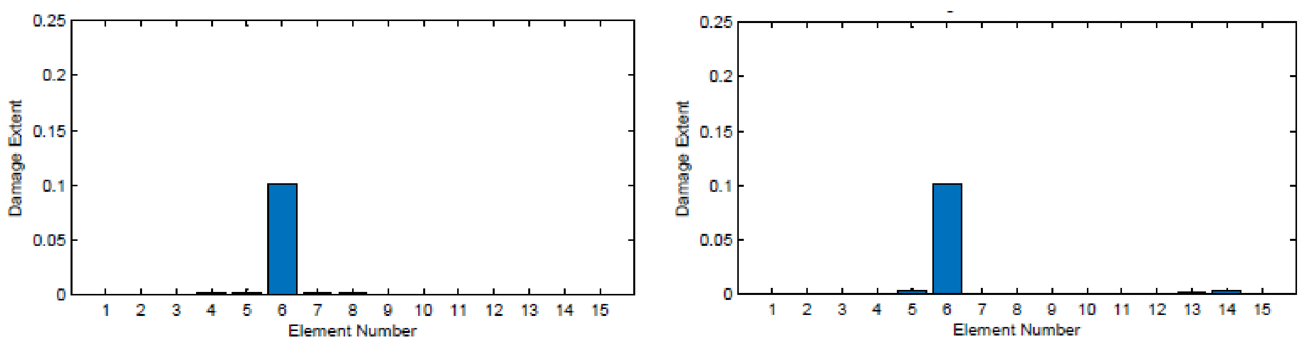
Fig. 1. Two-dimensional simply supported truss model.

Table 1. Damage scenarios for the 2-D truss structure.

Damage case	Damage	Mass variation
Single Damage (TD1-M0)	#6 (10%)	-
Single Damage (TD1-M10)	#6 (10%)	#6 (+10%)
Double Damage (TD2-M0)	#3 (20%) #6 (10%)	-
Double Damage (TD2-M10)	#3 (20%) #6 (10%)	#6 (+10%)
Triple Damage (TD3-M0)	#3 (20%) #6 (10%) #9 (15%)	-
Triple Damage (TD3-M10)	#3 (20%) #6 (10%) #9 (15%)	#6 (+10%)

Since it is not practical to eliminate noise in data acquisition, a reasonable percentage of noise is applied to the acquired modal data to confirm the robustness of the proposed damage quantification approach. The mode shapes extracted analytically from the damaged structure are contaminated with a noise level of 10%. The damage prediction results when noise is introduced are depicted in Figs. 5-7.

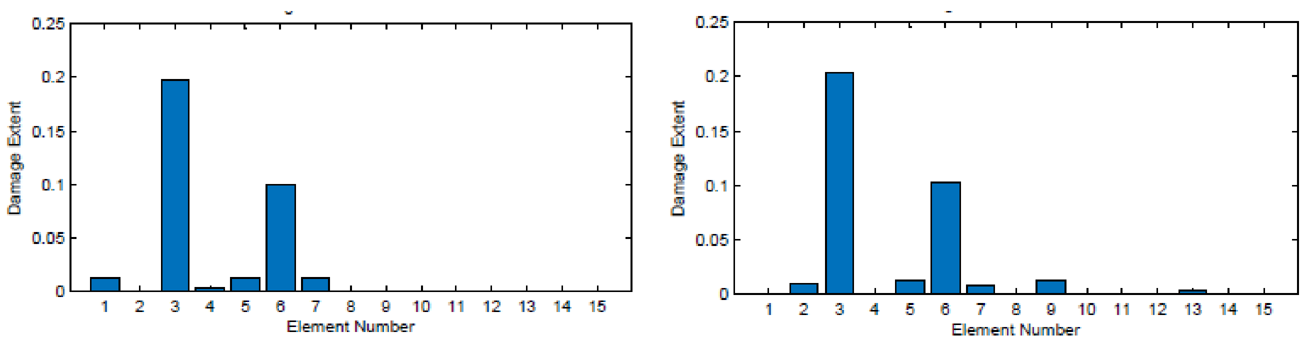
It is noticed from the simulation results that the estimated damage extents are closely matching with the actual damage extents. No significant change in the damage estimation results is observed when simulated without and with mass variation up to 10% and mode shape noise up to 10%. It is also observed that the tendency of false damage identification increases with the increase of mass variation and mode shape noise.



