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Fault diagnosis on beam-like structures from modal parameters using artificial neural networks

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ABSTRACT

Currently, visual inspection is performed in order to evaluate damage in structures. This approach is affected by the constraints of time and the availability of qualified personnel. Thus, new approaches to damage identification that provide faster and more accurate results are pursued. A promising approach to damage evaluation and detection utilizes artificial neural networks (ANNs) in solving these two problems. ANNs are a powerful artificial intelligence (AI) technique that have received wide acceptance in predicting the extent and location of damage in structures. In this study, the fundamental strategy for developing ANNs to predict the severity and location of double-point damage cases from the measured data of the dynamic behavior of the structure in I-beam structures is considered. ANNs are trained using vibration data consisting of natural frequencies and mode shapes obtained from experimental modal analysis and finite element simulations of intact and damaged I-beam structures. By using ANNs, some significant problems of conventional damage identification approaches can be overcome and damage detection accuracy can be improved.

1. Introduction

Damage in a structure is defined as changes to the geometric and material properties, which lead to a reduction in the stiffness and stability that negatively affects the performance of the structure. Damage detection at an early phase is very important to prevent the sudden and catastrophic collapse and failure of structural systems [1–3].

Many techniques have been used to locate and identify damage in civil structures. The current non-destructive (NDT) damage identification methods are based on visual inspections and the efficiency of these methods is restricted to accessibility of the structural location in limited areas and relies on initial information concerning the likelihood of damage [4–6]. In addition, if damage is deep within the structure it may not be detectable by these methods. Vibration-based methods are a global damage identification approach that has been considered for use on the dynamic properties of the structure to identify the location and severity of damage without prior information of the type or level of damage. These methods are based on the principle that a reduction in the structural stiffness produces changes in the dynamic characteristics, such as the natural frequencies, mode shapes, and damping ratios.

Most of the vibration-based damage identification approaches developed are considered as some form of pattern recognition since they look for differences between two categories, e.g. before and after a structure is damaged or differences in damage levels. It is observed that the ANNs constitute a powerful intelligence technique that has received wide acceptance for identifying the extent and location of damage in civil structures.

ANNs are inspired by the human brain and have the ability to learn from their experience in order to improve their performance and to adapt themselves to changes in

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Nomenclature

AE	absolute error	h	height
AI	artificial intelligence	L	length
ANN	artificial neural network	L_M1	damage location of individual network
B	beam	l_d/L	location of damage
BPNN	backpropagation neural network	l_d	damage location from support
d_d	damage depth	MLP	multilayer perceptron
E	Young's modulus at undamaged state	MSE	mean squared error
f	natural frequency	NDT	non destructive test
f_{rpe}	relative percentage error for natural frequencies	Nf	natural frequency
f_{exp}	natural frequency from the tested structure	S	severity (d_d/h)
f_{num}	natural frequency from the numerical model	S_M1	damage severity of individual network
FEA	finite element analysis	ϕ	mode shape
FRFs	frequency response functions		

the environment. ANNs are very strong in the presence of noise and other uncertainties. Once ANNs are trained, they are capable of pattern recognition and classification. Vibration-based damage identification is a pattern recognition problem, in which changes in the dynamic parameters of a structure are attributed to certain parameters of damage.

ANNs have been applied extensively in recent years due to their excellent pattern recognition ability, which is useful for structural damage identification purposes. For example, Aydin and Kisi [7] employed the natural frequencies and mode shape rotation deviation data as input to the neural network models to estimate the location and extent of cracks in Timoshenko beam structures. According to the results, ANN models can be applied in diagnosing multiple cracks in beam structures. Guo and Wei [8] proposed a method to detect damage to different locations of varying severity on a simply supported rectangular beam using ANN based on the frequency change parameters. The process was divided into damage detection, location and degree of injury identified, and combined the modal analysis with the neural network to achieve damage assessment. This method also had strong robustness, which was not impacted by small model errors, and the detection accuracy was not influenced by incomplete measurement information.

Damage assessment of prestressed concrete beams using the ANN approach incorporating natural frequency measurements was investigated by Jeyasehar and Sumangala [9]. Based on this work, the ANN was trained with natural frequencies, using only dynamic data obtained for different applied loads on a prestressed concrete beam; the damage level could be assessed with an error of less than 10%. It is shown that an ANN trained with post-crack stiffness and natural frequency is adequate for predicting the damage with reasonable accuracy.

A substructuring technique was applied with a multi-stage ANN method to detect the location and extent of the damage in a two-span continuous concrete slab structure by Bakhary et al. [10]. The mode shapes and natural frequencies of the substructures were used as the inputs to predict the E values of the segment in the identified substructure. The authors showed that by dividing the structure into substructures and analyzing each substructure separately, local damage can be better identified. Based on this technique, all the simulated damage in the structure was successfully detected. There have been many other research efforts that attempted to apply ANNs to identify damage in structural engineering [11–16].

In this research, experimental studies and numerical simulations of I-beam structures are applied to generate dynamic parameters of structures and also to investigate the applicability of ANNs for improved structural damage identification. A combination of natural frequencies and mode shapes are selected as the input parameters of ANNs to predict the severity and location of double-point damage cases in I-beam structures.

In this study, the inputs to the network for predicting the severity and location of damage include the first five flexural modes and all corresponding mode shape values at the points on the centerline of beams. For identification of the severity and location of double damage, initially, five individual neural networks corresponding to mode 1 to mode 5 are considered, and in the second step, a method based on the ensemble neural network is proposed to combine the outcomes of the individual neural networks to a single network. The ensemble neural network considers individual damage sensitivities of the different mode shapes and can predict the identification of damage based on the outputs of the single neural networks. By incorporating ANNs, the potential and accuracy of damage identification can be improved and some significant major problems of conventional methods can be overcome.

2. Artificial neural networks

Artificial neural networks (ANNs) are a family of massively parallel architectures inspired by the human biological brain that are capable of learning and generalizing from examples and experience to produce meaningful solutions to problems even when the input data contain errors and are incomplete. This makes ANNs a powerful tool for solving some complicated engineering problems. Basically, the processing elements of a neural network