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A User-friendly System for Evaluation of Three-Dimensional Stress Intensity Factors

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ABSTRACT

This study describes a PC-based system to evaluate three-dimensional (3D) stress intensity factors (SIFs) using various simplified formulas found in literature. In general, this kind of system has to be flexible in extending its functions, and easy for ordinary engineers to use. It is also important to keep system compact by sharing common functions among various formulas for different cracks and structure geometries. To meet those requests, the present system is fully designed based on an object-oriented approach, and built in a personal computer using one of object-oriented languages Visual C++. About 50 different formulas of 3D-SIFs are implemented in its first version. Better usability of the system is well demonstrated through actual tests for persons with and without experiences on SIF calculation.

INTRODUCTION

When a crack occurs in machines or structural components, it is very important to evaluate its severity under a certain operating environment and to estimate its growth behavior untill next inspection period. In these days, the fracture mechanics parameters such as the stress intensity factor (SIF) and the J-integral are widely used for this purpose [1]. Evaluation methods of those parameters can be roughly classified into two categories : (a) a simple analysis using simplified formulas given in handbooks [2, 3], and (b) a detailed analysis using computational mechanics simulations such as the finite element method (FEM). In many cases, the simplified formula have been derived based on a lot of parametric computational mechanics simulations. The latter method is a powerful tool to obtain solutions for general shape and elastic-plastic deformation. But it requires tremendous computation time and cost. Some of the present authors developed a FEM-based system to automatically analyze a three-dimensional stress intensity factor [4]. This system indeed saves turn-around time and human effort, but still requires big computation power. On the other hand, the handbook-based method is very popular in practical situations, since it is much simpler than numerical simulation and requires much less computation power. However, since a lot of simplified formulas have been proposed so far and given in handbooks, and the form of each formula is different, it is a troublesome work for a beginner of fracture mechanics to select an appropriate formula among numerous formulas, and to evaluate it appropriately. If the handbook-based method is computerized, any of the simplified formulas would be much more easily used, and be even extended to an advanced system for assessment of safety and integrity of structural components. Since such a system requires less computation power, it will be constructed on an ordinary personal computer.

In this study, data structure of numerous simplified formulas concerning three-dimensional (3D) SIFs is first analyzed by using an object-oriented approach [5]. Next they are systematized using Visual C++ which enables us to easily construct an object-oriented system with GUI (Graphical User Interface) on an ordinary PC/Windows environment. If a user has basic knowledge concerning the fracture mechanics, he can evaluate various types of 3D SIFs by simple operation.

BASIC DESIGN OF SYSTEM

Design requirements for this system are summarized as follows.

(a) Easy operation

Ordinary users do not need to remember special key operations, and perform analysis based on simple interactive operations with the system.

(b) Extensibility

Hundreds to thousand simplified formulas are included in handbooks, and new formulas are still being developed. Thus the system must extend its capability easily in order to implement those numerous formulas.

(c) Portability

Fracture mechanics-based evaluation is required in various practical situations and places. Therefore it is useful to implement the system in an ordinary personal computer.

(d) Compactness

Efficient memory usage is a key issue when implementing the system in a PC. Therefore, common functions among different formulas should be shared.

To satisfy those requirements, we employed one of object-oriented languages, Visual C++, which enables us to construct GUI efficiently, and PC/Windows is selected as a fundamental platform to implement the system.

OBJECT-ORIENTED ANALYSIS OF SIMPLIFIED FORMULAS OF STRESS INTENSITY FACTORS

Object Extraction

Before constructing the system, structures of a number of simplified formulas given in the Stress Intensity Factor handbooks [2, 3] are analyzed in detail using an object-oriented approach. For example, the Stress Intensity Factor handbook edited by the Society of Materials Science Japan [2] includes three volumes, about 2,500 pages which are classified into 18 chapters in terms of specimen and crack configuration, about 1,500 simplified formulas, and about 2,000 tables and figures. Figure 1 shows a typical page image of simplified formula given in the handbook. The object-oriented analysis is performed focusing on common features or common framework among formulas in order to find "objects" which play key roles in constructing the system.

