

# Structural damage detection method based on information fusion technique

Liu Tao Li Aiqun Ding Youliang Fei Qingguo

(School of Civil Engineering, Southeast University, Nanjing 210096, China)

**Abstract:** Multi-source information fusion (MSIF) is imported into structural damage diagnosis methods to improve the validity of damage detection. After the introduction of the basic theory, the function model, classifications and mathematical methods of MSIF, a structural damage detection method based on MSIF is presented, which is to fuse two or more damage character vectors from different structural damage diagnosis methods on the character-level. In an experiment of concrete plates, modal information is measured and analyzed. The structural damage detection method based on MSIF is taken to localize cracks of concrete plates and it is proved to be effective. Results of damage detection by the method based on MSIF are compared with those from the modal strain energy method and the flexibility method. Damage, which can hardly be detected by using the single damage identification method, can be diagnosed by the damage detection method based on the character-level MSIF technique. Meanwhile multi-location damage can be identified by the method based on MSIF. This method is sensitive to structural damage and different mathematical methods for MSIF have different preconditions and applicabilities for diversified structures. How to choose mathematical methods for MSIF should be discussed in detail in health monitoring systems of actual structures.

**Key words:** multi-source information fusion; structural damage detection; Bayes method; D-S evidence theory

Structural health monitoring (SHM) has become a hot field of studying civil engineering in the past twenty years. Usually, structural health monitoring systems include a few basic modules, such as sensors, data transmission, structural damage identification, condition assessment and so on. Among them, the theory and implementation method of structural damage identification plays a key role. Static and vibration data can be directly applied or transferred by mathematical methods to detect structural damage. But because the spatial scale is too large and loads vary with environments and working conditions, static data can hardly be directly utilized to identify structural damage for long-span bridges and other complex civil engineering structures. On the other hand, both mass and stiffness are structural inherent parameters. When they change due to rusting, cracking, large

displacement, fatigue etc., structural vibration characteristics, such as frequency, mode, vibration energy, will shift in a certain direction. Therefore, varieties of these dynamic parameters can be used as a token of structural states. On the basis of this, the theory of structural damage identification based on vibration was put forward<sup>[1-4]</sup>, which is a global method, contrary to local methods.

When structural health monitoring drew more and more attention of researchers, the theory and technology of information fusion based on multi-sensor systems came into being. Initially, there were experts and specialists in the military that played an important role in this field. In the beginning, data from many sensors were mixed and disposed to track enemy planes, predict contrails and assess situations. So this technique was named as multi-sensor data fusion (MSDF). From the 1980s, the MSDF technique was exported from the military into automatic control, information processing and so on<sup>[5]</sup>. Afterwards, the concept of data fusion expanded continuously. Researchers found that objects which could be fused were not only data but also images, audio frequencies, symbols, vectors and so on. So multi-source (or multi-sensor) information fusion (MSIF) came into being. MSIF is a new and developing technology based on signal processing, pattern recognition, artificial intelligence, control theory, statistics, decision theory, information theory etc., and it is the integration of many frontal fields (such as wavelet analysis, artificial neural networks, fuzzy logic and so on)<sup>[5-10]</sup>. It is obvious that data from many sensors include more information than from a single sensor. At the same time, the structural health monitoring system consists of many diversified sensors, which collect large numbers of data, signals and information everyday. Therefore, it is reasonable that MSIF be imported into structural health monitoring. In theory, the combination of MSIF and SHM can be realized not only in the parts of monitoring data pretreatment and damage detection but also in condition assessment. In the following portions, MSIF applied to structural damage diagnosis is analyzed in detail, and the ability of the structural damage identification method based on MSIF is verified via an experiment.

## 1 Multi-Source Information Fusion

The concept of data fusion was first proposed in America in the 1970s<sup>[11]</sup>. This technique was put forward to trace flight trails, identify enemies or friends and evaluate military situation. With the rapid and remarkable development over twenty years, the data fusion technique has been improved and enhanced to be a multi-source information fusion. Due to its complexity, there has been no uniform definition of MSIF. In general, MSIF is a technique that uses computers

Received 2007-05-08.