(a) Without mass change (TD1-M0)

(b) With mass change (TD1-M10)

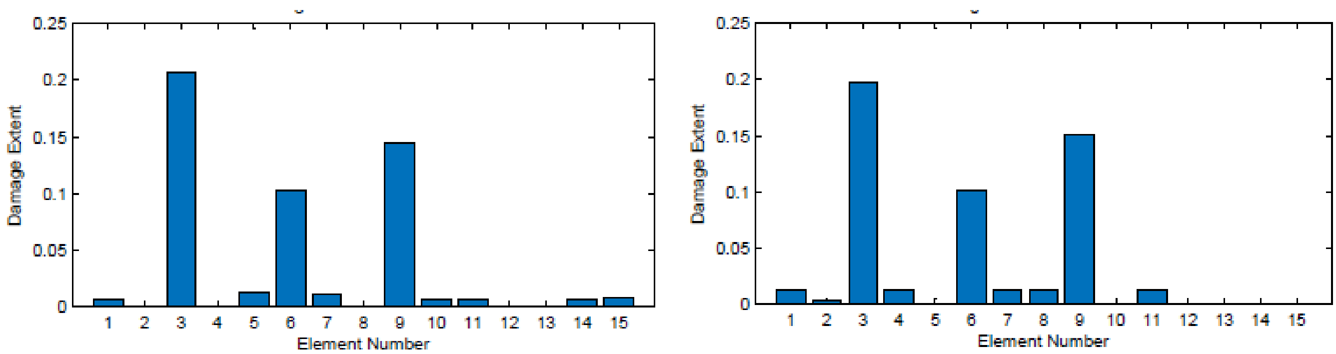
Fig. 2. Damage results for single damage cases – noise-free



(a) Without mass change (TD2-M0)

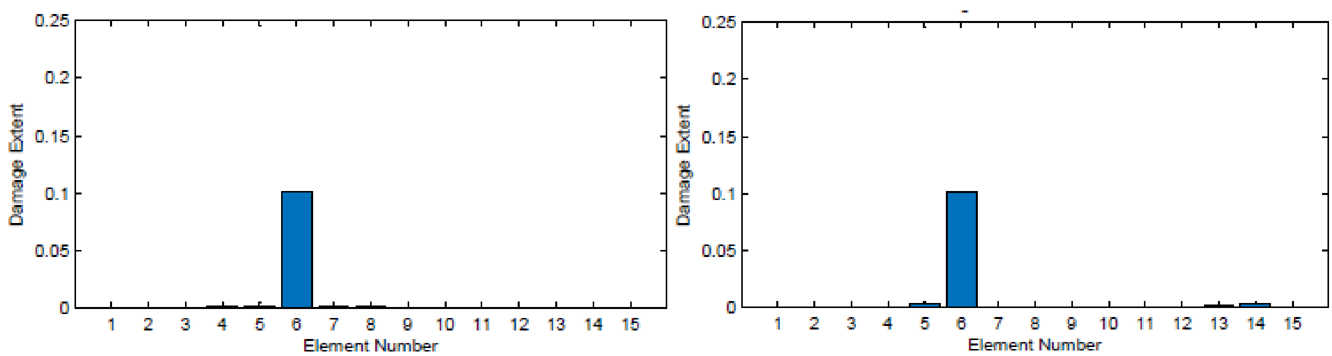
(b) With mass change (TD2-M10)

