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A CRACK GROWTH ANALYSIS IN CRITICAL STRUCTURAL COMPONENTS

ANALIZA RASTI RAZPOKE V KRITIČNIH KOMPONENTAH NAPRAV

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The supervising and health monitoring of structures is a new field that has been of increasing importance with regard to control durability, stability and safety as well as for estimating the life span of the structure. Crack growth is interesting for the proper evaluation of the reliability of structural parts. Different methods are used to record the actual situation in order to get reliable information about the on-site structure and structural elements. The experimental techniques in fracture mechanics are employed for determining the stress-intensity factors (SIFs) of the cracks in deformed structures. A procedure for the simulation of crack propagation for multiple cracks was introduced and SIFs have been calculated by using the finite-element method. The crack growth of a single crack or a periodic array of cracks initiated at the stiffeners in a stiffened panel has been investigated. The optical method of caustics is established for the application to mechanically isotropic materials through the process of SIF's evaluation and has advantageously improved applications with fiber-reinforced composites. Using high-speed photography and optical interferometric methods, we analyzed the phenomena of the dynamic failure process in composites and high-speed delamination.

Valuable information gathered by the analysis of critical structural components should be important for making decisions about the structural repairing or the halting of a plant's production. Significant examples are the analysis of structures of the deck of a ship, the jacket of a gas and oil platform and the aeolian vibrations in electrical transmission lines that can cause severe damage or even the breakdown of the conductor due to material fatigue.

Key words: caustics, CGS interferometry, risk assessment, FEM model, survey, aeolian vibrations

Nadzor in ugotavljanje integritete konstrukcij je aktivnost z naraščujočim pomenom zaradi kontrole trajnosti, stabilnosti in varnosti ter ugotavljanja preostale trajnostne dobe struktur. Raziskave rasti razpok so potrebne zaradi ocene zanesljivosti delov struktur. V uporabi so različne metode za ugotavljanje stanja. Eksperimentalne metode mehanike loma se uporabljajo za določanje faktorja intenzitete napetosti (SIFs) za razpoke v obremenjenih strukturah. Razvita je bila procedura za simulacijo propagacije razpoke v primeru več razpok in izračunana je bila SIFs uporabo metode končnih elementov. Raziskana je bila rast ene ali več razpok, ki so nastale ob ojačitvah v ojačanem panelu. Optična metoda svetlobnih odsevov je bila razvita za uporabo pri mehansko izotropnih materialih z določitvijo SIFs in prilagojena za uporabo pri vlaknatih kompozitih. Z uporabo fotografije z veliko hitrostjo in optično interferometrijo je bil analiziran pojav dinamičnega zloma kompozitov in hitre delaminacije.

Podatki, zbrani z analizo kritičnih komponent struktur, so temeljnega pomena pri odločitvah o popravilih ali ustavitvah proizvodnih naprav. Prikazani so primeri analize krova ladijske strukture, armatur plinskih in naftnih ploščadi ter vibracije zaradi vetra pri električnih daljnovodih, ki lahko povzročijo resno škodo ali celo zlom zaradi utrujenosti materiala.

Ključne besede: svetlobni odsevi, CGS-interferometrija, ocena rizika, FEM-model, pregled, svetlobne vibracije

1 INTRODUCTION

Structural life management requires the integration of design and analysis, materials behavior and structural testing. Used properly, the defined procedures can prevent over-design and provide a balance between safety and costs. The results will serve to optimize machine parts and they will also enable advantageous functionality, decreasing of maintenance costs and improvements to the fatigue life. An improvement of the numerical and experimental methods will provide an observation of the damage process in the contact of two structural elements and the assessment of the reliability of the parts of the mechanical system. This will serve for better endurance, stability and security of the structure as well as for a more reliable assessment of its life span.

In recent years, substantial advances in the understanding of the basic principles governing dynamic fracture, coupled with the development of new, relatively easy-to-use and verifiable computational methodologies have made it possible to utilize the concepts of dynamic fracture in a wide spectrum of very diverse applications. They are relevant to our rapidly developing technological world, such as accident prevention, manufacturing processes, and reliability in design.