**Biographies:** Liu Tao (1979—), male, graduate; Li Aiqun (corresponding author), male, doctor, professor, aiqunli@seu.edu.cn.

**Foundation items:** The National High Technology Research and Development Program of China (863 Program) (No. 2006AA04Z416), the National Science Fund for Distinguished Young Scholars (No. 50725828), the Excellent Dissertation Program for Doctoral Degree of Southeast University (No. 0705).

**Citation:** Liu Tao, Li Aiqun, Ding Youliang, et al. Structural damage detection method based on information fusion technique[J]. Journal of Southeast University (English Edition), 2008, 24(2): 201 – 205.

to automatically analyze, integrate and utilize spatial-temporal multi-source information following certain rules; as a result of this, it can achieve a consistent explanation and description of the measured objects and thus competently fulfill the decision-making and evaluation tasks<sup>[5, 7-8, 11]</sup>.

### 1.1 Function model of MSIF

The functional model of MSIF is defined consisting of four stages by JDL (Joint Direction of Laboratories, United States of America)<sup>[6]</sup>.

1) The first stage: object assessment. At this stage, the MSIF technique is used to perform data matching, data conjunction, parameter estimation and object identification.

2) The second stage: situation assessment. After the first stage, measures are taken to enter the second information processing course, in which it is a major task that a situation should be abstracted from incomplete data musters and evaluated by researchers.

3) The third stage: impact assessment. On the basis of the above two stages, the future situation is assessed by evaluating what the current situation represents.

4) The fourth stage: process assessment. In this more advanced approach, with some optimizing indices established, the whole fusion process undergoes a real-time treatment of monitoring and evaluation to realize self-adaptive achievements and management of information and optimization of resource distribution. Eventually, the entire system is enhanced and improved.

### 1.2 Classifications of MSIF

Due to different levels of data abstraction, MSIF can be described as three classifications: data-level fusion, character-level fusion and decision-making-level fusion. Different processing courses are taken to deal with different information (such as data musters, character vectors and primary decisions) at diverse levels.

1) Data-level fusion. At this level, all sensor data from a measured object are combined directly and the features are calculated. So, fusion of data at this level contains the most information<sup>[12]</sup>. But, there are some obvious limits to it, such as too great an amount of data to be delivered and calculated. Therefore, data-level MSIF technique is always to be used in image compounds, noise reduction of initial signals and so on.

2) Character-level fusion. At this level, it is clear that characters are first abstracted without fusion. Each data source is pre-processed to extract representative features. For example, signal data may be processed to obtain information about an emitter's direction and emission characteristics, while image data may be processed to obtain information about the size and shape of an observed object (which contains or hosts the emitter)<sup>[8]</sup>. Obviously, data to be dealt with in this classification are much less than at the first level, but, on the other hand, the loss of useful data will result in low performance of object identification in any case.

3) Decision-making-level fusion. It is the highest level of MSIF. At this level, the processes of feature calculation and pattern recognition are applied for single-source data obtained from each sensor. The decision vectors are then fused

using decision-level fusion techniques<sup>[12]</sup>. This level of MSIF needs only a low amount of communication and hardly depends on the types of sensors. But in this process more data and information may be lost.

### 1.3 Mathematical methods of MSIF

The MSIF technique can be realized by many mathematical methods: signal processing and estimation, artificial intelligence, control theory, statistics, decision theory, information theory, geometry methods and so on. In this paper, conclusion methods based on statistics are introduced in detail, and the structural damage detection method put forward in the next part is based on them.

#### 1.3.1 Bayes conclusion method

In a stochastic experiment, there are  $n$  events, separately named as  $A_1, A_2, \dots, A_n$ , which are mutually exclusive. Take  $P(A_i)$  as the probability of the event  $A_i$  occurring. Suppose that  $B$  is any event, and then

$$P(A_i | B) = \frac{P(B | A_i)P(A_i)}{\sum_{j=1}^n P(B | A_j)P(A_j)} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, n \quad (1)$$

This is the famous Bayesian formula<sup>[11]</sup>. When it is applied to MSIF, the method based on the Bayes conclusion method can be described as follows:

Take  $O_1, O_2, \dots, O_m$  as  $m$  objects to be identified, and  $D_1, D_2, \dots, D_n$  as  $n$  sensors. Suppose that the transcendental probability  $P(O_i)$  is known, and therefore from  $n$  sensors the precondition probability matrix can be obtained as follows:

$$\begin{bmatrix} P(D_1 | O_1) & P(D_1 | O_2) & \dots & P(D_1 | O_m) \\ P(D_2 | O_1) & P(D_2 | O_2) & \dots & P(D_2 | O_m) \\ \vdots & \vdots & & \vdots \\ P(D_n | O_1) & P(D_n | O_2) & \dots & P(D_n | O_m) \end{bmatrix}$$

Then, the probability of object  $O_1$  to be detected is

$$P(O_1 | D) = \frac{P(D | O_1)P(O_1)}{\sum_{i=1}^m P(D | O_i)P(O_i)} = \frac{\prod_{j=1}^n P(D_j | O_1)P(O_1)}{\sum_{i=1}^m \left[ \prod_{j=1}^n P(D_j | O_i)P(O_i) \right]} \quad (2)$$

#### 1.3.2 Dempster-Shafer evidence theory

Dempster and Shafer<sup>[13]</sup> brought forward evidence theory in the 1970s, which is an expanded development of probability theory. Owing to setting up the connection of propositions and musters, the uncertainty of propositions is transferred to musters. Suppose that  $A_1, A_2, \dots, A_n$  are  $n$  events;  $D_1, D_2, \dots, D_m$  are  $n$  sensors; and  $M_i(A_j)$  is the probability of the  $j$ -th event from the  $i$ -th sensor. Then, the probability of the event  $P$  is

$$M(P) = C^{-1} \sum_{\bigcap A_j = P} \prod_{1 \leq i \leq m} M_i(A_j) \quad (3)$$

where  $C = 1 - \sum_{\cap A_j = \phi} \prod_{1 \leq i \leq m} M_i(A_j) = \sum_{\cap A_j \neq \phi} \prod_{1 \leq i \leq m} M_i(A_j)$ .

## 2 Multi-Source Information Fusion Applied to Structural Damage Detection

As aforementioned, three-level MSIF methods can be used in structural damage detection. In this paper, structural damage identification methods based on character-level fusion are important contents to be discussed. It is known that every structural damage identification method has its own applicable range. These methods can provide data sources for MSIF. So, it is available that two or more damage identification methods are fused to detect damage by MSIF.

Some structural damage detection methods, such as modal strain energy, modal curvature, flexibility and ratio of frequency variety square, have been verified by researchers. But the feasibilities of these methods are actually case-dependent. With the help of the MSIF technique, two or more damage detection methods can be integrated. In section 3, in a concrete plate experiment, the modal strain energy method and the flexibility method are fused by the character-level MSIF technique. These two damage identification methods

can be looked upon as two sensors and damage detection indices from these two methods can be regarded as character vectors from two sensors. If these two damage character vectors were imported into the Bayesian formula or the D-S evidence theory formula as Eq. (2) or Eq. (3), the damage probability of every element would be obtained and damage would be localized.

## 3 Experimental Study

When static experiments of two concrete plates are performed, a dynamic measurement is carried out. And then, response information is imported in software for modal analysis, their and dynamic characteristics will be obtained. Set plate 2 as an example and the experiment course is described as follows:

The dimensions of plate 2 are 2.0 m × 0.64 m × 0.06 m. Steel braces are placed as supports. Measurement spots are emplaced on the middle of the short dimension along the long dimension. Element numbers and measurement spot numbers are shown in Fig. 1.

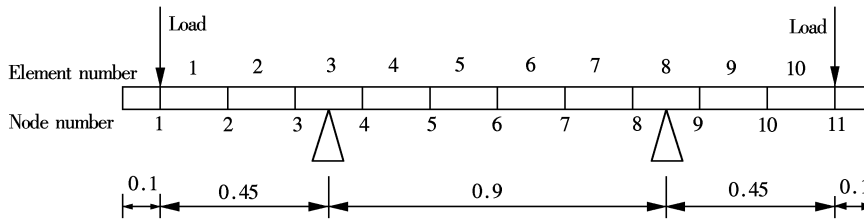


Fig. 1 Experiment of a RC plate (unit: m)

In the experiment, two levers are taken to bring loads on the plate. When pre-pressure is finished, modal data are collected and this state is noted as the initial case. And then, 20 kg is delivered on the plate as one level load until the first crack comes into being. Here, modal information is gathered again and this state is noted as damage case one. Subsequently, 10 kg is taken as one level load until many cracks appear. This state is named as damage case two and modal data are collected again. Thus, testing cases are delivered in Tab. 1.