Simplified formula have various forms, and kinds and number of parameters, i.e. specimen and crack configuration, and types of loading are different formula by formula. To treat them efficiently, one needs to find a general procedure overcoming those differences. In simplified formula, each parameter is treated as a variable. There are a number of variables. The number, names, and meanings of parameters are different, depending on formula. Different formulas can be treated by the same procedure if those parameters are dealt as "Objects". This is because variables such as specimen shape (height, width and thickness), crack shape (length and depth), and loading condition, etc. are classified into "User input variables", "Formula type variables" and others, and those variables can be dealt in the same fashion without considering their numbers or meanings. In addition, graphs and tables are regarded as a kind of formula type variable because a value of one variable is determined from other variables. Therefore, graphs and tables are dealt as "Graph variable" and "Table variable".

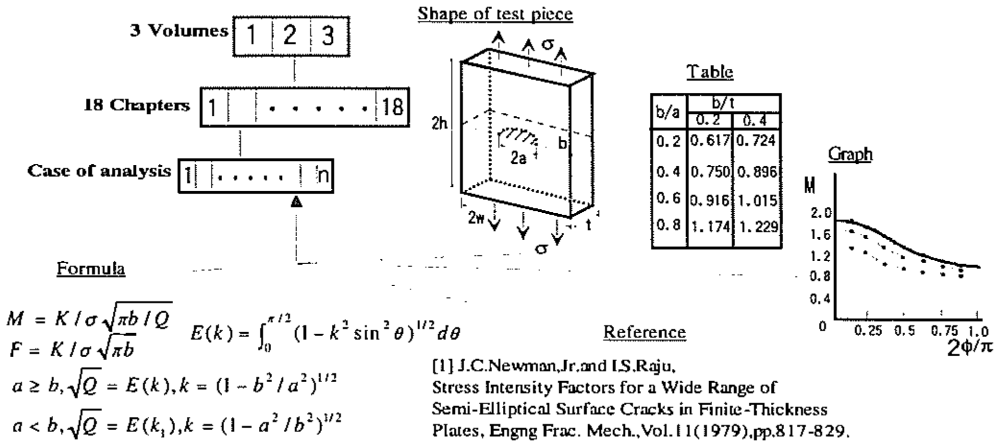

Fig. 1 Information in the Stress Intensity Factors Handbook

Object-oriented Analysis

(1) Object diagram

An object diagram shows the relation among objects. We obtained the object diagram shown in Figure 2 by analyzing a number of simplified formulas of SIFs. The diagram is drawn based on the OMT method proposed by J. Rumbaugh et al. [5]. For the purpose of easy understanding, the original expression in the handbook shown in Figure 1 is also given in Figure 2.

(2) Basic class

"Variable class" is defined as the most basic "Class". In this class, all variables have their own names, and the classes are administered by the names. To unify the procedure of treating variable, the variable name is defined as "Member data", and the I/O of name is defined as "Member function". Two classes are derived from the Variable class. The one is "BasicVariable class" which corresponds to the basic class for an ordinary variable. The other is "VariableSet class", which is the basic class for the variable determined by two different variables like graphs and tables. Two classes are further derived from the BasicVariable class. These are "UserVariable class" and "FormulaVariable class". The UserVariable class corresponds to the variable specified by a user, while the FormulaVariable class corresponds to the variable determined from other variables through formula. The FormulaVarible class has the one-to-many relation with Variable class. VariableSet class has also one-to-many relation with Variable class.

(3) Aggregation class

There are a number of simplified formulas of SIFs. It is indispensable to share similar processes in different formulas as a common procedure. Thus, "Formula class" is defined by consolidating BasicVariable class and VariableSet class. In the Formula class, variables and their relations in each simplified formula are stored in one data file. By accessing the data file, one can deal with object definition, object relation and selection of formula. The Formula class allows us to deal with various simplified formulas in a unified manner.

