assessment techniques for quantifying safety and adequacy of these important infrastructure assets. Implementation of these two technologies is already realising a significant improvement in cost efficient management of these assets – particularly in regard to risk management and public safety.

On going research projects are refining these techniques and improving their reliability. NDE technologies such as these are providing a new generation of essential tools for asset management of timber structures that enable public utilities to maintain aging infrastructure in a cost effective, whilst at the same time ensuring public safety.

ACKNOWLEDGEMENTS

The author would like to acknowledge the invaluable assistance of his research team in the Centre for Built Infrastructure Research at UTS in undertaking and completing the work presented in this paper. Each of the following has made significant contributions in achieving the outcomes described above:

Prof Bijan Samali, Dr Jianchun Li, Dr Fook Choi, Ms Ulrike Dackermann (PhD candidate) and Mr Peter Brown.

REFERENCES

[1] Crews, K I,. 'Electricity Association of NSW - NDE Timber Pole Project - Physical Testing' - UTS Centre for Built Infrastructure Research Report (R1997.03-1 Nov 1999), pp 1448.
[2] Crews, K., 'Summary Report: EANSW R&D Project – Development of Data Bases for Non Destructive Evaluation (NDE) Systems for Timber Poles in Service' – Commercial in Confidence Report, UTS – Sydney June 2001 (pp 27 + Appendices).
[3] Choi, F., et al,. 'Overview of Dynamic Based Damage Detection for Timber Bridges', paper 72, SACoMaTiS 2008.
[4] Dackermann, U,. et al,. 'Experimental Verification of a Vibration-Based Damage Identification Method in a Timber Structure Utilising Neural Network Ensembles', paper 66, SACoMaTiS 2008
[5] Department of Transport and Regional Services, 'Local roads and bridges - Other developments' Chapter 4: '*Local government infrastructure, 2002-2003 Report on the Operation of the Local Government (Financial Assistance) Act 1995*', Canberra, 2003 (Commonwealth of Australia, 2003) 74-76.
[6] Davis, D., Dunn, CS., 'From theory to field experience with the non- destructive vibration testing of piles' Journal Proceedings Institution of Civil Engineers Part 2, **57** (1974) 571-593.
[7] Haritos, N., et al., 'Load Capacity Testing of In-service Bridges', Proceedings: Austroads Bridge Conference, Brisbane, 1991.
[8] Higgs, JS., Tongue, DJ., 'Dynamic Bridge Testing System for the Evaluation of Defects and Load Carrying capacity of in-service bridges', Proceedings: International Conference on Current and Future Trends in Bridge Design Construction and Maintenance. Singapore October 1999.
[9] Peterson, S.T., McLean, D.I., Symans, M.D., Pollock, D.G., Cofer, W.F., Emerson, R.N., Fridley, K.J., 'Application of Dynamic System Identification to Timber Beams (Part I)', Journal Of Structural Engineering, April 2001, 418-425.
[10] Andersen, P., 'Identification of Civil Engineering Structures using Vector ARMA Models', PhD Thesis, Aalborg University, Department of Building Technology and Structural Engineering Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark.

SACoMaTiS 2008
International RILEM Conference
1-2 September 2008 Varenna (LC)
Como Lake - Italy
POLITECNICO DI MILANO
www.sacomatis.org
on Site Assessment of Concrete, Masonry and Timber Structures

OVERVIEW OF DYNAMIC BASED DAMAGE DETECTION FOR TIMBER BRIDGES

Fook Choon Choi, Jianchun Li, Bijan Samali and Keith Crews

CBIR, Faculty of Engineering, University of Technology Sydney, Australia

Abstract

Asset management of bridges throughout the world faces increasing challenges as a result of aging infrastructure and inadequate funding. Replacement of an old bridge is neither viable nor sustainable in many circumstances. As a consequence, there is an urgent need to develop and utilise state-of-the-art techniques to assess and evaluate the "health state" of existing bridges and to be able to understand and quantify the effects of degradation in regard to public safety. This paper presents an overview of experimental work for a project in developing and implementing several dynamic methods for evaluation of damage in timber bridges. The technique of detecting damage involved the use of modal strain energy commonly referred to in the literature as damage index methods. The project started with simple beams subjected to single and multiple damage and then was extended to a scale timber bridge constructed under laboratory conditions. It was found that after modification on the damage index method, it was well suited to detect single and multiple damage scenarios for a one-dimensional beam. For the laboratory bridge, the damage index method developed for plate-like structures was successful in detecting single and multiple damage with an acceptable degree of accuracy.