Fig. 3. Damage results for double damage cases – noise-free



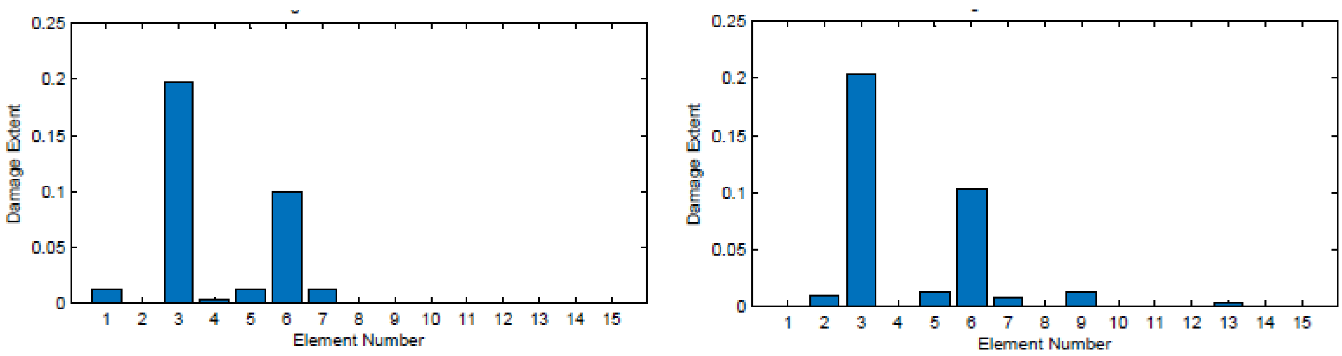
(a) Without mass change (TD3-M0) (b) With mass change (TD3-M10)

Fig. 4. Damage results for triple damage cases – noise free



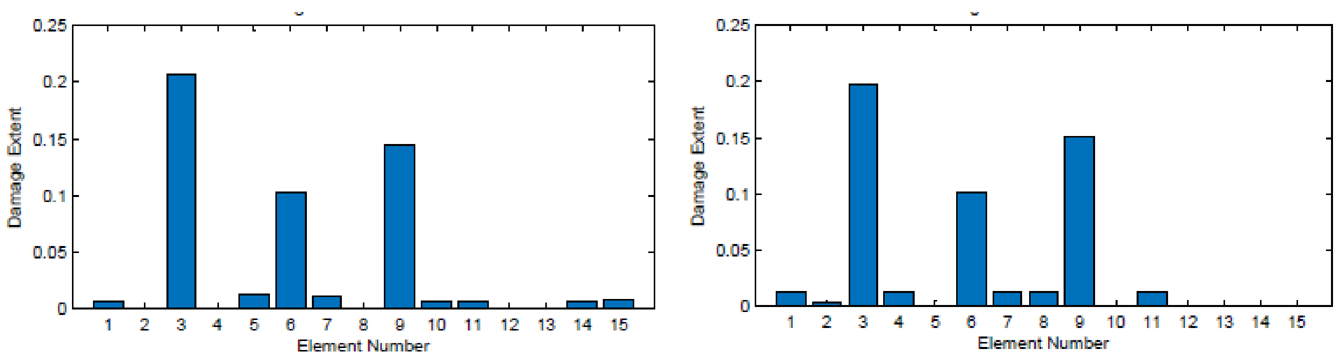
(a) Without mass change (TD1-M0) (b) With mass change (TD1-M10)

Fig. 5. Damage results for single damage cases – 10% noise



(a) Without mass change (TD2-M0) (b) With mass change (TD2-M10)

Fig. 6. Damage results for double damage cases – 10% noise



(a) Without mass change (TD3-M0) (b) With mass change (TD3-M10)