2 AN ANALYSIS OF THE STRESS-INTENSITY FACTOR USING THE OPTICAL METHOD OF CAUSTICS

A variety of modern optical interferometric methods, including the optical method of caustics, today provide the possibility of identifying and measuring the critical parameters governing the resistance of materials to both quasistatic and dynamic failure. Although existing experimental methodologies are well developed for isotropic solids, their application to the study of failure in anisotropic and/or heterogeneous materials is still new and limited.

The stress-intensity factor is one of the important indicators that can be determined on real structures, or their models, by several possible methods of experimental mechanics under real loading conditions. A comparison of the estimated or exactly determined stress-intensity factor K and the critical value K_c of the related factor as a material property, leads to a decision as to whether the structure is still safe enough for future exploitation. Particularly, mode I crack opening has to be examined through the K_I factor, as the most important factor for brittle cracking.

The optical method of caustics is a widely used technique in experimental solid mechanics [1]. In the area of fracture mechanics, in particular, it has been one of the primary tools for investigating both quasistatic and catastrophic failure. Solving the fracture mechanics problem is of great importance for the evaluation of structural parts and an estimation of material behavior in order to prevent uncontrolled crack propagation. The method of caustics has been successfully applied to cracks in mechanically anisotropic materials such as fiber-reinforced composites. The analysis of the shape and size of experimental caustics provides an experimental value for the stress-intensity factors, because initiating or growing cracks is a characteristic property of materials.

The experimental determination of the stress-intensity factors K by the optical method of caustics is commonly in use either in a transparent or a non-transparent light arrangement. The optical effect is generated when the specimen with the crack is loaded and illuminated by the concentrated field of light in the zone surrounding the tip. Light beams are propagated through the transparent material or reflected from the deformed surface and declined from the straight line. The result on the screen is a dark spot called caustics, surrounded by the concentrated light on its edge.

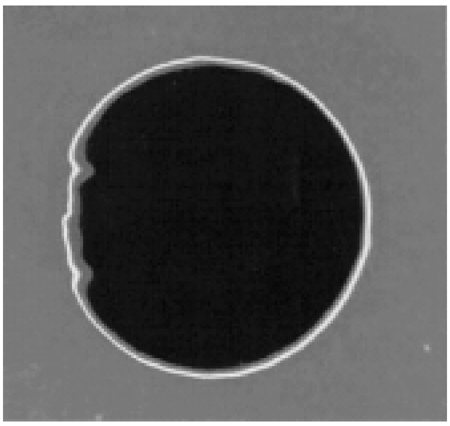

Figure 1: Isotropic caustics
Slika 1: Izotropni svetlobni odsevi

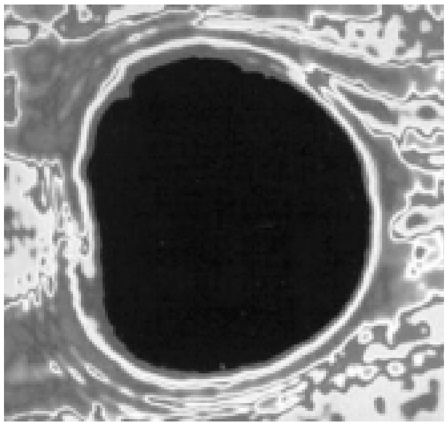

Figure 2: Anisotropic caustics
Slika 2: Anizotropni svetlobni odsevi

The general solution for the shape of a caustic curve for a mode I crack opening is of the same epicyclical form as for any kind of isotropic material, as is illustrated for araldite B (**Figure 1**). The size of a caustic curve (the bright line at the border of the dark spot) depends on the optical conditions, the mechanical characteristics and the load intensity applied to the specimen.

The invented method is applied to the non-transparent mechanically anisotropic materials [2]. The different shapes of the dark spots are caused by different mechanical properties in different directions and the position of the crack-tip. Therefore, it is necessary to simulate the unit value of K_I, and for a simultaneous situation. The actual value of K_I can be determined as being proportional to the load intensity.

An example of the optical effect is shown for a carbon-fiber epoxy composite and a crack in the direction of the fibers (**Figure 2**). The material's mechanical properties are completely different in its two principal axes (longitudinal L and transversal T) and representative for the orthotropic case: E_L = 189 Gpa, E_T = 28 Gpa, G_{LT} = 8 Gpa, ν_{LT} = 0.188.