Keywords

Damage evaluation, modal strain energy, damage index method, timber bridge

1. INTRODUCTION

Timber bridges have contributed significantly to the development of many countries. Besides serving as means for transportation, timber bridges, nowadays also have significant heritage values. According to the Department of Transport and Regional Services Australia (DOTARS) [1], there are approximately 29,000 timber bridges in Australia. DOTAR has estimated that a third of them are in excess of 50 years service life and some of these bridges are functionally obsolete and are structurally deficient. Due to their age and 'unhealthy' condition, it is necessary to perform periodic inspections on them to ensure the safety of the structures as well as to preserve these heritage-valued structures of the country.

Over the last few decades, many methods of structural integrity assessment for timber bridges have been developed. The development in research for in-situ non-destructive testing (NDT) for decay detection and subsequent strength assessment are highlighted as one of the needs for research. Proof load testing is a commonly used method, but it has a number of serious drawbacks including endangering the remaining strength of a tested bridge. Therefore, recently more research and developments have been carried out to assess the in-service stiffness of timber structures using vibration techniques. Application of vibration based techniques for condition assessments in timber bridges was also found in few literatures [2-8].

This paper provides an overview of experimental part of a project completed recently, which aims to develop and implement dynamic methods for evaluation of damage in timber bridges. The damage detection technique commonly known as damage index (DI) method was modified and implemented for locating and evaluating severity of damage. The method is based on the modal strain energy, a derivative of mode shape curvature. Timber beams subjected to various damage scenarios were used for verifying the damage detection methods. It was subsequent with a scale laboratory timber bridge. The original and modified damage index (DI & MDI) methods were used to detect single and multiple damage scenarios for timber beam. The results of both methods were discussed here. For the laboratory bridge, the DI method developed for plate-like structures (DI-P) was used to detect locations of damage.

2. EXPERIMENTAL SET UP AND TESTING

2.1 Test beams

Timber beams used in the experimental work were intended to represent the scaled girders of typical timber bridges in Australia. The scaling for the beams was based on dynamic similitude of the girders in terms of their first natural frequencies (5~20 Hz). The beams are of treated radiata pine sawn timber measuring nominal dimensions of 45 mm by 90 mm in cross section (see Figure 1) with a span length of 4,500 mm. A specially designed support system was used between the beam and the concrete supports to provide a well-defined 'pin-pin' boundary condition (see Figure 1). The timber beam was firstly tested to obtain the undamaged state. The test results of undamaged beam form the baseline in comparison to various damage cases. Using the DI methods, any uncertainty of a "real" timber bridge, such as support conditions and composite actions between girders and deck, can be eliminated as comparison of derivatives of modal data for undamaged and damaged state are employed to produce the damage detection results.

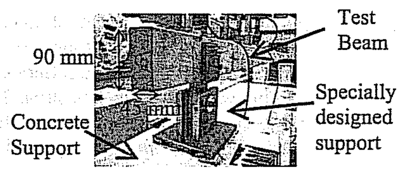


Figure 1: Specially designed pin support

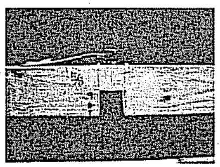


Figure 2: A typical inflicted damage

2.2 Inflicted damage in test beams

The goal of this study was to detect damage typically found in timber bridges, such as pockets of rot, for single and multiple damage on a timber beam. Some of the damage cases considered is described in Table 1. The damage consists of a rectangular opening along the span starting from the soffit of the beam, located at 2/8, midspan, 5/8 and 6/8 of the span length. 'M' and 'S' denote medium and severe damage, respectively. All inflicted damage are 1% of the total span length (45 mm) and consist of 30% and 50% of the beam depth, designated as damage cases 'M' and 'S' (see Table 1). The severity of the damage can also be interpreted as loss of 'I' (moment of inertia) from the depth of cut. The loss in section of 30% and 50% of beam depth, correspond to 65.7% and 87.5% loss of 'I', respectively. A typical damage inflicted is shown in Figure 2.