Fig. 7. Damage results for triple damage cases – 10% noise

Conclusions

A statistical-based damage identification method using the MKE concept is presented in this paper. The proposed approach utilises a new damage-sensitive parameter, M-MKER, to locate and quantify damage considering mass variation. The damage identification procedure is carried out by searching for the best correlation between the experimental and analytical M-MKER vectors using a sensitivity analysis and GA optimisation tool. Damage scaling coefficient is calculated using modal energy change vector to compute the damage extent. A numerical simulation of a two-dimensional simply supported truss structure is carried out, and the performance of the proposed approach is investigated for various damage scenarios with different mass variations and measurement noises. The simulation results revealed that the proposed method can successfully identify and quantify damage under various test conditions. Further investigation is required to confirm its applicability in real structures.

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Newsletter

Structural Damage Quantification using Extremely Randomised Tree and Impulse Response Functions

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Abstract

This work presents the development and application of a decision tree-based ensemble technique, an extremely randomised tree (ERT), as a multi-output regression model in structural damage quantification of civil engineering structures. Acceleration responses are measured from structures when an impact force is applied. Impulse response functions (IRFs) are extracted from the acceleration responses and are processed to feed as the input to the ERT. The damage level is defined in terms of elemental stiffness reduction. A steel frame structure is used for the study in the laboratory. The proposed method can provide good results for elemental structural damage quantification. The performance of the proposed approach is compared with RF in terms of identification accuracy and training efficiency.

Introduction

Machine learning's capability of deriving relationships in the datasets collected from sensors and generated from numerical simulations generates knowledge about the structure's health [1]. Ensemble methods based on decision trees are developed for structural health monitoring. Decision trees are non-parametric supervised machine learning algorithms that can be used for regression and classification problems[1]. However, a single decision tree usually suffers from overfitting, resulting in a high variance and a low bias. Breiman [2] proposed Random Forest (RF) to reduce the variance and increase the bias. Extremely Randomised Trees (ERT) is also a decision tree-based algorithm. The difference with RF is that for a given problem, ERT randomly selects a feature from a set of randomly chosen features to split at the node[3, 4], providing a higher level of randomisation. The other difference is that ERT does not bootstrap the initial dataset. It uses whole learning samples to grow the trees. Figure 1 shows an example of ERT.