3 AN ANALYSIS OF CRACK PROPAGATION USING CGS INTERFEROMETRY

Coherent gradient sensing (CGS) is a full field, lateral-shearing interferometric technique with an online spatial filter. CGS is convenient for measuring in-plane gradients of out-of-plane surface displacements around a crack tip [3]. The method produces high contrast fringes and provides a substantial degree of control with respect to the sensitivity of measurements during quasi-static and dynamic experiments. The method of CGS has already been applied to the study of fracture for several types of isotropic and anisotropic materials.

Composite structures, such as fiber-reinforced plastic laminates, and sandwich panels made with laminate skins and lightweight cores (e.g., PVC foam) have great

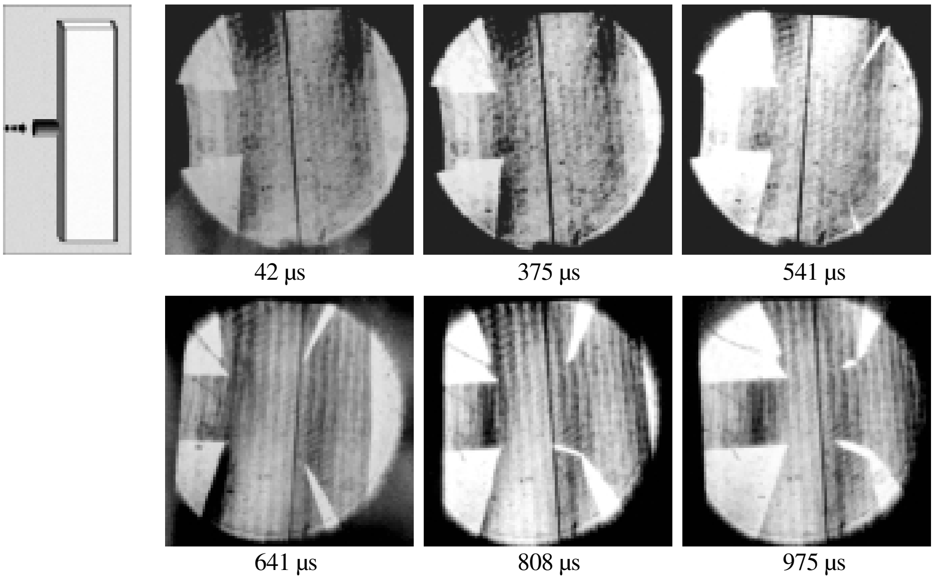

Figure 3: Propagation of cracks in the specimen since the moment of impact
Slika 3: Propagacija razpoke od trenutka udara

potential for use in aggressive environments. The high specific strength of composites offers weight savings, and their corrosion resistance gives them an advantage over traditional metallic materials. Such components, however, could be subjected to high-speed impacts by fragments, resulting from the effects of disintegrating machinery, as well as to low velocity impact by accidentally dropped objects or unexpected service loads [4]. It is commonly perceived that dynamic failure is mainly relevant to military applications, including armor/anti-armor problems and to situations involving explosive loading.

In order to investigate possible dynamic failure mechanisms (crack propagation), the dynamic loading experiments were done in a transmission arrangement in which the semi-transparent plates were "back" illuminated by means of a pulse laser. The process was then photographed by means of a rotating-mirror high-speed camera (Cordin 330A). Dynamic loading was provided by means of a semi-spherical end-cap projectile of a low-velocity gas gun at speeds ranging from 15–70 m/s (**Figure 3**).

4 SIMULATION OF CRACK PROPAGATION FOR MULTIPLE FATIGUE CRACKS

The crack-propagation simulation procedure for multiple fatigue cracks is based on a numerical integration of the Paris' equation, taking account of the interaction of several cracks.

A linear interpolation of the stress-intensity factors, K_I, has been used between the two stress-intensity values calculated. In FE modeling, shell elements are used, and the region surrounding the crack tip is meshed by singular elements [5]. A total of four different types of fatigue-test specimens were analyzed: a plate with a single crack (P-1), a plate with three cracks (P-3), a stiffened panel with a single crack (SP-1), and stiffened panel with three cracks (SP-3), (**Figure 4**).