Table 1: Dimensions of damage inflicted in timber beam

Damage Case	Location per 8th of span length	Length l (mm)	Depth h (mm)	% loss of 'I'
4S	4	45	45	87.5
4S6M	4, 6	45	45, 27	87.5, 65.7
4S5S6S	4, 5, 6	45	All 45	All 87.5
2S4S5S6S	2, 4, 5, 6	45	All 45	All 87.5

2.3 A laboratory timber bridge

A four-girder laboratory timber bridge was built in the laboratory to apply the damage detection method to timber structures. The basic dimensions of the structure are shown in Figure 3. The bridge consisted of four girders of treated radiata pine sawn timber measuring 45 mm x 90 mm in cross section with a span length of 4.5 m. The deck consisted of four pieces of 21 mm think x 2.4 m wide and 1.2 m long structural plywood of grade F11. The deck and girders were connected using 50 mm self-tapping screws with 137.5 mm spacing. No gluing was applied in order to avoid fully-composite action, to simulate the interactions in a real timber bridge. The ends of the bridge girders were supported on concrete blocks, and rigidly connected to the strong floor. A specially designed support system similar to the timber beam (see Figure 1) was used between girders and the concrete block to ensure a well-defined 'pin-pin' boundary condition. The full bridge model is depicted in Figure 4.

2.4 Inflicted damage in laboratory timber bridge

The goal of this study was to detect damage typically found in timber bridges, using the proposed modal-based damage detection methods to locate damage in single and multiple damage on a laboratory timber bridge. Some of the damage cases considered is described in Table 2. Damage scenarios for the timber bridge model are similar to the damage inflicted on the timber beam except the damage is positioned on different girders rather than concentrated on one girder. The inflicted damage locations are illustrated in Figure 3.

From Table 2, there are two damage scenarios. The type of damage is similar to the timber beam as shown in Figure 2. For example, case g2Sg4Sg3M denotes a cumulative damage scenario of medium damage on ¾ span of girder 3, severe damage on ¾ span of girder 2 and ½ span of girder 4.

Table 2: Dimensions of inflicted damage in the bridge

Damage Case	Location per 8th of span length/Girder number	Length l (mm)	Depth h (mm)	% loss of 'I'
g2M	6/g2	45	27	65.7
g2Sg4Sg3M	6/g2, 4/g4, 2/g3	45	45, 45, 27	87.5, 87.5, 65.7

2.5 Experimental modal analysis

The experimental modal analysis for the timber beam is shown in Figure 5. An impact hammer was used to excite the beam. Nine accelerometers were used to measure dynamic response of the beam. One of the accelerometers was used as the driving point measurement. Each accelerometer was attached onto a small steel plate using magnetic base, while the steel plate was screwed onto the top of the girders. These accelerometers were located at 1/8 intervals of the span length starting from one end of the beam as shown in Figure 5. The impact location, at ¾ of the span length, was selected so that more modes can be excited, simultaneously. The HP E1432A and LMS were used to record the dynamic response at 10,000 Hz sampling rate for 8,192 data points. Frequency domain direct measurement curve-fitting technique was used to obtain the frequencies, damping and mode shapes of the tested bridges from of the measured data. Five experimental vibrational modes were captured.

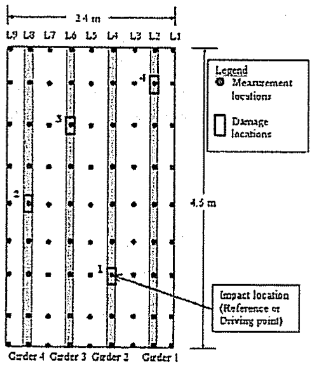


Figure 3: Plan view of damage locations and measurement locations for the bridge

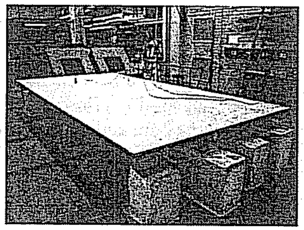


Figure 4: The laboratory timber bridge

The structural identification method used for the laboratory timber bridge is similar to the one used for timber beam. The slight difference is the impact location (reference or driving point) being set at ¾ of the span length of girder 2 (g2) (see Figure 3). The response signals along the span were measured using nine accelerometers and one was used at the driving point. For the laboratory timber bridge, there were 81 measuring points per test as depicted in Figure 3. Due to limited number of available sensors, the signal acquisition of the 81 measurement points was done by moving the nine sensors to the adjacent location along the span direction and repeating 9 times. The driving point measurement enabled the

experimental mode shape to be mass normalised. Nine experimental mode shapes were captured.