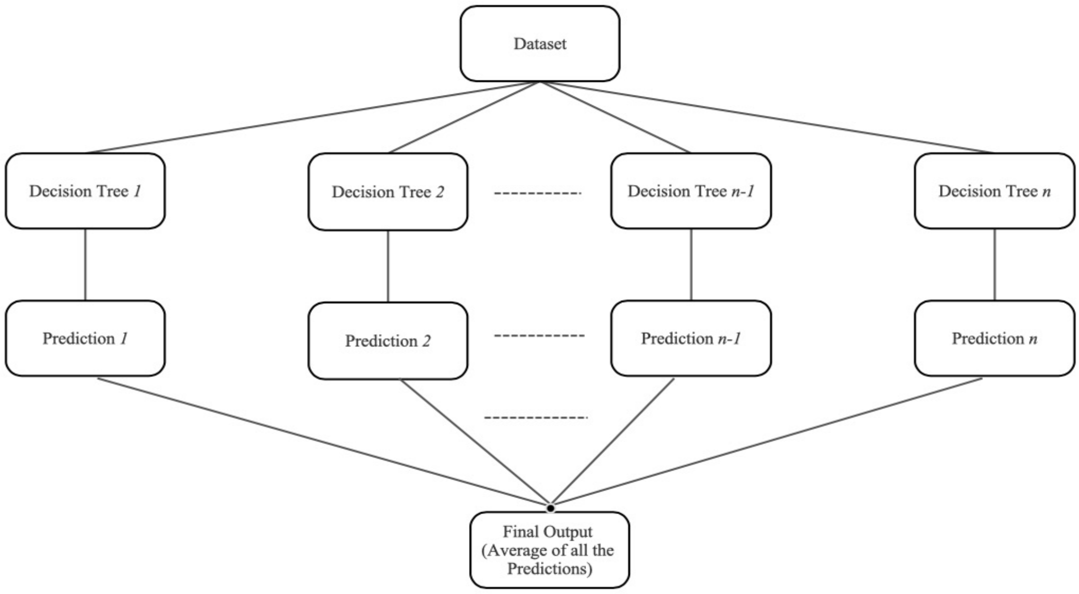

Figure 1: A schematic example of an Extremely Randomised Tree

Impulse Response Function

IRF is one of the dynamic characteristics of structures, which represents the time domain response of a structure under the input of an impulse excitation. It will vary owing to the change in physical properties of the structure, and it is related only to the excitation location[5]. IRF can be analytically derived from the general equation of motion [6, 7] and briefly summarised here. For a structure under a unit excitation, the structural equilibrium equation can be written as

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K\{x(t)\}]=D\delta(t) \tag{1}$$

where $\delta(t)$ is the Dirac delta function. Considering that the initial condition is in static equilibrium, the unit IRF is computed from the equation of motion using the Newmark $-\beta$ method and structural system with zero initial conditions under the general external excitation; the acceleration response $\ddot{x}_l(k)$ at location l at time instant k can be expressed as

$$\ddot{x}_l(k) = \sum_{i=0}^{k} \ddot{h}_l(i) f(k-i) \tag{2}$$

The matrix multiplication for the entire time domain response at location l can be written as

$$X = H \cdot F \tag{3}$$

where X is the output response vector, H is the IRF vector, and F is the input force matrix.

Therefore, IRF can be extracted by solving Equation (3)

$$H = X \cdot (F^T \cdot F)^{-1} \cdot F^T \tag{4}$$

where F^T is the transpose of the force matrix.

The proposed study extracts IRF from the acceleration responses generated from the finite element model using the impact force and Equation (4).

Experimental study

Experimental studies are conducted on a steel frame structure in the laboratory to validate the effectiveness of the proposed approach. The detailed structure descriptions can be found in Ref. [8]. The steel frame structure and the developed finite element model are shown in Figures 2 and 3, respectively. The number of sensors in the study is six. The finite element model of the steel frame has 70 elements. The target output will have 70 labelled output variables, the percentage of stiffness reduction in the elements. Training datasets are extracted from the acceleration responses measured from the updated finite element model. 15% of the total dataset is used as the validation dataset. Two samples of acceleration responses for the single-element damage and two-element damage cases are measured during the laboratory testing. The measured data are used as testing data.