The stress-intensity factors were calculated for all the specimens. The results have shown that a stiffened panel specimen with an array of cracks has higher stress-intensity factors and correspondingly higher crack growth rates than a specimen with a single crack (**Figure 5**). The center cracks show the highest K_I and, therefore, practically determine the crack-propagation lives.

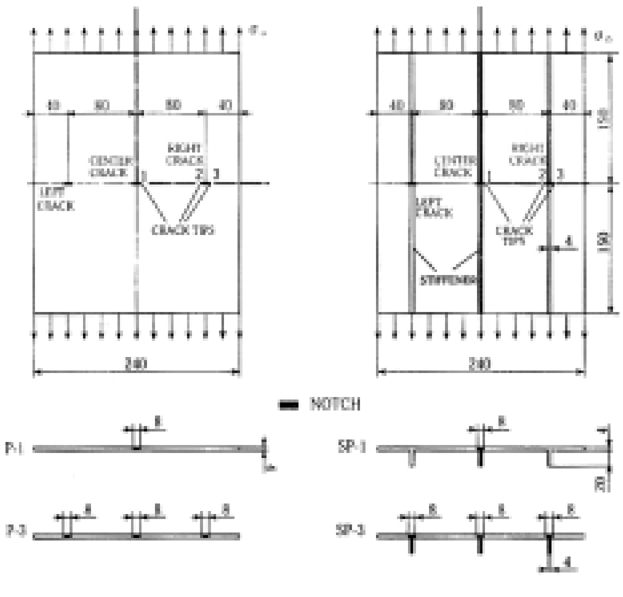

Figure 4: Fatigue test specimens and loading conditions
Slika 4: Preizkušanec za preizkus utrujenosti in pogoji obremenitve

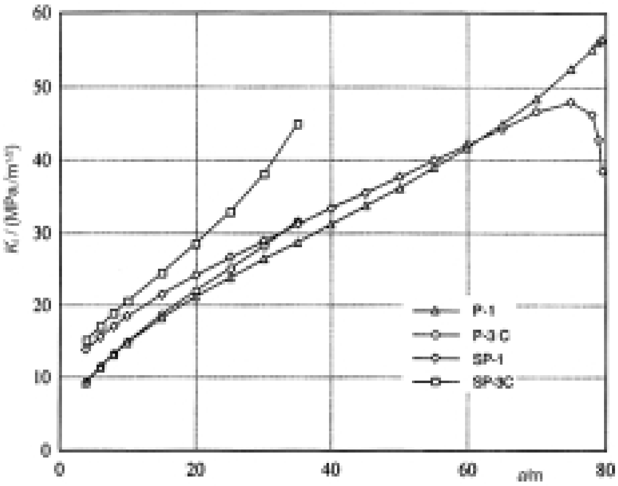

Figure 5: Simulated stress intensity factors
Slika 5: Simulirani faktorji intenzitete napetosti

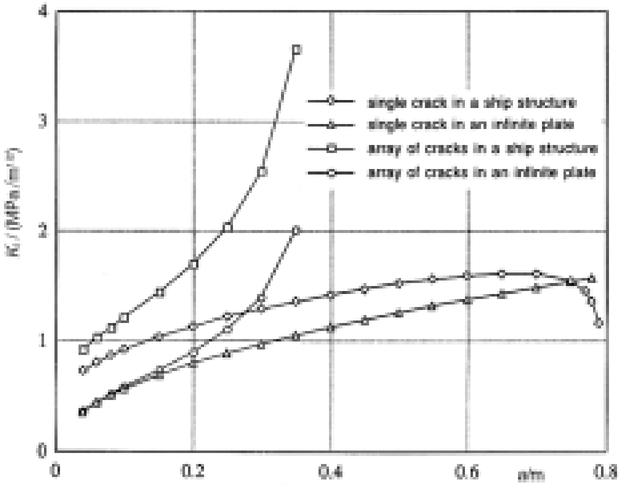

Figure 7: Stress intensity factors
Slika 7: Faktorji intenzitete napetosti

5 FATIGUE CRACK PROPAGATION IN A SHIP DECK STRUCTURE

For the remaining structural life assessment of a ship it is important to determine the crack-propagation rates of damage cracks. High stress concentrations due to geometrical discontinuity may often lead to crack initiation in the deck structure of a ship (**Figure 6**). The snipped end of the faceplate of a deck longitudinal is a typical location where a fatigue crack may initiate. The crack propagates through the stiffener and then it penetrates into the deck plate. When cracks initiate at several stiffeners, a multiple site damage in the deck structure of a ship is created.

