# 類神經網路結構健康監測及破壞診斷
# 之分析及實驗研究

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## 摘 要

透過廣泛的分析以及實驗研究，本文將提出一適用於智能結構之整合型結構監測及破壞診斷系統。此結構健康監測系統由多項必要之技術，如系統識別、結構行為監測、以及破壞診斷等所整合而成。

分析研究中包含了兩項主題：一為類神經網路系統識別模式之發展；二為類神經網路破壞診斷方法之發展。在第一項之研究主題中，本文首先提出一新的類神經網路系統識別模式，該模式由類神經網路以及時間域分析技術所組成。結構之系統模態參數可由一利用實測反應所訓練完成之網路權值中直接加以估算而求得，而這些模態參數便可作為診斷結構狀況之依據。此外，本文亦利用類神經網路來架構用於監測結構行為之整體監測網路以及分散式監測網路。這些監測網路除可用於結構系統識別之外，尚可透過觀察監測網路之輸出誤差來偵測破壞之發生或是其位置。在第二項研究主題上，本文提出兩階段的結構破壞診斷方式。第一階段之工作在於偵測破壞產生之位置。研究中證明基於結構模態參數而得之破壞特徵（DLF）僅與破壞位置相關，而與破壞程度無關。於是，DLF 便可作為辨識破壞位置之參考指標。另外，由觀測訊息進而推求結構可能之破壞狀態為一逆運算問題，其處理程序可視為樣本識別（pattern recognition），因此結構破壞偵測之問題相當適合以非監督式模糊神經網路來處理。利用合適的數值模型，吾人可事先建立不同破壞狀態下之解析破壞特徵。當真實之破壞情況發生時，依據系統識別模式所獲得的結構模態參數，便可用於計算實際之量測破壞特徵。接著利用非監督式模糊神經網路，藉由比對量測破壞特徵以及解析破壞特徵，便可診斷出破壞產生之位置。待破壞發生之可能位置決定後，第二階段便可透過本文所述之

演算法來評估破壞的程度。藉由數值或實驗室案例，於分析研究中所發展之模式或方法得以驗證，驗證之結果顯示其於應用上之可行性。

在實驗研究中，吾人設計了一棟四層樓鋼構架作為試體，以便進行勁度損失模擬之震動臺實驗。實驗中以樓層層間勁度之降低來模擬結構之退化(deterioration)。於該試體上共裝置了三種不同的感測器，如加速度計、光纖光柵感測器（FBG sensor）、以及傳統電子式應變計（RSG），以量測試體於實驗中之結構加速度以及應變反應。實驗研究之目的旨在於利用勁度損失模擬之實驗數據：(1）驗證所提系統識別方法；(2）驗證所提破壞診斷策略；(3）探討新式感測器 FBG 於結構監測上之應用性；以及（4）探討其他與破壞相關之破壞指標。經分析，無論使用加速度或是應變量測資料，各種勁度損失模擬情況下的模態參數皆可透過系統識別模式加以獲得，且模態參數之變化情形與模擬之勁度損失狀態具有相當程度之一致性。同時，絕大部分之勁度損失模擬狀況可透過所提之破壞診斷策略加以識別。另外，光纖光柵感測器於結構監測應用上之優勢亦於本實驗中直接或間接獲得證實，例如：其低雜訊特性可使得系統識別更加容易而且精確；而其質輕、體積小、以及單纖多點之特性使其於需要大量感測器之真實土木結構而言，將較傳統之應變計更具潛力。

因此，根據分析研究以及實驗研究之成果，本文提出一整合型的結構監測以及破壞診斷系統架構。該系統將具有即時系統識別、結構監測、破壞診斷、以及提供正確警示之功能。該系統之優點在於：(1）由於本文所提之破壞診斷方法由多種診斷策略所整合，因此儘管其中一種策略無法實行，卻不會造成系統的失敗；（2）由於系統內所包含之方法主要由類神經網路所建立，因此系統將具有可調性，因為該系統之功能將隨著其經歷事件的增加而改善。

# ANALYTICAL AND EXPERIMENTAL STUDY ON THE ARTIFICIAL-NEURAL-NETWORK-BASED HEALTH MONITORING AND DAMAGE DIAGNOSIS OF STRUCTURES


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## ABSTRACT


The main purpose of this dissertation is attempts to organize an integrated system for the health monitoring and damage diagnosis of smart structures through the extensive analytical and experimental study.

Two major researches are investigated in the analytical study, which are (1) development of ANN-based system identification model and (2) development of ANN-based damage diagnosis approach. On the first research, a novel ANN-based system identification (ANNSI) model was proposed for identifying the modal parameters of a structure from its vibratory responses. The modal parameters can be directly estimated from the weighting matrices of a trained ANN, and further be used for diagnosing a structure. Moreover, the proposed global and decentralized monitoring networks can be used for not only identifying but also monitoring the dynamic characteristics of the structure and sub-structure, respectively. On the second research, a damage detection approach, which is based on the damage localization feature (DLF) and an unsupervised fuzzy neural network (UFN), is proposed. It is shown that DLF is correlated with damage location but independent of damage extent. As a result, it is used as indicator to identify the damage location. Detection of structural damage is an inverse problem, and the solving procedure for this problem is a kind of pattern recognition which is very suited to be implemented by unsupervised fuzzy neural networks. Through the use of the UFN, the damage site is located by matching two sets of the damage feature, the analytical DLF which is generated from an analytical model and the measured DLF which is computed according to the identified modal data. Subsequently, estimation of the damage extent is implemented by the proposed

algorithms after the damage location is identified. The developed model or approaches in the analytical study are examined by either numerical or laboratory examples. The simulation results reveal the capability and practicability of the proposed methods.

In the experimental study, a scaled-down four-story steel frame structure was designed to conduct the health monitoring study on the shaking table. The structural deterioration is simulated by reduction of the story stiffness. Three types of sensors, such as accelerometers, fiber Bragg grating (FBG) sensors, and resistant strain gages (RSGs) were installed on the specimen to measure the structural acceleration and strain responses during the shaking table tests. The experimental program aims to perform four tasks: (1) verification of the proposed ANNSI model; (2) verification of the proposed damage diagnosis strategies; (3) investigation of the capabilities of the fiber Bragg grating sensors for structure monitoring; and (4) exploration of other damage related indicators. It is found from the experimental study that the modal data for each simulated deterioration case can be successfully identified form the acceleration and strain measurements by using the ANNSI model, and the variations of the identified modal data in various deterioration cases are highly correlated with the simulated deterioration states. Meanwhile, most simulated deterioration states can be identified by the proposed damage diagnosis strategies. Additionally, the FBG sensors are revealed promising for the structural monitoring because of their distinguishing advantages. For examples, the system identification becomes easier and more accurate as a result of the feature of low noise effect; and the characteristics of light weight, small size, and multiple sensors along a single fiber make the FBG sensors more potential than the RSGs for practical infrastructures where a great quantity of sensors is usually needed.

Based on the results from analytical and experimental study, an integrated health monitoring system is proposed in this dissertation. The system is designed to be capable of on-line system identification, monitoring, diagnosis, and warning. The advantages of the system are: (1) unsuccessful diagnosis by any of the damage strategies will not cause failure in the system performance since the system is integrated with various diagnosis strategies; (2) the system is adaptive because ANNs, which formed the basis of the system, are expected to improve their performance as they acquired more experiences from the environment.