Tab. 1 Cases of the RC plates experiment

Plate	Damage case one	Damage case two
1	Single crack between nodes 9 and 10	Multiple cracks
2	One crack between nodes 4 and 5 Another crack between nodes 8 and 9	Multiple cracks

Taking damage case one as an example, the flexibility method and the modal strain energy method are imported into MSIF as aforementioned in section 2. The Bayes method and the D-S evidence theory are applied to improve the validity of damage detection. So, results from the experiment are delivered in Fig. 2 and Fig. 3. From them, it is obvious that:

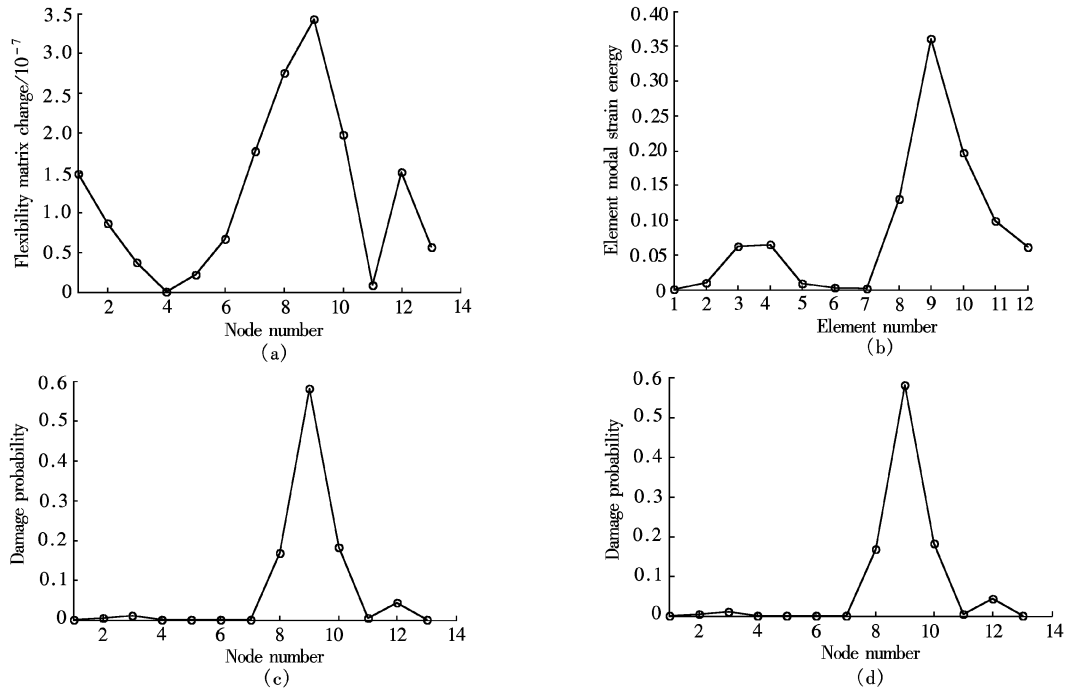
1) The damage case one of plate 1 can be effectively detected by neither the flexibility method nor the modal strain energy method. On the contrary, by the method based on

MSIF the damage case one of plate 1 can be identified correctly.

