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NUMERIC MODELING OF THE REFERENTIAL STATUS OF A STRUCTURE SUBJECT TO CORROSION DEGRADATION

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K e y w o r d s: cyclic load, corrosion degradation, energetic criterion.

A b s t r a c t

The paper concerns analytical and numeric tools for deterministic assessment of the behavior of structures operating in extreme conditions under the influence of multiparameterical and/or cyclic mechanical, thermal and chemical loads. Individual elements of the structure are subject to elastic and corrosive degradation and dissipate energy consisting of the contributions from irreversible phenomena of work on non-elastic strain type. The life of a structure and its elements is assessed using the energetic criterion. In this study the main focus was on modeling and numeric implementation of degradation phenomena such as cyclic elasticity caused by mechanical and thermal loads, stress corrosion, electrochemical corrosion and low cyclic corrosion.

NUMERYCZNE MODELOWANIE REFERENCJALNEGO STANU KONSTRUKCJI ULEGAJĄCEJ DEGRADACJI KOROZYJNEJ

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S ł o w a k l u c z o w e: obciążenie cykliczne, degradacja korozyjna, kryterium energetyczne.

S t r e s z c z e n i e

Przedstawiono analityczne i numeryczne narzędzia deterministycznej oceny zachowania się konstrukcji pracujących w ekstremalnych warunkach, znajdujących się pod wpływem wieloparametrowych i/lub cyklicznych obciążeń mechanicznych, termicznych i chemicznych. Poszczególne elementy konstrukcji ulegają plastycznej i korozyjnej degradacji oraz dysypują energię, na którą składają się wkłady od nieodwracalnych zjawisk typu praca na odkształceniach niesprężystych. Żywotność konstrukcji i jej elementów jest oceniana za pomocą kryterium energetycznego. W pracy główny nacisk położono na zamodelowanie i numeryczne zaimplementowanie zjawisk degradacyjnych, jak cykliczna plastyczność, wywołana obciążeniami mechanicznymi i termicznymi, korozja naprężeniowa, korozja elektro-chemiczna i korozja niskocykliczna.

1. Introduction

Operation of industrial devices and structures leads to exceeding the elastic states for which the structures had been designed and appearance of various forms of bearing material degradation, among which plasticity, creep, thermal fatigue, cracking and corrosion are the most dangerous ones. This paper deals with assessment of the behavior of structures using numeric modeling of operational cycles (Dudda, Badur, Chróścielewski 2000, Dudda, Badur 2001a). Studies of that type develop the new discipline known as “combined shakedown” expanded by the corrosion type modes of material degradation (stress, electrochemical, low cyclic) and destruction. Because of the requirement formulated by modern industry concerning high availability of devices and the demand to formulate reliable projections (referential states) concerning their further operation, this subject is of major practical importance, particularly where there are no probabilistic methods for estimation of residual life.

The Technical Supervision asks questions concerning by how much the load should be decreased to secure safe operation of the device until full amortization or how long a device or structure can still operate, even though its elements were subject to the above-mentioned operational degradation. The answers to that type of questions cannot be given exclusively on the basis of reliability theory based statistical estimates as they must take into consideration specific hazards of a specific structure possessing its own history of operation.

That leads to the question – *is it possible, using the advanced tools of numeric structural mechanics, to build a model allowing simulation of the referential state changing during cyclic, mechanical, thermal and chemical loading of the structures?*

The developed corrosion degradation models are fully compatible with 3D analysis, but currently the testing is limited to rod structures, digitized by one-dimensional finite truss elements. There are two main reasons for that:

1) The experimental material for stress, electrochemical and cyclic corrosion modeling is prepared in single axis stretching devices on rod shaped cylindrical samples. To properly calibrate the constants in the models used and proposed, it is necessary to adjust to the available experimental material (Gazzini et al. 1999, Razzini et al. 1999, Albarran et al. 1999, Olive et al.

1999, JAKUBOWSKI 2000, KOWN et al. 2000, TSAI, CHEN 2000, CHOI, KIM 2000, GAONA-TIBURCIO et al. 2001).

