PRACTICAL APPLICATION OF FRACTURE MECHANICS METHODS IN CAD SYSTEMS

I.I. KOKSHAROV
Computing Centre of Russian Academy of Sciences, Krasnojarsk, Russia

ABSTRACT

The paper presents results of practical application of fracture mechanics methods in CAD systems for strength calculations of machine–building constructions. Principal system's features led to higher efficiency are shown. To estimate the strength and crack resistance indices of complex constructions the superelemets method is used. After computations of stress values in structural elements of the model the special calculations of static or cyclic crack resistance are carried out. To demonstrate the systems possibilities special cases of design practice are considered.

KEYWORDS

Crack resistance, CAD, carrying ability exhaustion factor, FEM, strength, structural element, tolerant defect

INTRODUCTION

Creation and use of CAD systems for the crack resistance calculations cease to be an object of only one subject of knowledge, for example, the mathematical theory of cracks. In this case it is necessary to apply complex approach with use of contemporary achievements in different branches of scientific and engineering knowledge, such as fracture mechanics, the finite element method (FEM), the theory of reliability, the computational mathematics and other subjects. At this case such systems must use not only theoretical basis but their practical applications in the form accessible for customers - designers. In this paper more attentions are given to basic principles of CAD creation and using of the criterial correlations of the fracture mechanics. Based on the essential principles the efficient CAD system has been created. The system allows a designer to carry out the calculations of complicated elements of carrying constructions according to present-day methods of the fracture mechanics.

CAD SYSTEMS FOR STRENGTH CALCULATION

The CAD systems realizing calculations of the strength and crack resistance are used in designing of carrying constructions. Such systems solve the problems: 1) check of the strength condition; 2) definition of dimensions of the basical elements of the constructions; 3) comparative analysis of design variants, choice of the material type, determination of the sizes of tolerant defects and so on; 4) estimating of a sequence of failure for complex technical systems, diagnostics of accidents. The basic components of the CAD systems are 1) a preprocessor - the program for composing models of construction; 2) programs for calculating stresses and displacements in the model, for example FEM; 3) data base which stored the model parameters and mechanical properties of materials; 4) a postprocessor - the results analysis program which represents information of calculation of the strength and crack resistance; 5) a coordinating program for other components of the system and programs for intellectual support of acceptance of decisions. Software for graphical output is used in the subsystems either as an independent program or as included in these programs. For each component there are powerful universal programs, which have been used in designing of machine-building constructions.

There are systems which were created by connecting of the universal programs such as AutoCAD (graphical support), COSMOS (FEM), PARADOX (data base) and others. In the paper another type of the systems is considered. The system is a package of programs which have necessary features for CAD and work with the typical object of design. The automated system 'Strength and Durability ' AS SDP (Koksharov et al., 1989) makes calculations of the strength, static and cyclic crack resistances of carrying engineering structure - beams, casting details, foundations and others. The basical operations of the system are 1) creation of the finite element model for given construction, 2) determination of stresses and displacements in the model by FEM, 3) execution of the strength and crack resistance calculations by use of the stress and strain state data and the characteristics of mechanical properties, 4) fulfillment of the carrying ability analysis for the structure. There are some principles used in the creation of AS SDP here.

Closeness to the Ways of Designer Thinking. The methods for input and output of the information must be oriented in the first place to the ways of designer thinking, and then to the data processing in the CAD subsystems such as FEM programs. One of the basic features of the CAD system must be the brevity in descriptions of the initial data. The code AS SDP liberates a designer from necessity to number nodes and elements. The customer can create FEM model either with the interactive graphic support by putting blocks of finite elements (FE) or by writing a record consisting of few numbers and declaring significant volume of the elements. The FE mesh and the loading scheme for a caterpillar link of the EKG-15 dredger are shown in Fig.1. There are shown the external loads acting when the wheel run and links are stretched. Preparation of scheme with given volume of complexity (about 670 nodes and 400 FE) is realized during a working day. Output of results analysis must be obvious, with the use of 3-dimensional pictures without further calculations. The results of the system work are not any columns with numbers (values of stresses in the central points of FE) and pictures with distributions of stress intensity at the model surfaces, but information about dangerous zones and points. The designer must have the data about the principal factors promoting possible breakdowns and give characteristic of carrying ability of the whole construction. When solving these problems along with the known forms of data presentation the untraditional means of

