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An Associative Model for Damage Diagnosis of Existing Buildings

Modèle associatif pour le constat de dommages dans des bâtiments existants

Ein assoziatives Modell für die Schadensdiagnose an bestehenden Bauten

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SUMMARY
In many cases, damage phenomena are quite complex, and their causes may have different plausibility values. A knowledge-based associative model is introduced for coding more experience from domain experts. The present model can be used to obtain a number of possible damage causes and also to show the plausibility value for each damage cause. The model has already been applied in an expert system called "Reliability Assessment In Structural Engineering which has been recommended by the State Ministry of Construction of China.

RÉSUMÉ
Il n'est pas toujours possible d'établir des relations causales entre un dommage observé et ses causes. Pour les cas où plusieurs valeurs plausibles existent pour l'origine des dommages, un modèle associatif à base de connaissance a été réalisé, prenant en compte l'expérience des spécialistes. Le modèle donne la plausibilité pour chaque cause de dommage et son usage a été recommandé comme système expert en Chine.

ZUSAMMENFASSUNG
Nicht immer lassen sich für die Schadensdiagnose einfache kausale Beziehungen zwischen beobachtetem Schaden und seiner Ursache herstellen. Für den Fall, dass mehrere plausible Werte für Schadensursachen existieren, wurde ein wissensbasiertes, assoziatives Modell eingeführt, um mehr Erfahrung von Fachexperten zu kodieren. Das Modell gibt die Plausibilität für jede Schadensursache an und wurde als Expertensystem *in China empfohlen.*

1. INTRODUCTION

It is well known that the knowledge on damage diagnosis of existing buildings is dependent on the particular expert who has his own experience from his career and the diagnostic methodology for one expert is also quite different from others[1][2]. After collecting enough knowledge it is easy to find that the knowledge on damage diagnosis could be grouped into two ways, which can be expressed as follows.

(a) For more simple damage phenomena there may be only one or two causes existing. In this case, domain experts may use a hard mapping , such as "if A then B", to do the diagnosis. Here A means the damage phenomenon and B means the damage cause.

(b) For more complex damage phenomena more damage causes may exist. In this case, domain experts may consider their characteristics, and based on some association, may use a soft mapping, such as "if $A_1, A_2, A_3, \ldots$, then$B_1, B_2, B_3, \ldots$ ". Even then, it is also possible to give a plausibility for each damage cause by experience from domain experts.

Most expert systems for damage diagnosis or assessment of existing buildings are using the first simple way. Its advantages are obvious. Such as, it is easy to acquire knowledge and to build a knowledge base. The reasoning method is also relatively simple. But for more complex damage phenomena, the most plausible cause among all the damage causes may not be easy to be obtained. Since the simple rule is too strict, which may not be able to express different diagnostic experience from different expert. To the end, an association model introduced in the present paper is needed.

Based on the present model all the possible damage causes can be obtained, and according to the diagnostic knowledge from domain experts the most plausible cause can eventually be obtained. In fact, the first way using simple rules is a particular case of the introduced association model. This model has already been performed in an expert system called "**R**eliability **A**ssessment **I**n **S**tructural **E**ngineering (**RAISE**-3 and **RAISE**-4)"[3][4][5], which has been recommended by the State Ministry of Construction of China.

2. AN ASSOCIATION MODEL FOR DAMAGE DIAGNOSIS

Assume that $M_1, M_2, \ldots, M_n$ to be the various damage modes; $K_{c\_1}, K_{c\_2}, \ldots, K_{c\_m}$ to be the various kits of damage causes; and $C_{1\_1}, C_{1\_2}, \ldots, C_{2\_1}, C_{2\_2}, \ldots, C_{m\_1}, C_{m\_2}, \ldots$ to be the various damage causes.