2) Data on the plasticization area in the increased temperatures and in case of stress corrosion hazard available in the national standards encompass only single dimension stretching and compressing tests of standard samples. Additionally, in the standards there is no information on the decrease of plasticity limit depending on the degree of hydriding and only some materials possess defined plasticity limit and Young's module depending on the temperature.

2. Models of corrosion degradation

Corrosion occurring on the surface of a structure element leads to a decrease of the bearing surface of the element – that process coupled with cyclic thermo-mechanical loading of the structure within the plastic range may cause degradation many times more severe than the simple sum of influences by corrosion and plasticity. In this paper three forms of corrosion are analyzed (DUDDA, BADUR 2001b):

– stress corrosion

$$\dot{d}_{SC} = C_{SC}\,|\sigma_{eff} - \sigma_{gr}|^{n}\, e^{(T-T_0)/B} \tag{1}$$

– electrochemical and gas high temperature corrosion

$$\dot{d}_{HC} = \hat{C}_{HC}\,(T/T_0)^{\kappa}\left|\nabla T\right|^{m} \tag{2}$$

– low cyclic corrosion fatigue

$$\dot{d}_{LC} = C_{LC}\, N^{\mu}\,(\Delta\varepsilon_{eff})^{b}\, e^{(T-T_0)/B_1} \tag{3}$$

In the above formulas d means the thickness of the external layer of the material that is subject to corrosion (mm), the corrosion rate (mm/h) $\dot{d}$, T temperature, N number of cycles, σ_{eff} intensity of stress, σ_{gr} boundary stress below which no stress corrosion takes place, Δ_{eff} range of deformation intensity and C_{SC}, n, B, C_{HC}, κ, m, C_{LC}, μ, b, B_1 are constant values of the model calibrated in single dimensional experiments. The final loss of thickness is calculated as the sum $d = d_{SC} + d_{HC} + d_{LC}$. The constant values C_{SC}, C_{HC}, C_{LC} characterize the influence of corrosive environment on the construction material degradation rate. The influence of the values of individual constants on loss of material and corrosion rate is presented in Figures 1, 2 and 3. The corrosion rates determined using the above-mentioned constant values cover the range between the minimum and maximum degradation rates given in the literature. Verification of the given models and determination of the remaining constants of the models on degradation rate are presented in the monographic study by the author (DUDDA 2005).

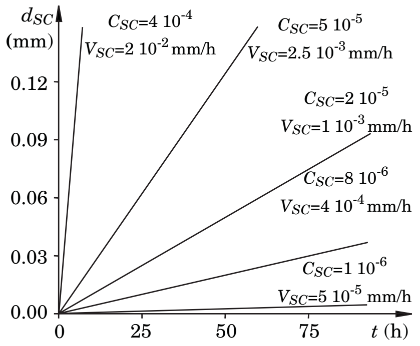

Fig. 1. Influence of CSC constant on loss of the material and stress corrosion rate for $(\sigma_{eff}-\sigma_{gr})$ = 50 MPa, n = 1, T = 20°C

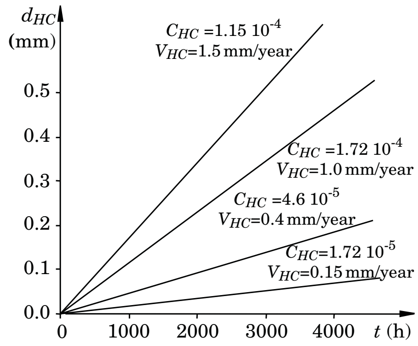

Fig. 2. Influence of CHC constant on loss of material and general corrosion rate ϑ = 1, T = 20°C