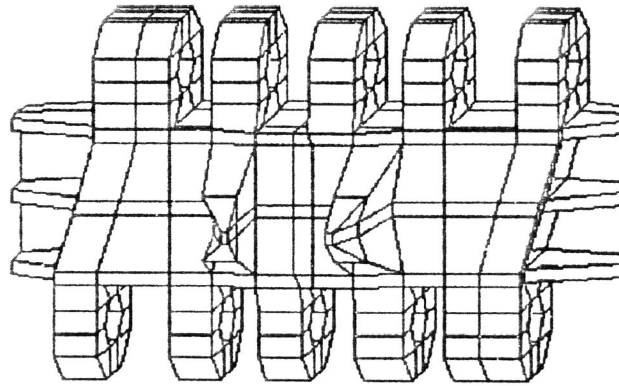

Figure 1: Calculation scheme of caterpillar link

information output may be used. Among them some ways may be mentioned: output of carrying ability factors, presentation of load lines, comparative data of deformed shapes of the structure and the geometry parameter of sections. All operations must be natural for a designer and must not demand any instructions and wordy descriptions. All these give results not only in contraction of education period but also in swiftness of the work.

A complex constructions consists of substructures, sections, details, which must be calculated separatly and after modelling assembly. Such calculations are conducted with the use of superelements method. In this case the calculation schemes for each superelement are made separatly and all operations for the data input fulfilled in local coordinates are similar to the actions for the FE mesh preparing methods described above. Then assemblage are carried out by putting each superelement in the given position of the global coordinates system. The assemblage is realized only in nodes with coincided coordinates. The calculation scheme of the travelling crane truck consisting of 14 superelements is shown in Fig.2. One of the superelements with displayed inner structural elements is alloted. Since there are memory restrictions for personal computers, solution of the FEM equations system is realized by computation of the rigity matrix for each superelement with joint nodes marking. Then the global problem calculations are carried out. Analysis of the crack resistance indices is realized both for each element and totally for whole structure.

Object of the Calculations Is Not Numbers, but Understanding. This known quote may lay in foundation of the intellectual system for the crack resistance calculations. The assertion corresponds to the present-day methods for evaluation of quality for complex technical systems, because the knowledge of structure's parameters are not absolute data

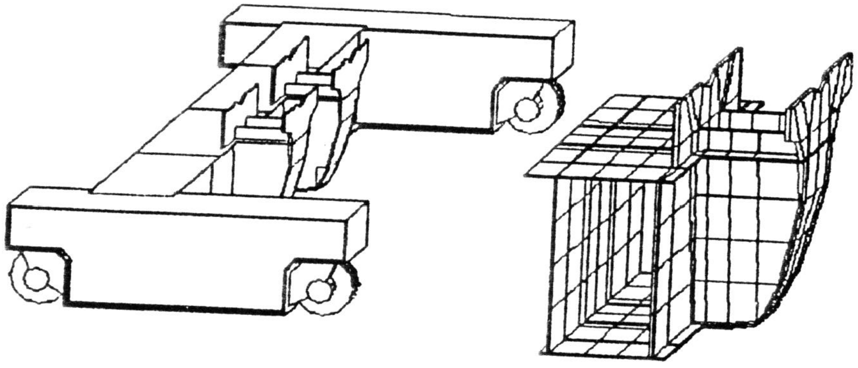

Figure 2: Model of the travelling crane truck

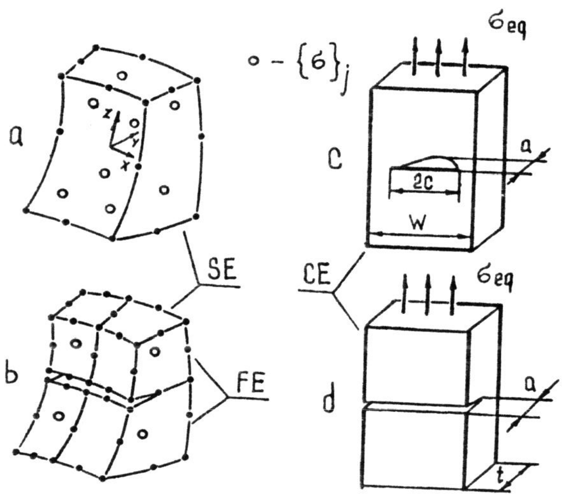

Figure 3: Finite (FE), structural(SE) and calculated (CE) elements.

and there are some modelling approximations to the real construction. It is important for the designer to have information about carrying ability of the whole technical system and its parts and the basical causes of possible variants of breakdowns. Comparative analysis for several variants of the construction allows to choose the optimal one. If under consideration there are some errors in the admissions, then it are present in all variants. The complex approach, multi-variant calculations, swiftness in operations, comparative analysis, full description of carrying ability properties - all these allow to receive complete understanding of the construction strength.