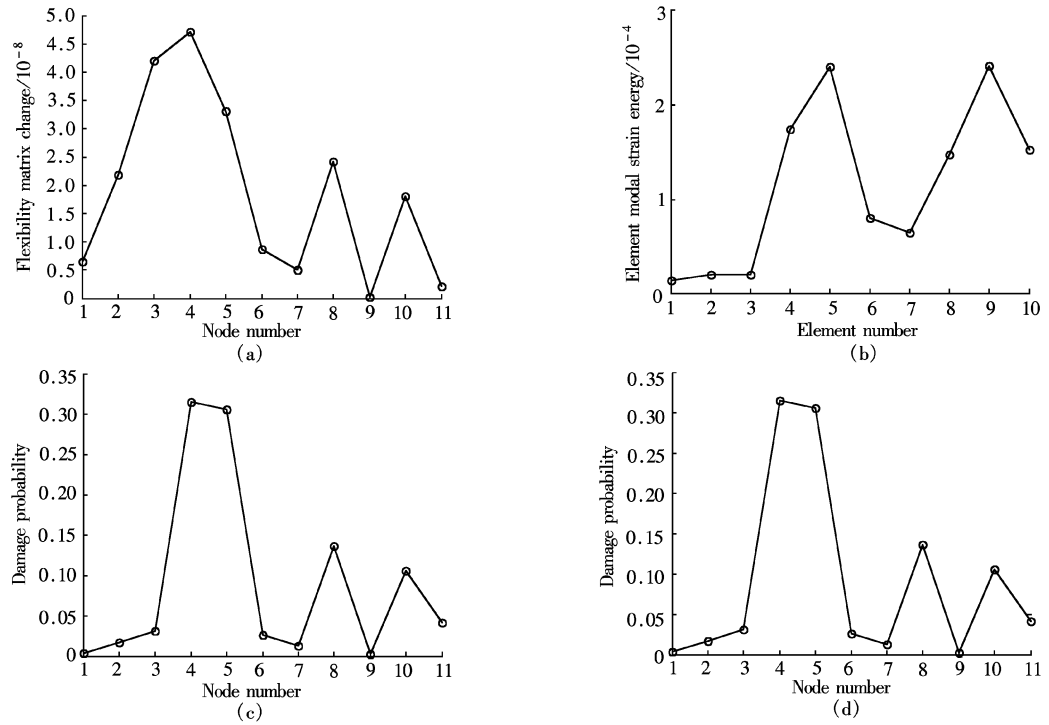
2) For the damage case one of plate 2, which is a multi-location damage case, damage can hardly be localized by the method of either flexibility or modal strain energy. After the MSIF technique is imported into damage identification, the crack between nodes 4 and 5 can be diagnosed effectively and efficiently. At the same time, the crack between nodes 8 and 9 can be easily identified, but maybe the misjudgment for an element around might appear.

Two or more structural damage identification methods fused by the Bayes method or the D-S evidence theory have a better damage diagnosis ability than one single damage identification method. Applying the MSIF technique into structural damage identification is useful for improving the validity of damage detection.

At the same time, identification results by the Bayes method are similar to those of the D-S evidence theory. That is because the D-S evidence theory is an expanded development of probability theory. So it is appropriate that the Bayes method be considered as a special case for the D-S evidence theory. In this experiment, when the transcendental probability  $P(A_i)$  is decided, two MSIF methods will obtain similar results.



**Fig. 2** Damage identification results of the damage case one for plate 1. (a) Flexibility method; (b) Modal strain energy method; (c) Bayes method; (d) D-S evidence theory



**Fig. 3** Damage identification results of the damage case one for plate 2. (a) Flexibility method; (b) Modal strain energy method; (c) Bayes method; (d) D-S evidence theory

4 Conclusions

Multi-source information fusion has played an important part in the military for twenty years and has been imported into civil fields. It is obvious that multi-source information fusion can be applied to structural health monitoring and damage diagnosis. In this paper, the structural damage identification method based on MSIF is put forward, which is to

fuse two or more structural damage identification methods on the basis of the character-level information fusion. Subsequently, with a concrete plate experiment, the ability of damage identification of this structural damage detection method is discussed in detail. So, some important and practical conclusions are drawn as follows:

1) It is feasible that multi-source information fusion be employed in structural damage diagnosis. After information fusion, the ability and reliability of damage identification

methods have been improved to a considerable extent.

2) For large-scale civil engineering, especially long-span bridges, detecting structural damage accurately is almost impossible only by one single damage identification method. The MSIF technique can be used to fuse two or more damage identification methods on the character-level or other level. Through an experiment of concrete plates, it is clear that this method has a better ability to identify damage than one single method. Because the D-S evidence theory includes the Bayes method to a certain extent, damage diagnosis results based on the D-S evidence theory are similar to those of the Bayes method. But, there are some differences between the two mathematical methods. So, how to choose mathematical methods for MSIF should be discussed in detail in health monitoring systems of actual structures.