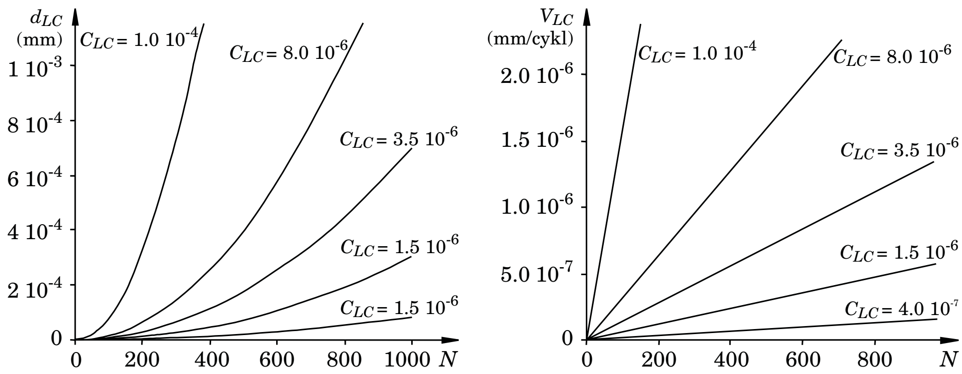

Fig. 3. Influence of C_{LC} constant and number of cycles N on decrease in material thickness (a) at μ = 1, $\Delta\varepsilon^p$ = 0,02 i b = 2 and corresponding low cyclic corrosion rates (b)

3. Energetic criterion of structure degradation

The elementary energy irreversibly dispersed (dissipated) in the material during variable loading up to destruction of the element is the basis of the energetic criterion. Energy dissipated by the element during cyclic load changes was described by the following formula

$$U^e = \frac{1}{V} \sum_{i=1}^{k \cdot N} \Delta W_i \tag{4}$$

where ΔW_i is the increase of work of stress on plastic deformations corresponding to the i increase of load, N is the number of load changes, k the number of load increases in a cycle and V the element volume.

The condition of destruction of the j element may be represented as follows

$$U_{kr} - U_j^e = 0 \tag{5}$$

The number of cycles N_{krj} corresponding to that condition represents the number of cycles until destruction of j element. When periods t_i of individual cycles are available, it is also possible to determine the t_{krj} until destruction of j element. The critical energy was assumed to be equivalent to border energy U of the deformation in case of static stretching (KOCAŃDA, SZALA 1997).

The total quantity of energy irreversibly dispersed in a structure is another parameter characterizing the status of structure. In case of structures consisting of n elements (e.g. truss structures) the global energy was determined as the sum of energies of its individual elements:

$$U^C = \sum_{i=1}^{k \cdot N} \sum_{j=1}^{n} \Delta W_{ij} \tag{6}$$

The above formula does not mean here the tensor parameter and W_{ij} means the increase of stress work on plastic deformations of the j element, corresponding to i load increase. If redistribution of load carried by the element that is subject to degradation to other elements of the structure is possible, the destruction of that element does not have to mean loss of structure durability in the global sense. That may lead to loss of load capacity by the other element or to revitalization of the structure as a whole. That is why the global energetic criterion is converted to observation of the increase of energy dissipated by the structure from cycle to cycle, and that in turn allows assessment of structure sensitivity to the loads program.

4. Numeric applications

The numeric D-KRAT code was built by the author (DUDDA 2005) on the basis of *Mini-Mod* library containing the MES solver procedures developed by CHRÓŚCIELEWSKI and BRANICKI (1989). In that code the developed models of physical phenomena such as stress, electrochemical, high-temperature corrosion and corrosive low cyclic wear were implemented. Additionally a module allowing consideration of the influence of thermal load on physical and mechanical characteristics of the material and determining thermal deformations was added. The model of cyclic strengthening/weakening of material was also introduced. The phenomena modeled here are generally nonlinear and that is why the numeric technique developed by CHRÓŚCIELEWSKI (1996) is applied for tracing nonlinear load paths. Thanks to sub-programs developed for visualization of calculation results (DUDDA 2005), the possibility was created to follow the equilibrium path, structure deformations, distribution of dissipated energy and degradation of the active cross-section of individual structure elements during numeric simulation.

5. Assumptions for numeric calculations

This part of the paper aims at determining the number of structure load change cycles until damage to one of its elements depending on the level of corrosive environment aggressiveness. According to the specified energetic criterion (5), the cycle during which the elementary energy dissipated by any element of the structure exceeds the limit value determined from the formula by BRONIEWSKI (KATARZYŃSKI, KOCAŃDA, ZAKRZEWSKI 1969) was assumed to represent the moment when damage occurs

$$U = 0{,}0025\,(3R_m + R_e)\,A_{10} \tag{7}$$

The truss of eleven elements presented in Fig. 4 was assumed as a model of structure (KLEIBER, KOTULA, SARAN 1987). The areas of cross-section of elements were: rod no. 2–6 cm^2; rod no. 11–4 cm^2; the other rods – 5 cm^2. The material constant values were assumed as follows: E=2.1 · 10^{5}MPa, E_T = 1 · 10^4 MPa, R_e = 200 MPa, R_m = 500 MPa. The structure was subjected to cyclic one parameter load where the load parameter was changed within the range 1.0–0.8; reference time t_0 = 100 h and temperature T = 20^{o}C. Two series of calculations were carried out.