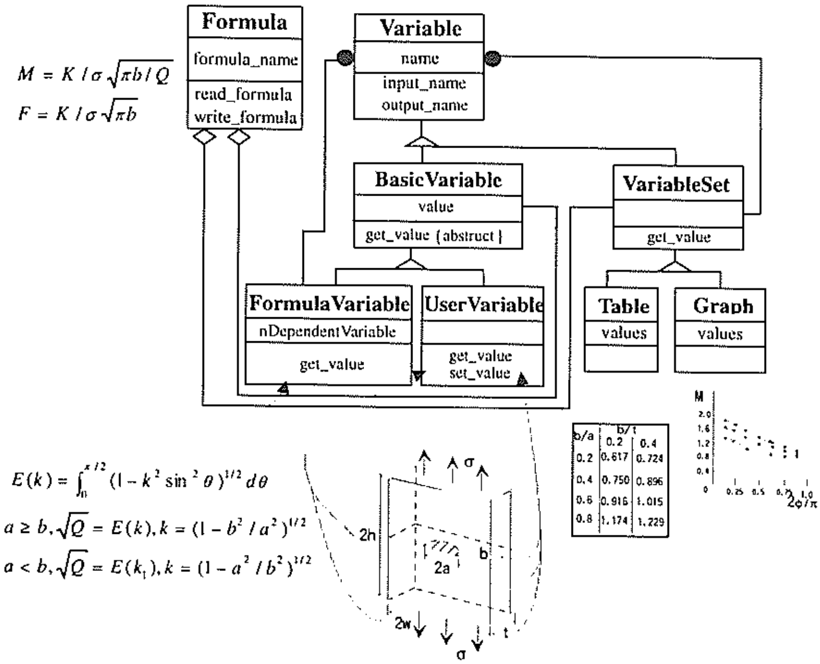

Fig. 2 Relations between object-diagram and information in the Handbook

OPERATION ENVIRONMENT OF SYSTEM

About 50 kinds of simplified formulas of 3D SIFs summarized in Table 1 are implemented in the first version of system. The system is built in an ordinary PC/Windows

Table 1 Classification of stored formulas

Specimen Configuration		Crack Configuration		Load	
Plate	39	Surface	40	Tension	37
Cylinder	9	Wall-through	4	Bend	7
Others	2	Embedded	6	Shear	3
Finite Body	40	Single	42	Others	3
Infinite Body	10	Multiple	8		

environment with Pentium 100MHz and 24MB memory and 800MB disk using Visual C++(Ver.4.0)/Windows 95.

EXAMPLE OF OPERATION

A typical procedure of operation is explained taking the evaluation of 3D SIF for a semi-elliptical surface crack in a plate subjected to tension.

Step 1

When the system starts, the analysis-mode-selection dialog is displayed as shown in Figure 3(a). Here, a user selects SIF analysis mode or J-integral analysis mode. However, the latter mode is not implemented in Version 1 yet. The J-integral evaluation based on the GE-EPRI method [6] with fully plastic solutions is scheduled to be implemented in the next version.

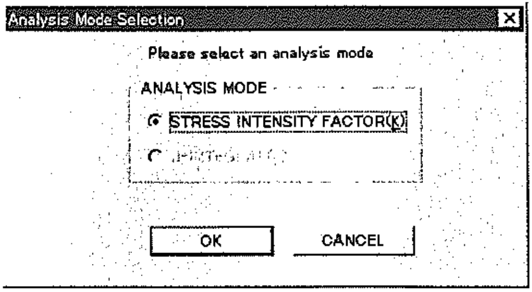

Fig. 3(a) Dialog for selecting analysis mode

Step 2

When the user selects the SIF-analysis mode, the analysis-condition-set dialog is displayed as shown in Figure 3(b). This dialog includes various buttons related to specimen types (plate, cylinder or others : finite body or infinite body), crack types (surface, through-wall or embedded : single, multiple or others), loads (tensile, bending, shear or others : concentrated or distributed). The user specifies his own desiring analysis condition by selecting buttons in the dialog. After this process, the system automatically retrieves one to several simplified formulas which satisfy the conditions specified by the user among a number of formulas stored in it.