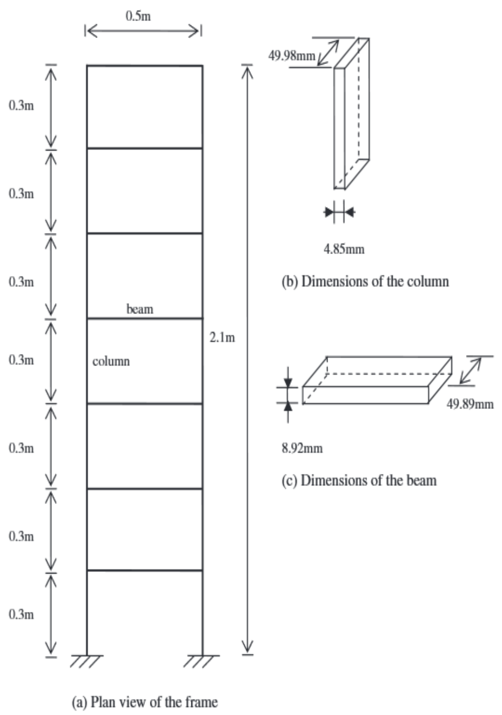

Figure 2: Frame Structure

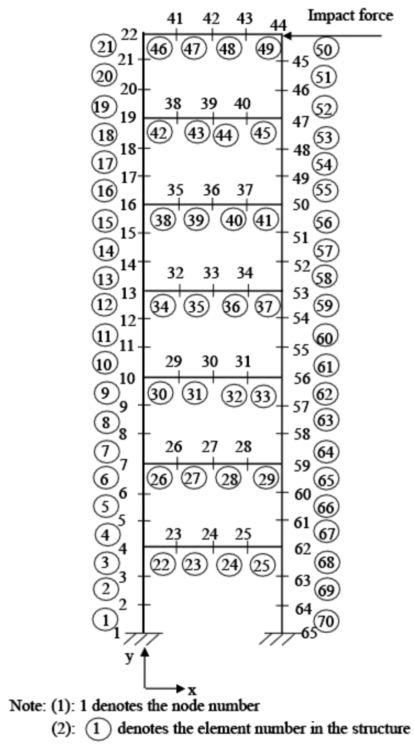

Figure 3. FEM of the frame structure

Sensor Locations

1. Single element damage case: *7x, 11x, 17x, 47x, 53x and 56x*
2. Two element damage case: *4x, 11x, 19x, 50x, 53x and 56x*, where numeric value is the node number and *x* is the horizontal direction

Data Generation and pre-processing

Acceleration responses are obtained when an impact force is applied at node 44 in the horizontal direction. Four samples of acceleration responses are collected for every damage case using random impact forces with a 1-2% variance of the measured force. Measurement is taken for one second at the sampling rate of 1000 Hz. Acceleration responses in the x-direction at nodes 7, 11, 17, 47, 53 and 56 are used for the single-element damage case and at nodes 4, 11, 19, 50, 53 and 56 for the two-element damage case. IRFs are extracted using Equation (4), and the error is reduced by using an ensemble of 50 and averaging the results, as explained in the study by Li et al.[6]. The IRF obtained are concatenated, and the trailing moving average is calculated with a window width of seven using equation (5):

$$ma(t) = \frac{1}{7}(ob(t-6), ob(t-5), ob(t-4), ob(t-3), ob(t-2), ob(t-1), ob(t)) \quad (5)$$

Further, PCA is performed for dimensionality reduction. The number of principal components is selected, taking more than 98.5% variance. Twenty-nine principal components are selected for the single-element damage case, and 19 are chosen for the two-element damage case. A total of 8404 samples are generated for the single element damage case. The stiffness reduction in each element is taken from 0% to 30% in steps of 1% for the single-element damage case. For the two-element damage case, the damage is introduced in any two elements with a maximum stiffness reduction of 20%. 20,883 samples are generated for the two-element damage case. The training of ERT models for single and two-element damage cases is carried out separately since the sensor locations used in the experimental tests under these two damage cases are different.

Results and Discussions

The proposed method is tested with two sample datasets from the real experimental data in the laboratory for the single-element and two-element damage cases, respectively. It should be noted that no ensembles are used in this test since only a limited number of experimental tests are conducted. For the single-element damage case, the stiffness reduction in the 12^{th} element is 12.5%. For the two-element damage case, 12.5% stiffness reduction is introduced in the 6^{th} and 12^{th} elements. The performance of using ERT and RF is compared here to demonstrate the superiority of the proposed approach for a relatively complex structure with more elements and parameters to be identified. Both ERT and RF are grown using 120 decision trees and setting a minimum requirement of six samples at the internal node for further split and three samples in each leaf.

For both single-element and two-element damage cases, ERT performs better than RF, as seen in Tables 1 and 2. The results demonstrate that the proposed approach provides good damage identifications for a structure with many elements and unknown parameters. Less training time is required by using ERT.