In the first series low influence of the corrosive environment on degradation rate (C_{SC} = 2 · 10^{-6}, C_{HC} = 1 · 10^{-5}, C_{LC} = 1 · 10^{-6}) was assumed. In the

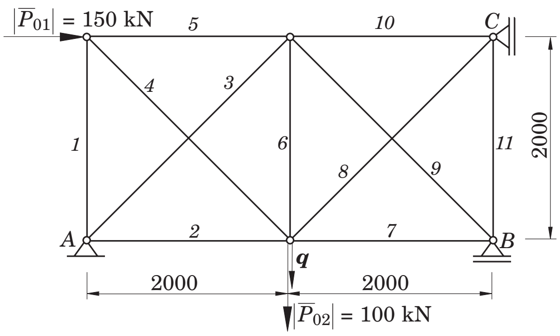

Fig. 4. Structure geometry

second series it was assumed that the degradation rates by individual types of corrosion are higher than in the first series by 10-fold for stress corrosion, 5-fold for chemical corrosion and 4-fold low cyclic wear ($C_{SC}=2\cdot10^{-5}$, $C_{HC}=5\cdot10^{-5}$, $C_{LC}=4\cdot10^{-6}$) respectively. The other parameters of corrosion models were as follows: $n = 1$, $\sigma_{gr} = 150$MPa, $\vartheta = 1$, $\mu = 1{,}6$, $b = 1$, for corrosive low cyclic wear the range of total deformations was considered. In consecutive load cycles the equilibrium path, i.e. the relation between displacement q and load parameter λ (Fig. 5 and 9), spectra of displacment q in time t (Fig. 6 and 10), increases of dissipated energy (Fig. 7 and 11), change in the area of cross-sections of selected rods (Fig. 8 and 12) and the change of structure geometry in consecutive load increases were traced.

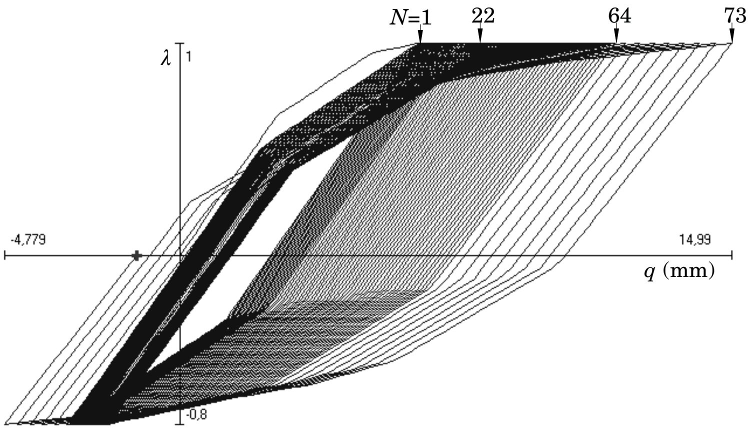

Fig. 5. Relation between displacement q and parameter λ in consecutive load cycles N