Call the set $MD\_S = \{M_1, M_2, \ldots, M_n\}$ to be the set of damage modes; $KC - S = \{K_{c\_1}, K_{c\_2}, \ldots, K_{c\_m}\}$ to be the set of damage cause kits ; and

$C\_S = \{C_{1\_1}, C_{1\_2}, \ldots, C_{2\_1}, C_{2\_2}, \ldots, C_{m\_1}, C_{m\_2}, \ldots\}$ to be the set of damage causes. Each of damage cause kits includes a number of the damage causes, such as

$$K_{C\_X} = \{C_{X\_1}, C_{X\_2}, \ldots\} \quad (X = 1,2,\ldots,m).$$

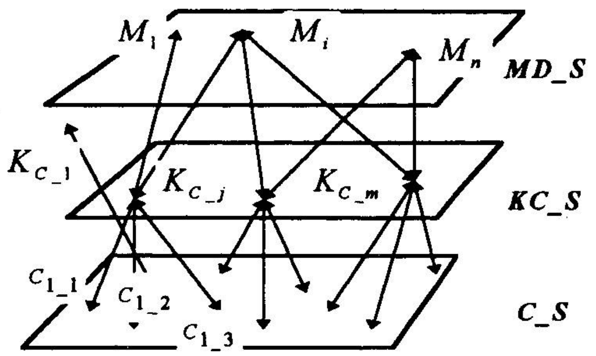

Fig. 1 The Association Model

The relationship between *MD_S*, *KC_S*, and *C_S* is shown in Fig.1. According to this model, any given element $M_i (i = 1,2,...,n)$ from the set of damage modes, *MD_S*, can be connected with several kits in the set of *KC_S* by association. On the other side, any given damage cause kit $K_{C\_j} (j = 1,2,...,m)$ from *KC_S* can also be connected with several damage modes from *MD_S* by association, and furthermore, they also can be connected with several damage causes from the set *C_S* by association as well. In other words, any element in the set of damage modes, *MD_S*, can be connected not only with elements in the set of damage cause kits (*KC_S*) directly but also with elements in the set of damage causes (*C_S*) indirectly. It means that, by association, it is possible to obtain all damage causes for any damage mode . Also, it is possible to obtain all damage modes for any damage cause by association.

In general, a damage phenomenon does not mean only one damage mode happened. Usually it includes several modes. Using the present association model all the possible damage causes for the several damage modes in a same damage phenomenon can be obtained. In order to determine the most plausible damage cause from a damage phenomenon the concepts on the plausibility of a damage cause, the medium set of damage modes, the medium set of a damage phenomenon, the intersection of the medium sets, and the union of the medium sets should be defined first, which will be introduced as follows.

3. THE PLAUSIBILITY OF DAMAGE CAUSES

As explained previously, any damage mode , in the most cases, can not be induced by one cause only. Among all the causes, some of them have higher possibility and some of them have lower. In the present paper, the plausibility is used to describe the possibility of a damage cause which induced a certain damage mode. It means that, for a certain damage cause, the higher possibility the higher plausibility and vice versa. At present, two different definitions on the plausibility should be introduced first.

(1) Plausibility A_{ij} : to describe the possibility of that the damage mode M_i is caused by the damage cause kit K_{C_j}.

(2) Plausibility a_{ijk} : to describe the possibility of that the damage mode M_i is caused by the damage cause C_{j_k} from the damage cause kit K_{C_j}.

In fact, the plausibility is a fuzzy measurement in the damage diagnosis. For different damage phenomena the plausibility values of the same damage cause kit (or of the same damage cause) may be different. Even for the same damage mode in the same damage phenomenon the plausibility values for different domain experts are different. In general, the plausibility can change between a certain interval. In RAISE-3 and RAISE-4, according to the experts' experience, the plausibility interval is chosen as [0,1].

4. THE MEDIUM SET, INTERSECTION, AND UNION

The medium set of a damage mode means a set, which includes all the possible damage cause kits for the damage mode and their plausibility values. The medium set of a damage phenomenon means a set of all the medium sets of the possible damage modes. They can be obtained as follows.

4.1 The Medium Set of a Damage Mode M_i

As shown in Fig. 1, all the possible damage causes of M_i, such as $K_{C\_1}, K_{C\_2}, \ldots$; can be obtained by association. According to the knowledge from domain experts the plausibility values of $K_{C\_1}, K_{C\_2}, \ldots$, such as $A_{i1}, A_{i2}, \ldots$, also can be determined. Thus, the medium set of damage modes MM_S_i can be expressed as

$$MM\_S_i = \{(K_{C\_1}, A_{i1}), (K_{C\_2}, A_{i2}), \ldots\} \qquad (1)$$

which is called the medium set of a damage mode M_i.

