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A rule-based fuzzy logic deduction technique for damage assessment of protective structures*

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Abstract: In order to obtain the overall damage level of a protective structure, the values of each variable of the damage criteria should be determined. Assessments by experts result in the production rules for use in a knowledge-based expert system. In cases where conflicting rules occur, fuzzy set operations can be used to solve the problem. The modus ponens deduction technique can be employed for partial matching or development of new rules.

Keywords: Damage assessment; expert system; fuzzy sets; fuzzy logic; protective structures.

Introduction

Earlier work relating the modes of failures to various damage levels of protective structures was performed by Ross et al. [8]. A study concerning the evaluation of the damage criteria and their variables was later performed by Hadipriono [6]. The damage level of protective structures depends on damage criteria, such as functionality, repairability, and the structural integrity of the structure.

Assessment of damaged protective structures is usually performed by experts through subjective judgments in which linguistic values are frequently used. Therefore, their values can be represented by fuzzy sets. In this study, three groups of expert judgments for assessing the values of these variables on various levels of damaged structures were collected. The results were used to develop the production rules of a knowledge-based expert system.

The following sections describe the damage criteria and their variables, fuzzy production rules, and fuzzy partial matching using the concept of fuzzy logic.

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Damage criteria and damage level

In this paper, functionality represents the intended use or function of a structure. A protective structure is constructed to protect equipment and its occupants. Therefore, the type of equipment being protected, equipment damage level, position of occupants (people), and occupant level of injury are the variables that determine the functionality and, subsequently, indicate the damage level of the structure. Table 1 shows these variables and their values.

A damaged protective structure should be repaired in order to restore it to an original or an acceptable condition. The term 'acceptable' is used here to indicate that during an 'attack period' command personnel may only require that a structure be partially repaired; hence, in this case the structure does not have to be restored to its original condition. Several variables determine the repairability of protective structures: the amount of repair, repair time, repair cost, and resource availability. The linguistic values of these variables are presented in Table 2.

Table 1. Variables and values of functionality

Variable	Symbol	Value	Symbol	Remarks
Type of equipment destroyed	TEQ	I	HMA	Heavy mach.: motors, gen'rs, etc.
		II	MMA	Med, mach.: pumps, conden., etc
		III	LMA	Light mach: fans, small motors.
		IV	LAE	Large elect.: Comm. eq, relays.
		V	SME	Small elect.: radios, lamps.
		VI	CRT	Cathode ray tubes.
		VII	TRC	Trans. comp., fixt's, nuke react.
		VIII	PDW	Piping, duct works
Equipment damage level	DEQ	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	SLI	
		None/neglig.	NNE	
		Undecided	UND	
Position of occupants	POC	IA, IB	STU	Standing Unrestrained
		IIA, IIB	SIT	Sitting Unrestrained
		IIIA, IIIB	PRU	Prone Unrestrained
		IVA, IVB	SIR	Sitting Unrestrained
		VA, VB	PRR	Prone Restrained
Occupant injury level	IOC	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	SLI	
		None/neglig.	NNE	
		Undecided	UND	

Table 2. Variables and values of repairability

Variable	Symbol	Value	Symbol	Remarks
Amount of repair	AR	Very substantial	VSB	
		Major	MAJ	
		Moderate	MOD	
		Minor/slight	MIN	
		Negligible/none	NNE	
		Undecided	UND	
Repair time	RT	Very long	VLO	More than 4 months
		Long	LON	2–4 months
		Moderate	MOD	1–2 months
		Short	SHO	2 days–1 month
		Very short	VSH	Less than 2 days
		Undecided	UND	
Repair cost	RC	Very expensive	VEX	More than $5 mill.
		Expensive	EXP	$1 mill–$5 mill.
		Moderate	MOD	$0.2 mill–$1 mill.
		Inexpensive	IEX	$0.01 mill–$0.2 mill.
		Negligible	NEG	Less than $0.01 mill.
		Undecided	UND	
Resource availability	RA	Very abundant	VAB	
		Abundant	ABD	
		Moderate	MOD	
		Scarce	SCC	
		Very scarce	VSC	
		Undecided	UND	

Structural integrity is defined as the stability or capacity of a structure or its component(s) to perform its intended function. Variables affecting the structural integrity are: deformation, displacement, and/or separation. A structure experiencing these variables suffers a certain level of degradation to integrity. Table 3 lists these variables and their values.

The above variables of the damage criteria and their values can be used to construct the production rules in an expert system. These rules can be obtained from experts through questionnaires or interviews. For example, a rule related to the repairability of a severely damage protective structure is shown as follows:

IF (a) major repair is required AND
 (b) repair time is long AND
 (c) repair cost is moderate AND
 (d) resource availability is scarce
THEN there is suggestive evidence that the damage level of the structure is severe.