Table 1. Performance evaluation for single-element damage case

Performance Metrics	ERT	RF
MSE	1.07×10^{-6}	1.11×10^{-6}
R-Square	0.999	0.997
Training Time (Seconds)	13.42	65.73

Table 2. Performance evaluation for two-element damage case

Performance Metrics	ERT	RF
MSE	2.8×10^{-5}	3.89×10^{-5}
R-Square	0.985	0.975
Training Time (Seconds)	22.70	101.59

Figure 4 shows the damage identification results for the single-element damage case from a sample experimental testing data. The identified stiffness reduction is 12.3% against the true stiffness reduction of 12.5% at the 12^{th} element with ERT and 9.5% with RF. Some false positives are observed in other elements, which are less than 2%. Figure 5 shows the damage identification results of the two-element damage case. The identified stiffness reductions are 13.4% and 11.68% in the 6th and 12th elements with ERT, compared with 12.51% and 5.58% using RF. The identified damage locations are very accurate, and the predicted severities are very close to the true stiffness reductions by ERT. The identification results in these experimental studies indicate that ERT outperforms RF in identifying the damage more accurately and efficiently.

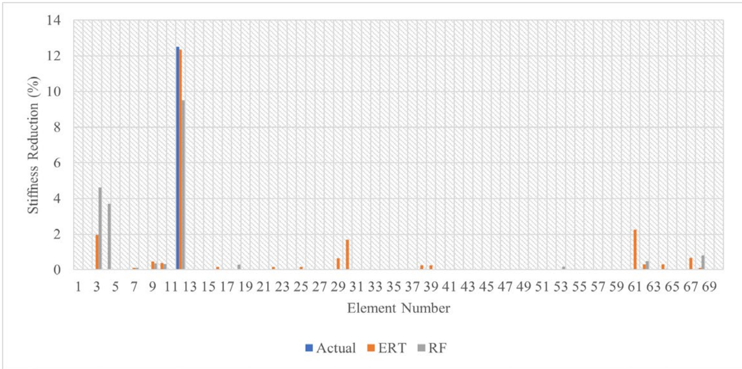

Figure 4. Single-element damage identification results of the experimental frame structure

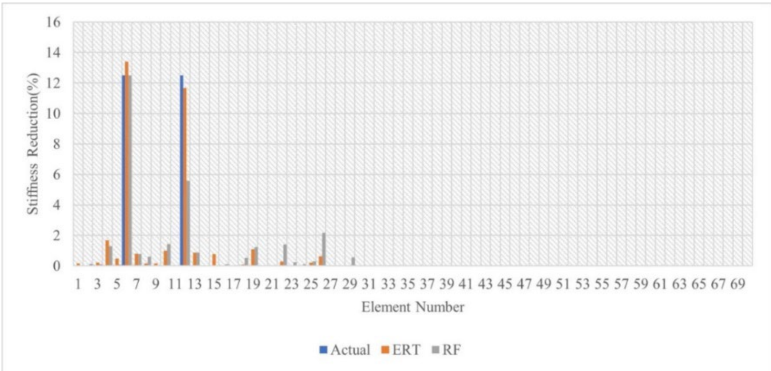

Figure 5. Multiple damage identification results of the experimental frame structure

Conclusions

The proposed method can give suitable damage localisation and quantification. However, the experimental structure fabricated in the laboratory is not exposed to external conditions like in the real world. A large-scale civil infrastructure in a real-world setting is exposed to different environmental conditions such as weather, other types of loading, boundary conditions and construction flaws. There is the possibility of generating erroneous data from the FEM model if such uncertainties are not appropriately considered. Therefore, there is a need to think of more uncertain cases in the existing work in the future.

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Conference News

- ANSHM minim-symposium "Emerging techniques for structural health monitoring of civil infrastructure" in the 18th East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-18), 13-15 November 2024, Chiang Mai, Thailand. Organized by Prof Jun Li, Prof Hong Guan and Prof Tommy Chan. https://easec18.org/
- The 11th European Workshop on Structural Health Monitoring, 10-13 June 2024, Potsdam, Germany. http://www.ewshm2024.com/
- The 1st International Conference on Engineering Structures, 8-10 November 2024 Guangzhou, China. https://www.ices2024.cn/

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