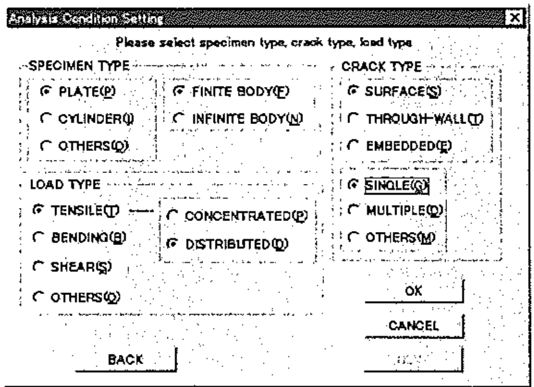

Fig. 3(b) Dialog for selecting analysis condition

Step 3

When the first retrieval process finishes, the analysis-object-selection dialog shown in Figure 3(c) is displayed. This dialog shows figures of the analysis objects which illustrate specimen and crack configurations and loading conditions. The user can easily select one analysis object

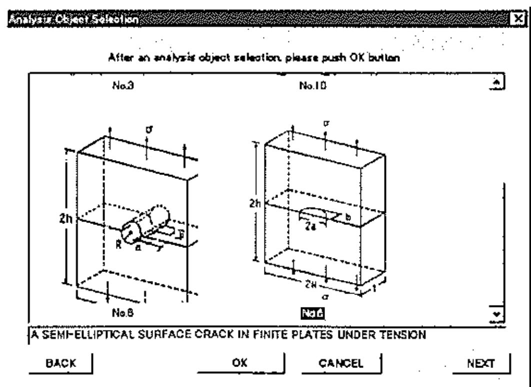

Fig. 3(c) Dialog for selecting object for analysis he desires.

Step 4
The analysis-parameter-input dialog shown in Figure 3(d) appears after the analysis object is selected. Here the user can input concrete numerical values, referring the illustration displaced. This dialog has many columns in order to deal with various types of simplified formulas. Therefore, columns not necessary in the particular formula are gray, and do not accept any input operation. The user inputs numerical values from the keyboard. If necessary, he can refer references and other additional information by pushing the information button.

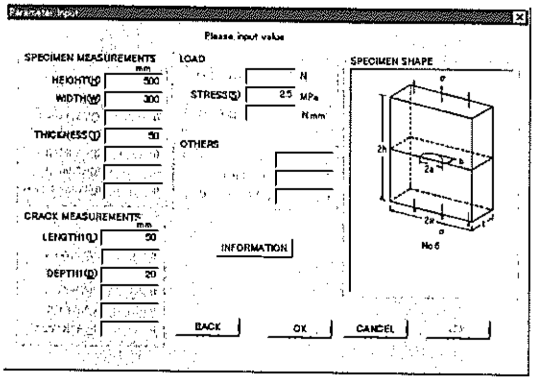

Fig. 3(d) Dialog for input of parameters for analysis

Step 5
After all necessary numerical values are input, the user pushes the calculation-start button. After the calculation ends, the analysis-result-display dialog appears as shown in Figure 3(e). In this particular example, the SIF value at the deepest point of the surface crack is shown.

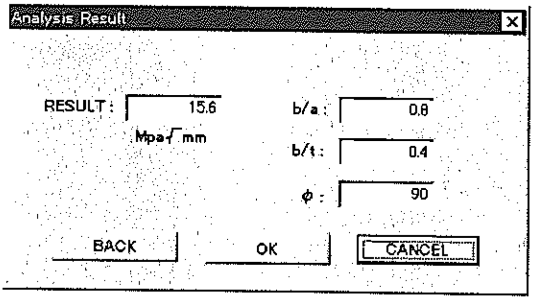

Fig. 3(e) Dialog for display of result

Step 6
Showing analysis results by graph is effective for users to better understand them. Some graph-display-function buttons are implemented in the main menu. Figure 3(f) shows one of examples. Here the X-axis denotes the elliptic angle of the surface crack scaled from the surface tip to the deepest point of the crack. The Y-axis denotes the SIF value.