FRACTURE MECHANICS METHODS IN CAD SYSTEMS

The basis of the presented approach for evaluation of the crack resistance properties of constructures is introduction of the structural element (SE) notion. SE may be composed (Fig.3) of one or more numbers of finite elements (FE). If in the first case it is difficult to consider the presence of defects, then in the last case it is possible. The greater FE number is used for exact modelling of the defected SE rigity. The mesh shown in Fig. 3b is not sufficient for direct calculations of the parameters such as stress intensity factor (SIF). This is why in the calculations of SIF values it is convinient to use SE nominal stresses σ_{eq} and known correlation functions $f_{IK}(a/W)$. In the n SE nodes (empty points at the figure) — Gauss integration nodes the stresses components $\{\sigma\}_j = (\sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{yz}, \sigma_{zx})$; $(j = 1 \ldots n)$ are calculated. The crack resistance calculations are carried out for calculated element (CE), to which equivalent stresses are applied (Fig. 4, 5). Transition from the data array $\{\sigma\}_j$ to equivalent stress are realized by different ways. For example, $\sigma_{eq} = \max((\sigma_1)_j)$, where $(\sigma_1)_j$ — maximal main stress in the node j. Another way of equivalent stress determination is $\sigma_{eq} = \max(\max(\sigma_x, \sigma_y, \sigma_z)_j)$. Since $\{\sigma\}_j$ are defined in the finite number of SE nodes, then σ_{eq} may be considered as average characteristics of SE stress state. The values of average stresses are used in the integral criterial approach of the fracture mechanics (Koksharov, 1989). The detailed 3–dimensional FE meshes with condensation of elements for direct SIF estimation are used for solving of the problem with a crack and simple geometry of SE (Koksharov, Moskvichov, 1991).

When the transition of SE to CE is considered it is necessary to determine the calculated parameters of CE geometry (thickness t, width W). Thickness is determined by the sections' sizes gone through SE weight center, for example, $t = \min(t_x, t_y, t_z)$, where t_i — SE thickness along the local coordinates axes X, Y, Z. The tolerant defect sizes either for each SE or for group of them are chosen from specialized data base. Calculation schemes are not restricted only to the cases of Fig. 4, 5. There are the library of special procedures for calculation of correlation functions $f_{IK}(a/W, a/t)$. In the AS SDP strength and crack resistance calculations are carried out with different parameters (stress, strain, SIF, defect size and others) for which limit values are given. The designer receives total informations in the form of one parameter. This is a value of carrying ability exhaustion factor (CAEF) k_i, where i is determined by criterion type. The factor shows how calculated parameter exceeds its tolerant value. If the factor reaches one and exceeds it, then under given conditions SE will be fractured. There are equations for CAEF calculations:

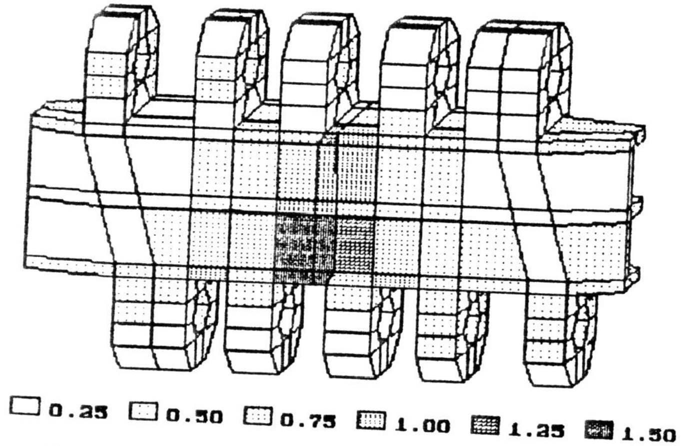

Figure 4: CAEF distribution for the caterpillar link

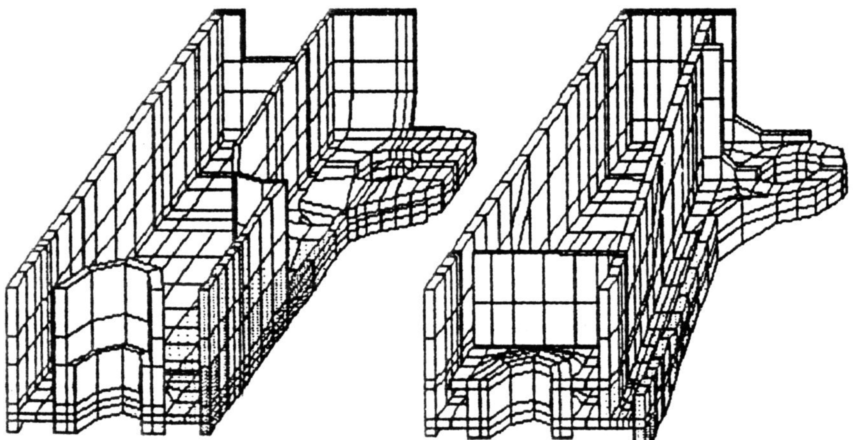

Figure 5: Comparison of two variants of the welding balancer

1. static crack resistance:

$$k_s = \frac{K_I}{K_C} \le 1, \quad K_I = \sigma_{eq}\sqrt{\pi a_0}\, f_{IK}(a_0/W) \qquad (1)$$

2. tolerant flaw (static loads):

$$k_f = \frac{a_0}{a_C} \le 1, \quad a_0 = (\sigma_{eq} f_{IK}(a_0/W)/K_C)^2/\pi, \qquad (2)$$

3. cyclic crack resistance:

$$k_N = \log(N_C) - \log(N) \le 0, \quad N = \int_{a_0}^{a_N} \frac{da}{C(\sigma_{eq}\sqrt{\pi a_0}\, f_{IK}(a_0/W))^n}, \qquad (3)$$

$$a_N = (\sigma_{eq} f_{IK}(a_N/W)/K_C)^2/\pi \qquad (4)$$

4. tolerant flaw (cyclic loads):

$$k_c = \frac{a_N}{a_C} \le 1 \qquad (5)$$

a_N from equation (4) under condition $N = N_C$;

where K_I, a_0, N, K_C, a_C, N_C — the calculated value of SIF, the defect size, the number of cycles before fracture and their critical values correspondingly; a_0, a_N — the initial defect size and the crack length grown after N cycles; C, n — the constants in the Paris equation. All crtitical values of the parameters are stored in the special data base. CAEF value shows the result not only for single points in the SE, but for the whole SE. In the equation such as (4) it is impossible to receive a_N in the obvious form, therefore the equations are solved for this parameter by the numerical iterative procedures.

CRACK RESISTANCE INDICES

When considering the crack resistance indices for each SE it is possible to give an estimation for the properties of the structure in general. The CAD system AS SDP is used in maintenance of structural integrity of the damaged constructions. Fig. 4 shows CAEF distribution in the model of the catapillar EKG-15 link (the link is turned over - view from the foundation). The most dangerous part is the link foundation in the zone where wheel runs. The survival time calculated according to (3) with initial flaw of length amount 1/10 of the SE thickness is less than tolerant value $N_C = 200,000$ cycles. By considering these results the designer can take one of decisions: 1) to choose material types of the link and consequently to change the crack resistance characteristics K_C, C, n ; 2) to prescribe special methods of nondestructive control and to reduce the tolerant size of the initial defect; 3) to enter alterations in the geometry.

Fig. 5 shows CAEF distribution for two models of welding balancer of the travelling crane. Weights of these variants of crane parts are practically equal. Under previous exploitation of the first variant there is fatigue crack growth in welding zones and full destruction of the balancer. The second variant was made after detailed calculations for the first project and efficient discussions designers with specialist in the strength analysis. The figure shows that sizes of tolerant defects in the welding zones undergoing by ultrasonic control are sufficiently less for the first variant of the balancer. Some constructive alterations in the project are made and substantiative demands for defect tolerance are set.

Besides evaluation of new projects AS SDP is applied to operational diagnostics and investigations of causes of accidents and carrying structures breakdowns. The system is not closed for further introduction of modern calculation methods when great experience of scientific knowledge is used outright in the design practice.

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