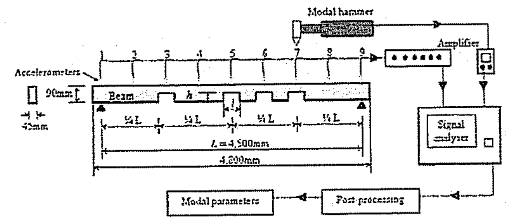


Figure 5: Instrumentation set up for experimental modal analysis

3. DAMAGE DETECTION

3.1 Damage index (DI)

In this investigation, the damage index method developed by Kim and Stubbs [9] was adopted and modified to detect the inflicted damage. The original method pertaining to damage localisation is based on the relative differences in modal strain energy between an undamaged structure and that of the damaged structure. The modal strain energy utilises derivative of mode shape (mode shape curvature) and the algorithm used to calculate the damage index for the jth element and the ith mode, β_{ij}, is given below.

$$\beta_{ij} = \frac{\int_j \{\phi_i''^*(x)\}^2 dx \int_0^L \{\phi_i''(x)\}^2 dx}{\int_j \{\phi_i''(x)\}^2 dx \int_0^L \{\phi_i''^*(x)\}^2 dx} \qquad (1)$$

It should be noted that in Eq. (1) the terms $\phi''(x)$ are vectors of mode shape curvature coordinates of a one-dimensional (1-D) system. The asterisk denotes the damage cases. It was suggested by Peterson et al. [3] that each mode shape coordinate in the mode shape matrix be divided by the Euclidean norm of the matrix to obtain a normalised mode shape matrix. The damage index method was then used to compare the normalised mode shape vector for each girder from each of the damage cases versus the corresponding normalised undamaged mode shape vector. To account for all available modes, NM, the damage indicator value for a single element j is given as

$$\beta_j = \frac{\sum_{i=1}^{NM} Num_{ij}}{\sum_{i=1}^{NM} Denom_{ij}} \qquad (2)$$

where Num_{ij} = numerator of β_{ij} and $Denom_{ij}$= denominator of β_{ij} in Eq. (2), respectively. Transforming the damage indicator values into the standard normal space, normalised damage index Z_j is obtained:

$$Z_j = \frac{\beta_j - \mu_{\beta j}}{\sigma_{\beta j}} \qquad (3)$$

where $\mu_{\beta j}$ = mean of β_j values for all j elements and $\sigma_{\beta j}$ = standard deviation of β_j for all j elements. A judgment based threshold value is selected and used to determine which of the j elements are possibly damaged which in real applications is left to the user to define based on what level of confidence is required for localisation of damage within the structure.

The severity of damage in the jth member is estimated using the expression as follows,

$$\alpha_j = 1 - \frac{1}{\beta_j} \tag{4}$$

3.2 Modified damage index (MDI)

In the modified damage index (MDI) equation, the terms $\bar{\phi}_i''^{*}$ or $\bar{\phi}_i''$ (referring to Eq. (1)) are normalised mode shape curvature coordinates, which are normalised with respect to the maximum value of the corresponding mode, corresponding to mode i for a beam structure. The asterisk denotes the damage cases. In the MDI, in order to account for all available mode shapes, the summation of the combination of mode shape curvatures are necessary. Although mode shape vectors have been normalised to the Euclidean norm of the matrix, the mode shape curvatures used for the DI calculation are not normalised. Values of mode shape curvature are dependant on the shapes of each individual mode shape. Instead of reflecting the changes in the curvature due to damage, the summation of non-normalised mode shape curvatures will distort the damage index in favour of higher modes, which results in false damage identifications. The modified severity estimator is as per Eq. (4).