The crack-propagation analysis was performed for a single crack and a periodical array of collinear cracks in the deck structure of a ship by using the simulation procedure [6]. With increasing crack length, the Mode I stress-intensity factor, K_I, significantly increases in the case of an array of cracks, while in the case of a single crack K_I increases slowly. Furthermore, as the crack tip approaches the intact stiffener, the K_I decreases (**Figure 7**). Consequently, an instantaneous deck fracture could occur for the multiple crack propagation, while the load-carrying capacity of the deck structure could be expected for single fatigue crack propagation. It is observed that, in the case of a stiffened panel with a single crack, the intact stiffener has a tendency to act as a crack arrester.

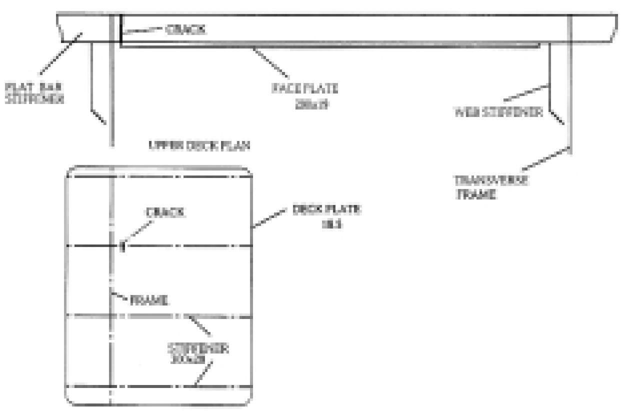

Figure 6: Fatigue crack damage in a deck structure of a ship
Slika 6: Utrujenostna poškodba v krovu ladijske strukture

6 STRUCTURAL SURVEY OF OFFSHORE PLATFORMS

Also important for this study is a description of the survey of different parts of structures, we use as an example offshore platforms, where there is a request for the survey rules defined to ensure the control of selected structural elements [7]. The selection of structural elements of jacket & deck, where it is necessary to perform the monitoring and survey should be based on a design project documentation of platforms. The ultimate strength analysis is a requirement just in cases when the structure does not pass the design level analysis by using the reserve strength ratio (*RSR*) criteria as the ratio between the environmental load at collapse and the design environmental load.

An assessment of service life should be given due to accumulated fatigue degradation effects. An analytical procedure can be performed alternatively for pre-selected elements. The pre-selection of areas to be surveyed should be based on an engineering evaluation of areas particularly susceptible to structural damage, or to areas where repeated inspections are desirable in order to monitor their integrity over time. A close visual inspection of the pre-selected areas for corrosion monitoring should be included in the survey. Flooded member detection (FMD) can provide underwater crack recognition as an acceptable alternative to close visual inspection[8] (**Figure 8**).

Figure 8: Underwater inspection of structural elements [8]
Slika 8: Podvodni pregled strukturnih elementov

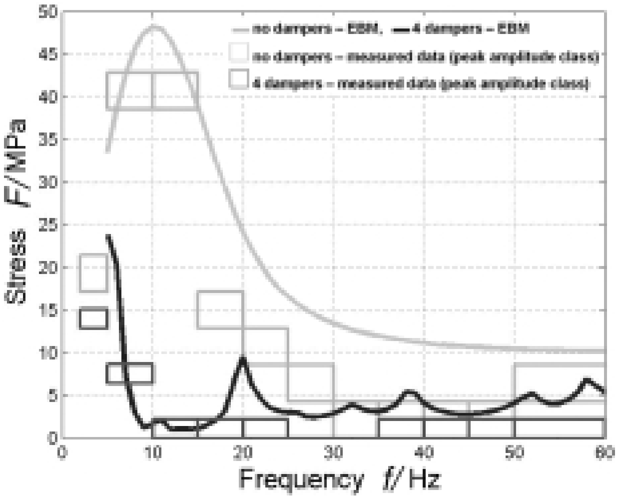

Figure 10: Analytical results and measurements data
Slika 10: Rezultati analize in podatki o meritvah