4.2 The Medium Set of a Damage Phenomenon App_i

It is assumed that a damage phenomenon App_i is consists of a number of damage modes, such as $M_1, M_2, \ldots, M_d$ (in Fig. 1, d usually is less than n). There is a set,

$$AM\_S_i = \{MM\_S_1, MM\_S_2, \ldots, MM\_S_d\} \qquad (2)$$

which is called the medium set of the damage phenomenon App_i.

Unlike the classical definitions , the concepts on intersection and union used here have some different meanings, which can be shown as follows.

4.3 The Intersection of Medium Sets

Since the damage phenomenon App_i consists of several damage modes $M_i(i=1,2,...,d)$, the intersections between the medium sets of the damage modes $M_i(i=1,2,...,d)$, i.e. $MM\_S_i(i=1,2,...,d)$, and the medium set AM_S_i of App_i can be obtained respectively, by the following way.

(a) According to the association model shown in Fig.1 and considering the plausibility values find the medium sets of damage modes $M_i(i=1,2,...,d)$ as Eg. (1).

(b) As introduced previously, find the medium set of damage phenomenon App_i as Eg. (2).

(c) Compare each element of MM_S_i *(i=1,2,...,d)* with elements of AM_S_i , respectively. If one of $K_{C\_j}(j=1,2,...,m)$ appears in t elements of AM_S_i and t $(t \le d)$ is bigger enough, which means that it may cause the most damage modes in App_i , then this K_{C_j} and its plausibility can be treated as one element in the intersection. Otherwise take the next MM_S_i to continue. Finally the intersection between MM_S_i *(i=1,2,...,d)* and the medium set AM_S_i of App_i can be done. It can be called IS_i .

4.4 <u>The Union of Medium Sets</u>

Among the damage modes $M_i(i=1,2,...,d)$ of App_i such a damage mode always exists: when it appears, its major cause or a few of causes of it can be confirmed. It means that for some damage modes the numbers of possible damage causes are very limited and they are easy to be determined. In this case, such damage mode in App_i should be considered as **"more important"** and its weight also should be bigger than others. If there are many damage causes for a damage mode, and they are also different from those of other damage modes, then such damage mode is considered as **"not so important"** and may have smaller weight. Based on this consideration, the importance order of $M_i(i=1,2,...,d)$ in App_i can be done by domain experts. The union can be obtained as follows.

(a) Rearranging the damage modes $M_i(i=1,2,...,d)$ in App_i by their importance order and assuming that the importance order of $M_i(i=1,2,...,d)$ in App_i has been done as the original order, the medium set of App_i will be the same as Eq.(2).

(b) Find the intersection between MM_S of the damage mode M_1 and the medium set AM_S_i of App_i , i.e. ,

$$IS_1 = \{...,(K_{C\_j}, A_{1j}),....\} \quad (j \le m) \qquad (3)$$

Rearranging the elements (K_{C_j}, A_{1j}) in $IS_{\_1}$ by the order of A_{1j} a new set MS_i is obtained. Herein it is assumed that the order of elements in $IS_{\_1}$ is the same as in MS_i.

(c) Find the rest of intersections between $MM\_S_i(i=2,...,d)$ of the damage modes $M_i(i=2,...,d)$ and the medium set AM_S_i of $App_{\_i}$, respectively. They are, $IS_2,...,IS_d$. Rearrange the elements (K_{C_j}, A_{ij}) in $IS_2,...,IS_d$ by the order of their plausibility values.

(d) Compare the elements in $IS_{\_i}(i=2,...,d)$ with those in MS_i, respectively. If the element (K_{C_j}, A_{ij}) has appeared in MS_i already, then there is no need to modify MS_i. Otherwise the mentioned element (K_{C_j}, A_{ij}) should be treated as a new element to be put on the tail in MS_i. Finally, the modified union MS_i can be done. It should be noted that the MS_i is also a medium set of $App_{\_i}$, but it is different from AM_S_i.

5. THE MOST PLAUSIBLE DAMAGE CAUSE

As mentioned previously, the order of chosen damage cause kits $K_{C\_i}(i \le m)$ in MS_i, is determined by their plausibility values. Thus, the most plausible damage cause for the damage phenomenon $App_{\_i}$ can be inferred by the following way.