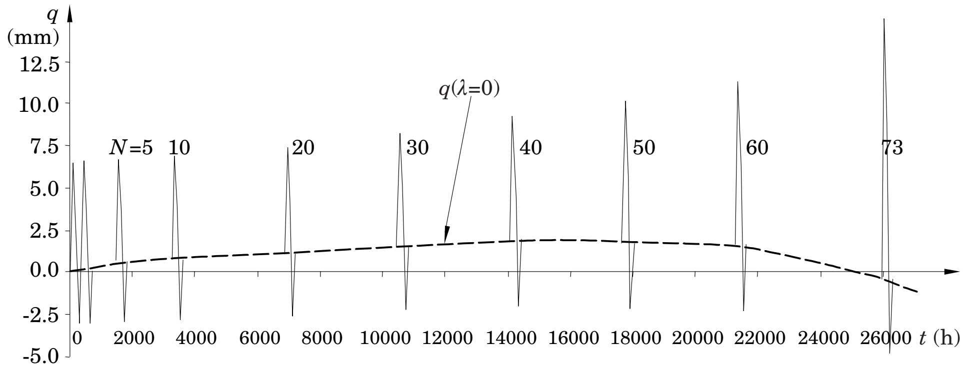

Fig. 6. Spectra of displacement q in time t for selected load cycles

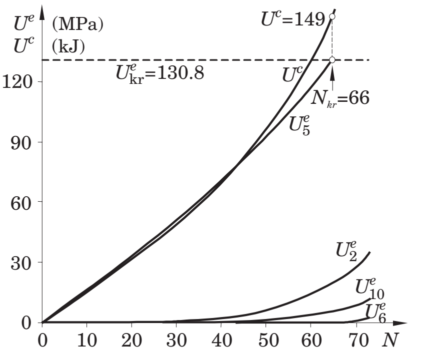

Fig. 7. Dissipated energies U^e by rods 2, 5, 6 and 10 as a function of load cycles number N

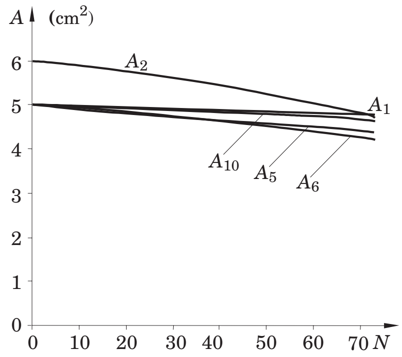

Fig. 8. Decrease of cross-section area A for rods no.1, 2, 5, 6 and 10

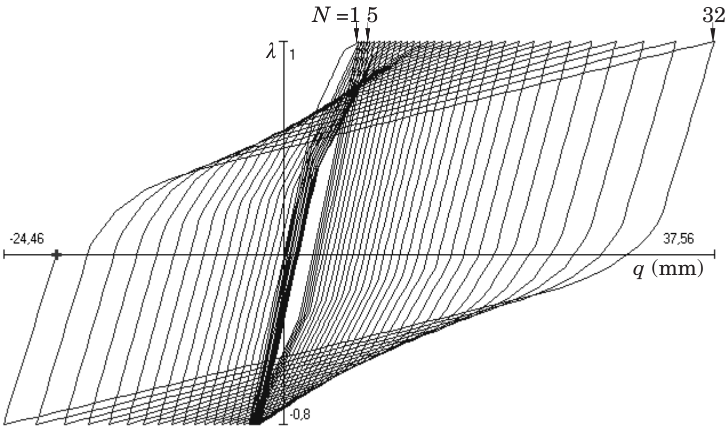

Fig. 9. Relation between displacement q and parameter λ in consecutive load cycles N