3.3 Damage index for plate-like structures (DI-P)

Cornwell et al. [10] extended the damage index method for beam-like structures to include the detection of damage for plate-like structures characterised by a two-dimensional (2-D) mode shape slope and curvature. The algorithm used to calculate the damage index for the jkth subregion and the ith mode, β_{ijk}, is given below for detecting location of damage.

$$\beta_{ijk} = \frac{\left\{\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}}\left[\left(\frac{\partial^2\phi_i^*}{\partial x^2}\right)^2+\left(\frac{\partial^2\phi_i^*}{\partial y^2}\right)^2+2\nu\left(\frac{\partial^2\phi_i^*}{\partial x^2}\right)\left(\frac{\partial^2\phi_i^*}{\partial y^2}\right)+2(1-\nu)\left(\frac{\partial^2\phi_i^*}{\partial x\partial y}\right)^2\right]dxdy\right\}\left\{\int_0^b\int_0^a\left[\left(\frac{\partial^2\phi_i}{\partial x^2}\right)^2+\left(\frac{\partial^2\phi_i}{\partial y^2}\right)^2+2\nu\left(\frac{\partial^2\phi_i}{\partial x^2}\right)\left(\frac{\partial^2\phi_i}{\partial y^2}\right)+2(1-\nu)\left(\frac{\partial^2\phi_i}{\partial x\partial y}\right)^2\right]dxdy\right\}}{\left\{\int_{b_k}^{b_{k+1}}\int_{a_j}^{a_{j+1}}\left[\left(\frac{\partial^2\phi_i}{\partial x^2}\right)^2+\left(\frac{\partial^2\phi_i}{\partial y^2}\right)^2+2\nu\left(\frac{\partial^2\phi_i}{\partial x^2}\right)\left(\frac{\partial^2\phi_i}{\partial y^2}\right)+2(1-\nu)\left(\frac{\partial^2\phi_i}{\partial x\partial y}\right)^2\right]dxdy\right\}\left\{\int_0^b\int_0^a\left[\left(\frac{\partial^2\phi_i^*}{\partial x^2}\right)^2+\left(\frac{\partial^2\phi_i^*}{\partial y^2}\right)^2+2\nu\left(\frac{\partial^2\phi_i^*}{\partial x^2}\right)\left(\frac{\partial^2\phi_i^*}{\partial y^2}\right)+2(1-\nu)\left(\frac{\partial^2\phi_i^*}{\partial x\partial y}\right)^2\right]dxdy\right\}} \tag{5}$$

It should be noted that in Eq. (5), ν represents Poisson's ratio and the term $\partial^2\phi_i/\partial x^2$ is a vector of second derivatives of mode shape coordinates (curvatures) with respect to x-axis. Similar convention is applicable to second derivatives with respect to y-axis and cross derivatives with respect to x- and y-axes. This equation denotes a matrix describing the mode shape curvatures corresponding to mode i for a bridge structure. The asterisk denotes the damage cases. To account for all available modes, NM, the damage indicator value for a single subregion jk, β_{jk}, is computed as per Eq. (2). The normalized damage index Z_{jk} is obtained as per Eq. (3).

4. RESULTS AND DISCUSSION

In the following results for timber beam, all damage indicator indices, Z_j, for each damage case are computed using the first five modes and they are plotted against the beam span length (4.5 m). In principle, the statistically normalised damage indicator values Z_j larger than zero

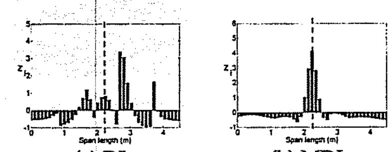
(the probability-based criterion for damage), indicates that damage has occurred at that location. The actual damage locations are indicated with vertical dashed lines in all figures.

For the laboratory timber bridges results, the damage indicator, Z_{jk}, for each of the damage cases is plotted against the laboratory timber bridge span length (4.5 m) and width (2.4 m). In principle, when the statistically normalised damage indicator value of Z_{jk} for a given subregion is larger than or equals to two ($Z_{jk} \geq 2$), it is considered that damage existed at that location.