(a) According to the given damage phenomenon $App_{\_i}$ to find the medium set MS_i.

$$MS_i = \{....,(K_{C\_j}, A_{ij}),....\} \quad (i=1,...,d; j \le m) \qquad (4)$$

(b) Following Fig. 1 to find all the damage causes $C_{j\_1}, C_{j\_2},...$ for each of the K_{C_j} in MS_i.

(c) Find the most plausible damage cause among $C_{1\_1}, C_{1\_2},...$, which causes the first damage mode M_1 in $App_{\_i}$. If there is no possibility to cause M_1 by $C_{1\_1}, C_{1\_2},...$, then do the same for the second damage mode M_2. Similarly it can be done for other damage modes. Finally the most plausible damage cause C_{i_x} for some damage mode should be certainly obtained.

(d) According to Fig. 1 check the number of damage modes in $App_{\_i}$, which are caused by C_{i_x}. If the number r is bigger than a certain value (it can be determined by domain experts) then the damage cause C_{i_x} can be considered as the most plausible damage cause for the damage phenomenon $App_{\_i}$. In this case, the chosen C_{i_x} also can be shown to users to confirm it.

(e) If the number r is less than the required value or users do not agree with the chosen C_{i_x}, then we can continue to find it among the others of $C_{j\_1}, C_{j\_2}, \ldots$. If we can not find the most plausible damage cause from K_{C_j}, then we can continue to do the same process for $K_{C\_(j+1)}, K_{C\_(j+2)}, \ldots$.

In general, following the mentioned steps, the most plausible damage cause should be diagnosed, which can be seen in the following example.

6. EXAMPLE

Assume that a damage phenomenon App_1 is found in a reinforced concrete industrial workshop and the damage phenomenon consists of four damage modes, such as M_1, M_2, M_3, M_4 (here $d=4$), which are: M_1 Diagonal cracks on the wall closed to both ends of the workshop; M_2 Horizontal cracks on the internal sides closed to the columns' bottom; M_3 Vertical cracks on the lower wall; and M_4 Squeeze between Rail and crane wheels (Fig.2).

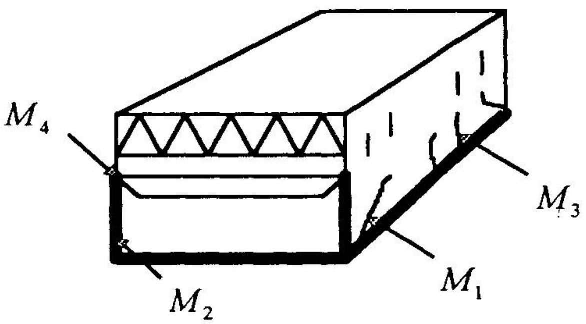

Fig.2 A Damage Phenomenon App_1

Also assume that the association mode for damage diagnosis of the present building has been made and all the plausible damage cause kits in the present case are known (as shown in Fig.1 $m=4$), which are: K_{C_1}: Foundation ; K_{C_2}: Temperature ; K_{C_3} : Construction ; K_{C_4} : Load . Thus, the diagnostic process can be done as follows.

(a) Based on the mentioned association model, such as shown in Fig.1, and according to the related plausibility values known from domain experts, the medium sets of the damage modes, as explained in Section 4.1, can be obtained. In the following parentheses, the first term means the plausible damage cause kit and the second term means its plausibility. They are,

M_1 MM_S_1={(Foundation, 0.8), (Temperature, 0.7)}

M_2 MM_S_2={(Construction, 0.6), (Foundation, 0.5), (Load, 0.55)}
M_3 MM_S_3={(Foundation, 0.7), (Temperature, 0.6), (Load, 0.3)}
M_4 MM_S_4={(Load, 0.6), (Foundation, 0.3), (Construction, 0.4)} .