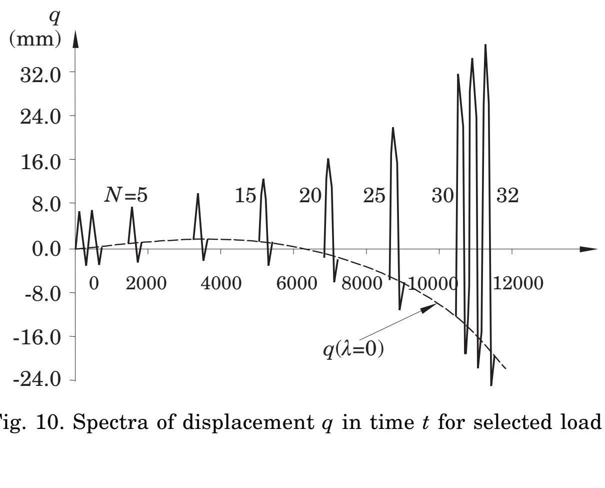

Fig. 10. Spectra of displacement q in time t for selected load cycles

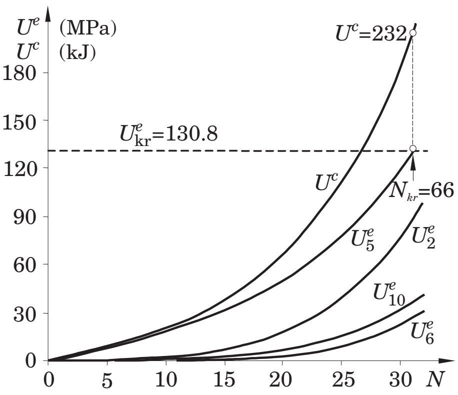

Fig. 11. Dissipated energies U^e by rods 2, 5, 6 and 10 as a function of load cycles number N

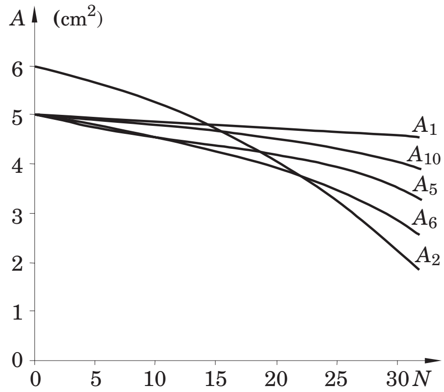

Fig. 12. Decrease of the cross-section area A for rods no. 1, 2, 5, 6 and 10

6. Results of calculations and analysis

6.1. Cyclic loading of structure with constant values of corrosion models: $C_{SC} = 2 \cdot 10^{-6}$, $C_{HC} = 1 \cdot 10^{-5}$, $C_{LC} = 1 \cdot 10^{-6}$

In the relation between displacement q and parameter presented in Fig. 5 it can be seen that up to cycle 64 of loading the displacement hysteresis loops increase in a stabile way and starting with cycle 65 those loops were characterized by a significant increase of the displacement amplitude. According to the assumed energetic criterion, rod number 5 is destroyed 5 (Fig. 7), however, the degradation of its bearing cross-section was not as big as that of rod number 2, the cross-section area of which was subject to the largest degradation (Fig. 8).

6.2. Cyclic loading of structure with constant values of corrosion models: $C_{SC} = 2 \cdot 10^{-5}$, $C_{HC} = 5 \cdot 10^{-5}$, $C_{LC} = 4 \cdot 10^{-6}$

In this case displacement hysteresis loops q clearly increase from cycle to cycle starting from the very beginning (Fig. 9). Comparison of graphs presented in figures 5 and 9 shows that more corrosive environment clearly influences the behavior of the structure and excessively strong corrosive environment may lead to loss of the stabile period of structure work. The same as series one, rod number 5 would be the first to be destroyed while rod number 2 would come second (Fig. 11). Rod number 2 was subject to the largest degradation and rod number 6 was second in rate of cross-section area degradation rate, which, in turn, had the lowest quantities of energy (Fig. 11). The individual elements of the structure were subject to degradation at different rates despite the fact that corrosion models constants were the same for all elements of the structure. That manifests clearly the influence of states of stress and deformation on differentiation of degradation rates for individual rods in the structure. Those states are then closely linked to the corrosion phenomenon. Analysis of results allows assessment of sensitivity of the entire structure (Fig. 5, 6, 9 and 10) subjected to the aggressive environment influence to the given program of loads and determination of degradation degree for individual components of that structure (Fig. 7, 8, 11 and 12). Analysis of individual rods degradation allows drawing conclusions concerning modifications of the most severely threatened elements in a was leading to even degradation of the structure as a whole, i.e. the situation where all its elements would wear equally.

7. Conclusion

The sample calculations for a truss of eleven elements and analysis of the results, e.g. cyclic graphs of displacements show that using advanced tools of numeric mechanics of structures it is possible to build models allowing simulation of the reference state changing during cyclic loading of the structure. The results of calculations provide information on both the behavior of the structure as a whole and the information on degradation of its individual elements. Thanks to storage of results after each calculation step, we have access to the complete history of structure operation. The accuracy of the behaviors description for real devices and structures depends not only on calibration of mathematic models constants, but mainly on how many factors influence the structure degradation.

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