4.1 Damage localisation using DI and MDI

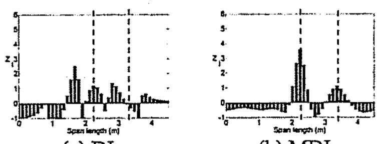
In Figure 8, for single damage case 4S, the first five flexural modes were utilised to compare the capability of the damage index (DI) and the modified damage index (MDI) methods in locating damage. Figure 8 shows that the DI method failed to convincingly identify the severe damage (4S) located at midspan (2.25 m). Using the MDI method (see Figure 8b), on the other hand, the damage indicator is able to show accurately the location of damage at position 2.25 m. It is observed that the DI method is not able to identify single damage well compared to the modified method.

The damage localisation results for the two damage location scenario (case 4S6M) involving two damage locations positioned at 2.25 m and 3.375 m applying the DI and MDI methods are presented in Figure 9. Using the DI method, the damage locations are not clearly identified as shown in Figure 9. All damage locations using the MDI method (see Figure 9b) was precisely identified by the damage indicator at the midspan (2.25 m) and 3.375 m. It is observed that the MDI method is capable of detecting damage in dual damage locations. The method is also capable of providing a distinct relative difference of probability of existing of medium and severe damage.



(a) DI (b) MDI

Figure 8: Single damage case 4S



(a) DI (b) MDI

Figure 9: Two damage case 4S6M

For three damage location scenarios in damage case 4S5S6S, the damage localisation results are illustrated in Figure 10. Again, using the MDI algorithm in the method clearly located all damage as shown in Figure 10b, while using the DI method (see Figure 10a) the damage locations are not all clearly identified. This shows that the modified algorithm is reliable in detecting localised damage accurately for up to three damage locations. The MDI method yields a quite evenly distributed damage index values, reflecting the actual damage severity level for all damage.

The four damage location scenarios are depicted in Figure 11. Using the DI method, not all damage could be detected as shown in Figure 11a. These results indicate that the DI method is not able to detect damage well for single and multiple damage locations using the first five flexural modes. Hence, the DI algorithm using higher modes (>2) is not recommended for damage localisation as it may miss the severe damage that could cause catastrophic failure of a structural system. Using the MDI method (see Figure 11b), it is noticed that most damage locations are identified. From the damage cases discussed above, it is obvious that the MDI method is basically preferred to the DI method in identifying the damage location. This may attribute to the ability of the MDI method to evenly utilise contribution from all the five modes and not dominated by only higher modes as in the DI method, which may distort the damage detection results.

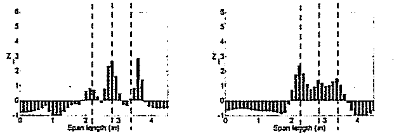

(a) DI (b) MDI

Figure 10: Three damage case 4S5S6S

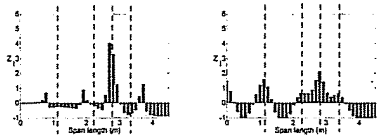

(a) DI (b) MDI

Figure 11: Four damage case 2S4S5S6S

4.2 Estimation of severity of damage using MDI

The MDI algorithm was further developed to numerically correlate to a meaningful physical damage condition. The estimation of damage severity using the MDI algorithm is presented in terms of percentage of loss of "I" (moment of inertia). The first five modes were chosen for the calculation of the damage severity estimation.

Table 3: Estimation of damage severity using MDI method

Damage Case	Location per 8th of span length	Simulated Damage Severity (%)	Predicted Damage Severity (%)	% of Error
4S	4	87.5	87.5	0
4S6M	4, 6	87.5, 65.7	87.0, 54.2	0.6, 17.5
4S5S6S	4, 5, 6	ALL 87.5	81.4, 65.4, 67.8	7.0, 25.2, 22.5
2S4S5S6S	2, 4, 5, 6	ALL 87.5	51.4, 70.8, 56.2, 45.0	41.3, 19.1, 35.8, 48.6

Similar damage cases used in damage localisation were used in the estimation of severity of damage using the derived formula from the MDI method. The severity of damage below zero percent is not meaningful, thus they are shown zero. Employing the experimental data that contains noise, a weighting factor of 1.23 was adopted in the method based on calibration to the case 4S. The results of the severity evaluation (the magnitude of simulated and predicted damage) using the MDI method for the five types of damage scenarios are tabulated in Table 3. For the single damage location case 4S, there is no error as it is the baseline of calibration. For the two damage location case (4S6M and 4S6S), the predicted damage is 87.0% and 54.2% loss of "I" for severe and medium damage, respectively. The highest error is about 17%. For the damage location case (4S5S6S), the severity of damage was all under predicted with highest error of 25%. This trend is similar for the four damage locations scenario (case 2S4S5S6S). In general, the percentage of error between the simulated and predicted severity of damage reveals that the MDI method generally underestimates the

severity of inflicted damage for all scenarios. From these few cases, the errors of the estimated damage severity are ranging from 20 to 50%, which is considered reasonably acceptable. This initial effort to estimate severity of damage in wood is believed to have advanced the knowledge of NDT for wood or timber structures significantly.