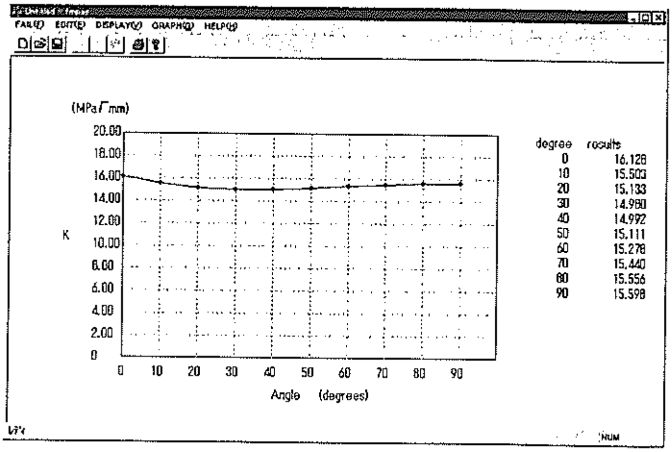

Fig. 3(f) Window for display of result

USABILITY TEST

To validate usability of the developed system, we performed the following usability test. Two kinds of user groups are considered. Group A consists of two persons who have no experience on fracture mechanics evaluations. Group B consists of two persons who have experienced fracture mechanics evaluations. Each person in both groups are requested to calculate the SIF value for the semi-elliptical surface crack in a plate subjected to tension by using the SIF handbook and the present system. In this test, we show them specimen and crack configurations and explain sizes and loading conditions. Here we measure the time till selecting an appropriate simplified formula, and that of calculating the SIF value for the formula. The results are summarized in Table 2. When using the handbook, the experienced users take about three minutes to select the formula, while non-experienced users take about five minutes. Since there are several similar figures with sightly different specimen and crack configurations and loading conditions in the handbook, non-experienced users are often confused in the selection process. Calculation time is also about 18 minutes for experienced users, and about 27 minutes for non-experienced users. For the experienced users, the SIF calculation using the formula is just a simple operation to input numeric data. On the other hand, the non-experienced users sometimes make simple mistakes due to misunderstanding of some parameters.

When using the present system, the non-experienced and the experienced users take about one minute to select a correct formula. They also calculate the correct SIF value in about two minutes. This is because the GUI well guides users to select formula and the system automatically checks input mistakes. These usability tests clearly demonstrate that the present system is very useful for both non-experienced and experienced users.

Here we considered a special case to use one simplified formula only once. In practical situations of safety and integrity assessment and fracture mechanics based design, engineers use a formula repeatedly changing some of parameters, and sometimes use multiple formulas simultaneously. In those situations, the present system would be more effective than in the present simple usability test.

Table 2 Result of Usability test

Fracture Mechanics Evaluations		SIF Handbook[SIFHB] (min)	Present System[S] (min)	S / SIF HB (%)
Experienced user	a	3.0	1.0	12
	b	18.5	1.5	
Non-experienced user	a	4.5	1.0	10
	b	26.5	2.0	

a: Time for selecting appropriate simplified formula

b: Time for calculating the SIF value

CONCLUSIONS

Huge results of fracture mechanics researches performed in the world have been stored as simplified formulas of fracture mechanics parameters. Especially, fracture mechanics parameter handbooks have been playing important roles to push fracture mechanics approaches forward to practical engineering fields. However, it is not still an easy task for ordinary engineers to select an appropriate formula among a huge amount of formulas stored in the handbooks, and to appropriately calculate values with the formula. Thus, the present authors developed the system to evaluate 3D SIFs using numerous simplified formulas on a PC/Windows environment. Even non-experienced users who has basic knowledge on fracture mechanics but has not necessarily knowledge on computer can easily and accurately calculate 3D SIFs. An object-oriented analysis and programming approach is effectively adopted to efficiently handle a number of simplified formula. About 50 kinds of simplified formulas for 3D SIFs are registered in the first version. More formulas and some simplified J-integral evaluation schemes will be implemented in the next development.

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