In this study, the term 'damage level' is used as a measure of the extent of damage to a structure. Also, damage here is associated with structural damage, representing the response of the structure to various short term loading

Table 3. Variables and values of structural integrity

Variable	Symbol	Value	Symbol	Remarks
Deformation	DF	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	NEG	
		Negligible/none	NNE	
		Undecided	UND	
Displacement	DP	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	NEG	
		Negligible/none	NNE	
		Undecided	UND	
Separation	SP	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	NEG	
		Negligible/none	NNE	
		Undecided	UND	

Table 4. Variables and values of damage level

Variable	Symbol	Value	Symbol	Remarks
Damage level	DL	Very severe	VSE	
		Severe	SEV	
		Moderate	MOD	
		Slight	NEG	
		Negligible/none	NNE	
		Undecided	UND	

conditions. Damage level will be treated in this study as a variable whose values are listed in Table 4.

Fuzzy production rules

A knowledge-based expert system (KBES) developed for assessing the damage level of protective structures uses a knowledge base and inference mechanisms through the use of computer programs to solve problems usually performed by experts in a specific field. The knowledge base includes the acquisition from expert(s) or other sources of information, such as historical or experimental data, concerning the values of functionality, repairability, and structural integrity. This information will be collected from three groups of experts associated with the damage criteria.

The fuzzy set concept is then used to quantify the linguistic values of the variables of damage criteria and to construct the rules. Assessments from the same group of experts may result in rules with the following cases: (1) similar antecedents and consequents, (2) similar antecedents but different consequents, (3) similar consequents but different antecedents, or (4) different antecedents and consequents.

In the case of similar antecedents and consequents, fuzzy set operations need not be used. The total number of similar rules determines the weight of damage levels in the rules. In the case where several rules have similar antecedents but different consequents, these rules can be combined. For example, consider a case in which there are five rules with similar antecedents but three of the consequents indicate that the damage level is very severe or "DL is VSE" and two others indicate that the damage level is severe or "DL is SEV". The combined consequents of rules 1 and 2 can be represented by the following:

CONS 1: DL is VSE (0.6) AND
CONS 2: DL is SEV (0.4)

where CONS denotes 'consequent' and where (0.6) and (0.4) are obtained from 3/5 and 2/5, indicating the weight of CONS 1 and CONS 2, respectively.

Two rules can have similar consequents but different antecedents, as is shown below:

Rule (expert 1):	Rule (expert 2):
ANT 1: DEQ is VSE AND	ANT 1: DEQ is SEV AND
ANT 2: IOC is VSE	ANT 2: IOC is VSE

where ANT denotes the antecedent, DEQ is equipment damage level, and IOC is the injury level of the occupants; then these rules can be combined through the use of and OR gate as follows:

ANT. 1: DEQ is (VSE OR SEV) AND
ANT. 2: IOC is VSE

The antecedents and consequents of the rules may be different:

Rule (expert 1):		Rule (expert 2):	
ANT 1:	AR is MAJ AND	ANT 1′:	AR is VSB AND
ANT 2:	RT is VLO AND	ANT 2′:	RT is VLO AND
ANT 3:	RC is EXP AND	ANT 3′:	RC is VEX AND
ANT 4:	RA is ABD	ANT 4′:	RA is ABD
CONS 1:	DL is VSE	CONS 1′:	DL is SEV

where AR, RT, RC, and RA are the amount of repair, repair time, repair cost, and resource availability, respectively. The linguistic values MAJ, VSB, VLO, EXP, VEX, and ABD denote major, very substantial, very long, expensive, very expensive, and abundant, respectively.

Then if the rules do not conflict with each other, they will stay as they are. But if conflicting rules occur as in the ANT 1 and ANT 1′, ANT 3 and ANT 3′, and CONS 1 and CONS 1′ in the above example, a combined rule should be sought through the use of a fuzzy relation such that $R11 = \text{MAJ} \times \text{VSE}$, $R31 = \text{EXP} \times \text{VSE}$, $R1'1' = \text{VSB} \times \text{SEV}$, and $R3'1' = \text{VEX} \times \text{SEV}$, where Rij is the fuzzy relation between ANT i and CONS j; $R11$ and $R1'1'$ are contained in the classes of all fuzzy sets of ($\text{AR} \times \text{DL}$); and $R31$ and $R3'1'$ are contained in the classes of all fuzzy sets of ($\text{RC} \times \text{DL}$).

The combined relations of $R11$ and $R1'1'$ can be obtained through the use of the modified combined fuzzy relation method introduced by Boissonnade which is an extension of Mamdani's approach which combined all relations through fuzzy disjuctions [7]. The method uses modified Newton iterations to reach an optimal solution for the combined fuzzy relations. Details of these techniques can be found in the references cited above. Through the use of this method, the combined relations of R11 and R1'1' yield R111'1'. A similar procedure is performed for R31 and R3'1' to yield R313'1'. The fuzzy composition between R111'1' and R313'1' results in R131'3', contained in the classes of all fuzzy sets of ($\text{AR} \times \text{RC}$). The fuzzy set value for AR and RC, is the projection of R131'3' on planes AR and RC, respectively. The result now yields two rules with similar antecedents but different consequents. Hence, the same procedures can be applied as in case (2).