(b) The medium set of the present damage phenomenon App_1 can be found as shown in Section 4.2, which is,

$AM-S_1=\{MM-S_1, MM-S_2, MM-S_3, MM-S_4$
= {((Foundation, 0.8), (Temperature, 0.7),
((Construction, 0.6), (Foundation, 0.5), (Load, 0.55)),
((Foundation, 0.7), (Temperature, 0.6), (Load, 0.3)),
((Load, 0.6), (Foundation, 0.3), (Construction, 0.4))}

(c) According to Section 4.3 the intersections between the medium sets $MM\_S_i(i=1,2,3,4)$ of damage modes $M_i(i=1,2,3,4)$ and the medium set AM_S_1 of App_1 can be obtained respectively. They are,

IS_1= {(Foundation, 0.8)}
IS_2= {(Foundation, 0.5), (Load, 0.55)}
IS_3= {(Foundation, 0.7), (Load, 0.3)}
IS_4= {(Load, 0.6), (Foundation, 0.3)} .
It should be noted that, as mentioned in Section 4.3(c), t is taken as 3.

(d) As explained in Section 4.4, the importance order of damage modes of App_1 should be: M_1, M_3, M_2, M_4 . In this case, following Section 4.4 (b) (c) (d), the union should be

MS_1= ((Foundation, 0.8), (Load, 0.3))

(e) At this step, the most plausible damage cause of App_1 can be inferred . Since the association model has bee given, the damage causes contacted with the foundation problem and the load problem should be known. Their related damage modes and corresponding plausibility values can be shown as follows.

Foundation K_{C_1} C_{1_1} Uneven settlement
$(M_1,0.8),(M_3,0.5),(M_2,0.3)$
C_{1_2} Soil freeze-thaw
$(M_2,0.4),(M_1,0.3),(M_4,0.1)$

		C_{1_3}	Soil holes $(M_4,0.3),(M_3,0.5),(M_2,0.4)$
Load	K_{C_4}	C_{4_1}	Overloading horizontally $(M_2,0.6),(M_3,0.15),(M_4,0.3)$
		C_{4_2}	Overloading vertically $(M_2,0.1),(M_3,0.5),(M_4,0.6)$

According to MS_1, It is known that the most plausible damage cause for the damage phenomenon $App_{\_1}$ should be found among the damage causes of the foundation, i.e. K_{C_1}. The inference process is shown as follows.

(a) As explained in Section 5(c) previously, among $C_{1\_1}, C_{1\_2}, C_{1\_3}$, the most plausible damage cause to induce the damage mode M_1 is C_{1_1}. In this case, it is assumed that C_{1_1} is also the most plausible damage cause for the given damage phenomenon $App_{\_1}$.

(b) Following Section 5(d), since C_{1_1} causes three damage modes, i.e. M_1, M_2, M_3 (in this case $r=3$), it can be considered as the most plausible damage cause for $App_{\_1}$, and send it to users to confirm it.

(c) If users do not agree with C_{1_1}, then the most plausible damage causes also can be found from C_{1_2}, C_{1_3} by the bigger plausibility values of M_1. Thus, C_{1_2}(with $r=3$) can be found. Similarly, it should be sent to users also.

(d) If users still refuse to agree with it, then the same process can be done for M_3, M_2, M_4, respectively. In this case, C_{1_3}(with $r=3$) should be found.

(e) If it is impossible to find the most plausible damage cause from the foundation problem (in the damage cause kit K_{C_1}), then following the order M_1, M_3, M_2, M_4 , the same process can be done in K_{C_4} (loading problem). Similarly, C_{4_2} and C_{4_1} can be found.

The final diagnostic result for the damage phenomenon shown in Fig.2 should be in the following plausibility order: *Uneven settlement of foundation, Soil freeze-thaw of foundation, Soil holes of foundation*. If there is no problem on foundation. The damage causes may be *Overloading vertically*, or *Overloading horizontally*.

7. REMARKS

Obviously, the structure of the association model and its relative plausibility values should be determined by domain experts first. Comparing with the simple rule "if *A* then *B*" it is more general. It also should be mentioned that unlike neural network models[6][7] the present model can code the diagnostic experience in explicit form. Therefore, It is more efficient in practice. Besides, it is very flexible to improve the model structure and plausibility values for coding new knowledge.

The present model, as one of useful models, has already been used in an expert system called "Reliability Assessment in Structural Engineering"(RAISE). It was written in GCLISP and FROTRAN under windows. There are two versions available: RAISE-3 (English version) and RAISE-4(Chinese version). According to the assessment results from 160,000 M^2 existing industrial building, the comparison between system RAISE and experienced engineer is very satisfactory. RAISE with the present association model has been recommended by the state Ministry of Construction of China since 1994.

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