## References

- [1] Doebling S W, Farrar C R. The state of the art in structural identification of constructed facilities [R]. Los Alamos: Los Alamos National Laboratory, 1999.
- [2] Yeung W T, Smith J W. Damage detection in bridges using neural networks for pattern recognition of vibration signatures [J]. *Engineering Structures*, 2005, **27**(5): 685 – 698.
- [3] Ding Y L, Li A Q, Miao C Q. Theoretical research on structural damage alarming of long-span bridges using wavelet packet analysis [J]. *Journal of Southeast University: English Edition*, 2005, **21**(4): 459 – 462.
- [4] Farrar C R, Lieven N A. Damage prognosis: the future of structural health monitoring [J]. *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences*, 2007, **365**(1851): 623 – 632.
- [5] Xiao C, Qu W L, Tan D M. An application of data fusion technology in structural health monitoring and damage identification [C]//*Smart Structures and Materials 2005: Smart Sensor Technology and Measurement Systems*. Bellingham, WA, USA, 2005: 451 – 461.
- [6] Steinberg A N, Bowman C L, White F E. Revisions to the JDL data fusion model [C]//*Sensor Fusion: Architectures, Algorithms, and Applications III*. Orlando, Florida, USA, 1999: 430 – 441.
- [7] Liang A, An D X, Zhou D H, et al. A finite-horizon adaptive Kalman filter for linear systems with unknown disturbances [J]. *Signal Processing*, 2004, **84**(11): 2175 – 2194.
- [8] Niu G, Han T, Yang B, et al. Multi-agent decision fusion for motor faults diagnosis [J]. *Mechanical Systems and Signal Processing*, 2007, **21**(3): 1285 – 1299.
- [9] Liu T, Li A Q, Ding Y L, et al. Damage identification method for continuous beam bridges based on information fusion and modal strain energy [C]//*Proceedings of International Conference on Health Monitoring of Structure, Material and Environment*. Nanjing: Southeast University Press, 2007: 602 – 606.
- [10] Bao Y Q, Li H. Application of information fusion and Shannon entropy in structural damage detection [C]//*Health Monitoring of Structural and Biological Systems 2007*. San Diego, California, USA, 2007: 101 – 109.
- [11] Hall D L. *Mathematical techniques in multi-sensor data fusion* [M]. Boston: Atech House, 1992: 20 – 25.
- [12] Hall D L. Perspectives on the fusion of image and non-image data [C]//*Proceedings of the 32nd Applied Imagery Pattern Recognition Workshop*. Los Alamitos, California, USA, 2003: 217 – 220.
- [13] Shafer G A. *A mathematical theory of evidence* [M]. New Jersey: Princeton University Press, 1976: 33 – 36.

## 基于信息融合技术的结构损伤诊断方法

刘 涛 李爱群 丁幼亮 费庆国

(东南大学土木工程学院, 南京 210096)

**摘要:**为提高结构损伤识别的准确率,将多源信息融合技术引入到结构损伤诊断中.在介绍多源信息融合技术的基本理论、功能模型、级别分类和数学方法的基础上,将2种或多种结构损伤识别方法提取的损伤特征向量进行特征级融合,建立了基于信息融合的结构损伤诊断方法.在钢筋混凝土板损伤试验中测试其模态信息,利用基于信息融合的结构损伤诊断方法进行裂缝位置识别,并与单独使用模态应变能法和柔度法进行损伤识别的结果进行对比.结果显示基于特征级信息融合的结构损伤诊断方法能够准确识别单一损伤识别方法无法识别的结构损伤,对于多位置损伤识别亦有效果.基于信息融合的结构损伤诊断方法具有良好的损伤敏感性.不同的信息融合算法有不同的适用范围,在实际结构健康监测中,要通过详细分析选择合适的多源信息融合算法.

**关键词:**多源信息融合;结构损伤诊断;Bayes方法;D-S证据理论

**中图分类号:**TU311.41;TB123