A complete rule may require the participation of the three damage criteria. Therefore, the rules should also be combined to incorporate the functionality, repairability, and structural integrity of the damage structure. Zadeh developed the extension principle to extend the ordinary algebraic operations to fuzzy algebraic operations [9]. One method based on this principle is the DSW technique introduced by Dong, Shah, and Wong [3, 4]. The technique uses the lambda-cut representations of fuzzy sets and performs the extended operations by manipulating the lambda-intervals. For brevity, further details of these techniques can be obtained in the above references.

In order to accommodate the effect of each damage criteria on the total damage, in this study, we include the weighting factor of each criterion. For example, if the weights of the damage level assessed, based on the above three damage criteria, are assumed to be 'high' (HIH), 'fairly high' (FHI), and 'moderate' (MOD), respectively, and the values of the damage level are DL1, DL 2, and DL 3, respectively, then the overall combined damage level becomes

$$\text{DL tot} = \frac{(\text{HIH} \times \text{DL1}) + (\text{FHI} \times \text{DL2}) + (\text{MOD} \times \text{DL3})}{\text{HIH} + \text{FHI} + \text{MOD}} .$$

Based on the complete rules, new or intermediate rules can be constructed through partial matching.

Partial matching using fuzzy logic

Consider the following production rule: IF deformation (DF) is very severe (VSE), THEN damage level (DL) is severe (SEV). When a fact shows that DF is VSE, the consequent is then realized. However, when the value of DF does not match exactly, e.g., the fact shows that "DF is SEV," then partial matching is in order.

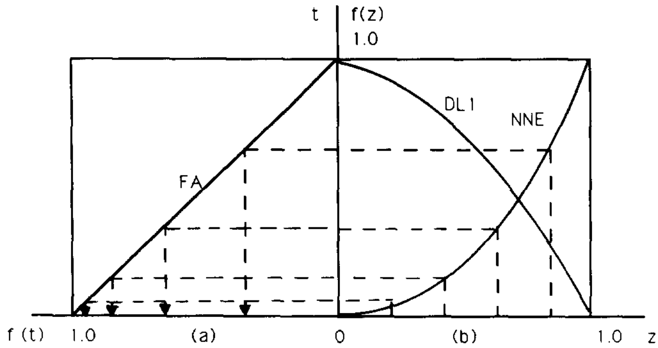

Fig. 1. TFM graphical solution.

This can be performed by the following fuzzy logic operations: (1) truth functional modification (TFM), (2) inverse truth functional modification (ITFM), and (3) modus ponens deduction (MPD). All of these are elaborated on in [2, 5]. Brief descriptions of these operations are provided as follows:

TEM, first introduced by Zadeh [10], is a logic operation that can be used to modify the membership function of a linguistic value in a certain proposition with a known truth value. Suppose that damage level (DL) is 'negligible' or NNE and is believed to be 'false', or FA. This proposition can be expressed as

$$P\text{:}\quad (\text{DL is NNE}) \text{ is FA; NNE} \subset \text{DL, FA} \subset T$$

where DL is a variable (universe of discourse), T is the truth space, and NNE and FA are the values of DL and T, respectively. The symbol $\subset$ denotes 'a subset of ·'. Modification of this proposition yields

$$P'\text{:}\quad (\text{DL is DL1})\text{: DL1} \subset \text{DL}$$

where DL1 is a value of DL. A graphical solution is shown in Figure 1 where the fuzzy set NNE and FA are represented by Baldwin's model [1] and plotted in Figures 1b and 1a, respectively. Further discussion of this model is provided in [2]. Note that the axes of Figure 1a are rotated 90° counterclockwise from Figure 1b. Since the elements of FA are equal to the membership values of NNE, they are represented by the same vertical axis in Figure 1. This means that for any given element of NNE, we can obtain the corresponding element of FA. Also, since the membership values of FA and DL1 are the same, the membership values of DL1 can be found as shown by the arrowheads and plotted in Figure 1b.