7 MEASURING AND MODELING OF TRANSMISSION-LINE CONDUCTOR VIBRATIONS

Aeolian vibrations of overhead transmission line conductors and wires (wind-induced vibrations due to the shedding of Karman vortices) are usually recorded at frequencies of 5–50 Hz. They are the main source of damage to conductors and wires due to material fatigue, and can thus significantly shorten their life span. The motion induced by aeolian vibration results in fatigue of the conductor strands as the most common form of damage, and has been a serious problem in the overhead lines industry [9]. Conductor fatigue is largely encountered at the suspension clamps, where the incidence is directly associated with the rigidity with which conductor motion is restrained.

The conductor motion due to vibration creates sliding at some contacts adjacent to the supporting clamp. The dynamic bending stresses increase simultaneously as the vibration amplitude increases. At some amplitude, the combined effects of the bending stress and the surface damage initiate a fatigue crack that propagates across the strand, and finally a failure of the strand occurs.

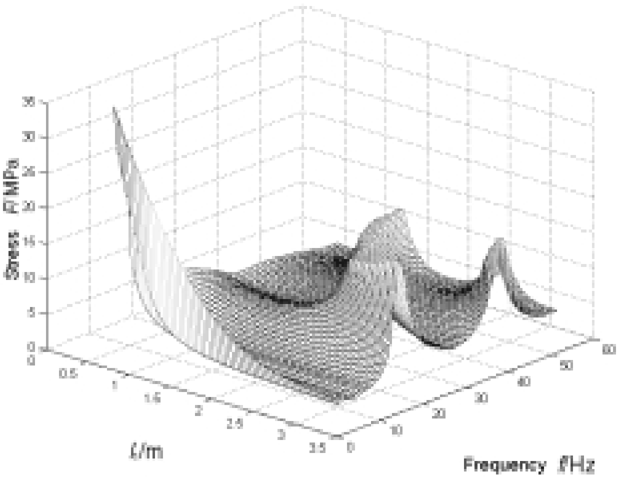

Figure 9: Stress versus frequency and distance from the clamp edge
Slika 9: Napetost v odvisnosti od frekvence in od razdalje od roba zagozde

The developed computer program enables an estimation of aeolian vibrations (the amplitude of vibrations, deformations and stress in the outer layer of the conductor) as a function of the vibration frequencies and the distance from the damper to the clamp edge (l_1), as well as the estimation of the optimal position of the damper. An example (conductor ACSR 490/65, length 520 m, 25 % UTS, two Stockbridge dampers) is shown in **Figure 9**.

Figure 10 compares the results generated using the developed EBM (Energy Balance Method) computer program and data from field measurements using the VIBREC 400 device, which is intended for automated measuring of the aeolian vibrations of overhead transmission lines at all the voltage levels. Within the device there is a microprocessor that records the data (amplitudes, frequencies, wind velocity and surrounding temperature) in its memory. The device is fastened to the suspension clamp of the conductor. The above-mentioned span was considered before and after the application of the Stockbridge damper (two dampers at each suspension clamp). The span is in the valley of the riverbed, which indicates a high probability of intense aeolian vibrations. After the application of the dampers the stress was greatly reduced and the estimated life span is more than 500 years. A very high correlation between the measured data and the developed EBM computer program generated data was achieved.

8 CONCLUSIONS

Structural life management requires the integration of design and analysis, materials behavior and structural testing. Supervising and health monitoring of any kind of structure is of great importance with regard to control durability, stability and the safety of the structure.

The accumulation of creep and fatigue damage over time are two principal degradation mechanisms, which usually lead to crack initiation in critical structural components. In extreme situations, the growth of these cracks can lead to the collapse of the structure. Damaging process analysis is significant for the determination of the reliability of mechanical components, while the numerical simulations of crack appearances and growing will process the phenomena of structural damages.

Advanced experimental methods will provide the verification of the behavior of elements with structural damage analysis. The valuable information gathered by the analysis of critical structural components should be important for making decision about the structural repairs or halting the plant's production.

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