4.3 Damage localisation using damage index for plate-like structures (DI-P)

The single damage case (for the laboratory bridge) applied in the damage index for plate-like structures (DI-P) and computed using the first nine modes for the experimental studies are illustrated in Figure 12. For single damage case g2M (medium damage), the DI-P method was able to identify the damage location at position (3.375 m, 0.9 m) (used as a convention in all the following discussions to indicate location of damage at 3.375 m along the span length and 0.9 m across the width) as shown in the contour plot of Figure 12. It can be seen that the experimental data used in the DI-P method is capable of detecting the medium damage. The spurious damage locations shown in the experimental result may due to the fact that the data contain noise.

The result of three damage locations (case g2Sg4M) is shown in Figure 13. The severe damage at positions (3.375 m, 0.9 m) and (2.25 m, 2.1 m) is identified. It is also obvious that the experimental results are contaminated with a serious spurious damage location near the actual severe damage. The medium damage at position (1.125 m, 1.5 m) is not identified. The shadow spurious damage near to the actual severe damage may due to the cubic nature of the interpolation used in the reconstruction of mode shapes and may be avoided by using a high-order interpolation technique. It is anticipated that such data distortion may also happen to the free edges.

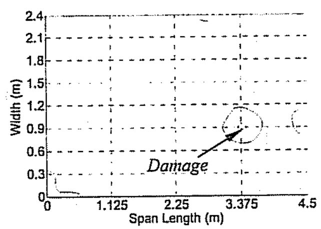


Figure 12: Single damage case g2M

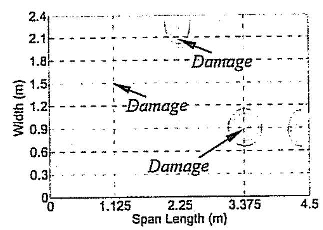


Figure 13: Three damage case g2Sg4Sg3M

5. CONCLUSION

In this paper, an overview of a research project, which was completed recently, is presented. Part of the overall experimental work and results were reported. Application of testing data (obtained from experimental modal analysis) using the damage index and modified damage index methods for damage detection of a timber beam and a laboratory timber bridge was performed. For the timber beam, the damage detection method, MDI, is capable of detecting medium and severe damage in comparison to the unreliable results from its original formula (DI). The modified method also works well in detecting multiple damage locations up to four damage locations. To estimate damage severity in the timber beam, the

MDI method (utilising a weighting factor) estimated reasonably well the severity of damage. The results of applying the DI-P method to locate damage in the laboratory timber bridge showed that it is capable of detecting all severe damage for damage cases with less than three damage locations. Nevertheless, it does encounter some problems in detecting medium damage that forms part of the multiple damage scenarios. Significant development is needed to transfer this technique from laboratory investigation to actual field testing.

ACKNOWLEDGEMENTS

The authors wish to thank the Centre for Built Infrastructure Research (CBIR), Faculty of Engineering, University of Technology, Sydney (UTS) for supporting this work. Within the Faculty of Engineering, the authors wish to thank the staff of UTS Structures Laboratory for their assistance in conducting the experimental works.