ITFM is a logic operation that can be used to obtain the truth values of a conditional proposition. Suppose a proposition, P, is expressed as' 'damage level is negligible given damage level is severe'; then the proposition can be rewritten as

$$P\text{:}\quad (\text{DL is NNE}) \mid (\text{DL is SEV})\text{; NNE, SEV} \subset \text{DL}$$

The ITFM reassesses the truth of (DL is NNE) by modifying this proposition to yield

$$P'\text{:}\quad (\text{DL is NNE}) \text{ is } T1\text{; } T1 \subset T$$

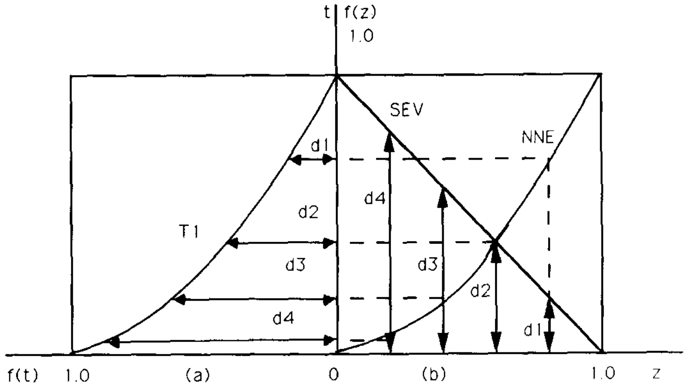

Fig. 2. ITFM graphical solution.

where $T1$ is the new truth value for (DL is NNE). The truth value, $T1$, can also be obtained through the graphical solution shown in Figure 2. Suppose NNE and SEV are again represented by Baldwin's model. The values NNE and SEV are first plotted as shown in Figure 2b. Since the truth level is equal to the membership value of NNE they lie on the same vertical axis. Hence, for each membership value of NNE, the corresponding element of $T1$ is also known. Then too, since the membership value of $T1$ equals that of SEV, for any given element of both NNE and SEV, we can find the corresponding element and membership value of $T1$. The truth value, $T1$, in Figure 2a is constructed by successively plotting the membership values of SEV ($d1$, $d2$, etc.) from Figure 2b at each truth level. Note that the axes in Figure 2a is rotated 90° counterclockwise from Figure 2b.

Modus ponens deduction (MPD) is a fuzzy logic operation whose task is to find the value of a consequent in a production rule, given the information about the antecedent. A simple MPD is: A implies B and given A, then the conclusion is B. Consider again the proposition: 'if deformation is very severe, then damage level is severe,' (IF DF is VSE, THEN DL is SEV). However, suppose further information is available, i.e., 'deformation is severe' (DF is SEV). These propositions can be represented by the following:

P: (DF is VSE) $\supset$ (DL is SEV)
P': (DF is SEV)

where the symbol $\supset$ represents the implication relation between (DF is VSE) and (DL is SEV). This example can be conveniently solved through the following graphic representation. Through the ITFM, P and P' can be combined:

P'': (DF is VSE) is $T1 \supset$ (DL is SEV)

We can obtain the truth value of (DL is SEV), i.e., $T2$, through the use of the implication relation operation introduced by Lukasiewicz [2]. He incorporated the truth relation, denoted as I, of 'if $P1$ then $P2$' or '$P1 \supset P2$'. The parameters of the truth relations, I, are the elements of $T2$ and $T1$. These relations, for different values of the elements of $T2$, are shown in Figure 3a as parallel lines.

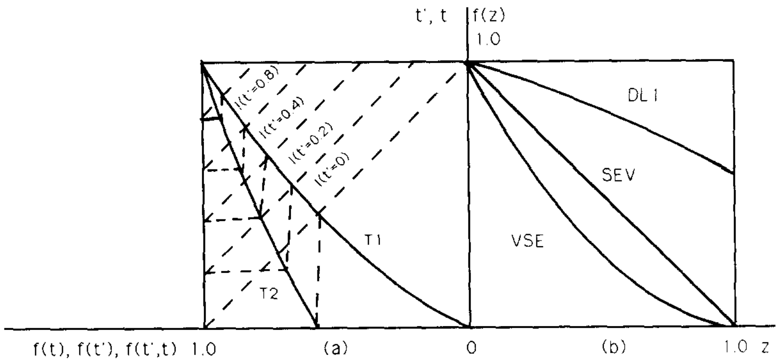

Fig. 3. MPD graphical solution.

The intersections of I and $T1$ yield the membership values of $T2$. Subsequently, the truth value, $T2$, can be found and plotted as in Figure 3a. Now (DL is SEV) is $T2$ can be modified through the TFM process to give DL is DL1 in Figure 3b, which concludes that DL is 'close to fairly severe'.

Summary

In this paper, the use of the fuzzy set concept to develop fuzzy production rules is presented. The development of the rules includes the manipulations of expert judgment through fuzzy set operations, particularly when conflicting opinions occur. The application of modus ponens deduction operations to develop additional or intermediate rules is presented. The operations can also be used as an inference mechanism when the facts or observations are available. Graphical solutions showing the modus ponens deduction operations are provided for simple production rules.

The study discussed in this paper is still subject to further research. Much research has to be done and more will be presented on the area of expert system as it progresses.

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