REFERENCES

[1] Department of Transport and Regional Services, 'Local roads and bridges - Other developments' in 'Chapter 4: Local government infrastructure', 2002-2003 Report on the Operation of the Local Government (Financial Assistance) Act 1995, Canberra, 2003 (Commonwealth of Australia, 2003) 74-76.
[2] Peterson, S.T., McLean, D.I., Symans, M.D., Pollock, D.G., Cofer, W.F., Emerson, R.N. and Fridley, K.J., 'Application of dynamic system identification to timber beams I', *J. Struct. Eng.* **127** (4) (2001) 418-425.
[3] Peterson, S.T., McLean, D.I., Symans, M.D., Pollock, D.G., Cofer, W.F., Emerson, R.N. and Fridley, K.J., 'Application of dynamic system identification to timber beams II', *J. Struct. Eng.* **127** (4) (2001) 426-432.
[4] Peterson, S.T., McLean, D.I. and Pollock, D.G., 'Application of dynamic system identification to timber bridges', *J. Struct. Eng.* **129** (1) (2003) 116-124.
[5] Yang, X.Y., Ishimaru, Y., Iida, I. and Urakami, H., 'Application of modal analysis by transfer function to nondestructive testing of wood I: determination of localized defects in wood by the shape of flexural vibration wave', *J. Wood Sci.* **48** (2002) 283-288.
[6] Morison, A., VanKarsen, C.D., Evensen, H.A., Ligon, J.B., Erickson, J.R., Ross, R.J. and Forsman, J.W., 'Timber bridge evaluation: a global nondestructive approach using impact generated FRFs', Proceedings of IMAC-XX, Los Angeles, California, US, February, 2002 (Society for Experimental Mechanics Inc., 2002) 1567-1573.
[7] Morison, A., VanKarsen, C.D., Evensen, H.A., Ligon, J.B., Erickson, J.R., Ross, R.J. and Forsman, J.W., 'Dynamic characteristics of timber bridges as a measure of structural integrity', Proceedings of IMAC-XXI, Kissimmee, Florida, US, February, 2003 (Society for Experimental Mechanics Inc, 2003) Published on CD-ROM.
[8] Hu, C. and Afzal, M.T., 'A statistical algorithm for comparing mode shapes of vibration testing before and after damage in timbers', *J. Wood Sci.* **52** (2006) 348-352.
[9] Kim, J.-T. and Stubbs, N., 'Model-uncertainty and damage-detection accuracy in plate girder', *J. Struct. Eng.* **121** (10) (1995) 1409-1417.
[10] Cornwell, P., Doebling, S.W. and Farrar, C.R., 'Application on the strain energy damage detection method to plate-like structures', *J. Sound Vibrat.* **224** (2) (1999) 359-374.

SACoMaTiS 2008
International RILEM Conference
1-2 September 2008 Varenna (LC)
Como Lake - Italy
S.A.Co.Ma.Ti.S.'08
POLITECNICO DI MILANO
www.sacomatis.org
on Site Assessment of Concrete, Masonry and Timber Structures

ANCIENT TIMBER STRUCTURE ANALYSIS APPLYING NDT AND TRADITIONAL METHODS OF ASSESSMENT

Liliana Palaia, José Monfort, Rafael Sanchez, Luisa Gil, Ángeles Álvarez, Vicente López, Santiago Tormo, Carmen Pérez and Pablo Navarro

Polytechnic University of Valencia, Spain

Abstract

In the absence of appropriate maintenance intervention, the degradation of wood along with factors such as timber quality, carpenter accuracy, and lack of maintenance, all damage the structural integrity and serviceability of timber structures. Historic timber structures, as part of our cultural heritage, should be preserved when possible. This aim should be addressed by architects and technicians, who are responsible for building conservation. In this paper, a method to assess old timber structures is proposed. It is a method based on the analysis of data gathered systematically at the building site regarding the characteristics of the wooden structural elements. This method has been developed from scientific research and building site inspections. The authors have developed a R&D&I Project, (Ministerio de Fomento, Spain, 2004), to apply NDT to the evaluation of timber structures, with a visual inspection to be performed by qualified site surveyors using a minimum of destructive testing to determine parameters and obtain conclusions of the structural elements mechanical characteristics. Instrumental techniques applied *in situ* are micro drilling, ultrasonic and wood hardener. NDT techniques allow researchers to save time in diagnosis and minimize damage to the sound timber. These methods may also be applied for monitoring the condition of historic timber structures, obtaining data on the building at inspection points (marked on the surface of the members), and other critical parts of the structure.

Keywords

Timber, NDT, micro drilling, ultrasonic, wood-hardener

1. INTRODUCTION

Traditional building systems are based on experience. The fact that timber was not always seasoned when used for building, its quality not being the best, and that the carpenters were not as accurate as they should have been, must be taken into consideration for the negative