UDK: 531:061.3(047)
COSATI: 20-11,20-12

The 16th European Conference on Fracture

Marinko Ugrčić, PhD (Eng)[1)]
Stevan Maksimović, PhD (Eng)[1)]
Zijah Burzić, PhD (Eng)[1)]

THE *16th European Conference on Fracture (ECF 16)* took place July 3-7, 2006 in Alexandroupolis, Greece. Started in 1976, the European Conference of Fracture (ECF) is held every two years in a European country. Its scope is to promote world-wide cooperation among scientists and engineers investigating fracture and fatigue of solids. ECF16 was under the auspices of the European Structural Integrity Society (ESIS) and was sponsored by the American Society of Testing and Materials, the British Society for Stain Measurement, the Society of Experimental Mechanics the Italian Society for Experimental Mechanics, and the Japanese Society of Mechanical Engineers. The technical program of ECF16 was the product of hard work and devotion of more than 150 world-leading experts.

Fracture mechanics analysis has been successful for many years in the prevention of failures of engineering materials and structures. It is based on the realistic assumption that all materials contain crack-like defects from which failure initiates. At this conference, computation methods are intensively used in many papers considering failure of structural components. Special attention has been given to developing computation methods in fatigue life estimations.

The two general approaches are researching in the field of the computation methods in life estimations of structural components up to crack initiation and crack propagation. The first one is the fatigue life prediction for cracked structural parts with the classical finite element method and it is not an obvious task for industrial structures. The second is improved computation methods, based on using special singular finite elements and X-FEM (eXtended Finite Element Methods) presented in some of the papers.

These methods are reliable and efficient in crack growth analyses of damaged structural components, especially in the design of aircraft and flight structures. The X-FEM allows embedding physical surfaces of discontinuity into a mesh without modifying it, thanks to the use of two combined level-sets, the partition of unity method and enrichment with compact support. The use of specific enrichment function for cracks, singular at the crack tip and discontinuous on the surfaces enables carrying out a complete analysis of the crack without having to change the mesh.

ECF16 focused in all aspects of structural integrity with the objective of improving the safety and performance of the engineering structures, components, systems and their associated materials. Emphasis was given to the failure of nanostructured materials and nanostructures and micro and nanoelectromechanical systems (MEMS and NEMS). Micro-electro-mechanical systems (MEMS) technology is on the verge of revolutionizing wireless applications. Their low power consumption, small physical size and weight, low cost and high performance make this technology ideal for the next generation of wireless communications. Layered materials and especially thin film/substrate systems are becoming important in small volume systems used in micro and nanoelectromechanical systems. In thin film systems, failure often occurs via fracture mechanisms, either through thickness cracking or interfacial delamination leading to failure of the device or layer. In all these problems, fracture mechanics plays a major role in the prediction of failure and safe design of materials and structures. Failure of materials and structures at the micro and nanoscale levels are adequately presented at ECF16 with 93 papers referred to in this area. To predict failure of MEMS and NEMS finite elements (FE) simulations are intensively used. Many papers that are presented in this conference use FE simulations to describe the behaviour of MEMS and NEMS.

More than nine hundred participants attended ECF16, while more than eight hundred fifty papers were presented, far more than any other ECF over a thirty year period. The participants of ECF16 came from 49 countries: USA (82), France (75), Japan (54) UK (49), Italy (49), Germany (49), Greece (46), Serbia (31), Russia (30), Austria (22), Spain (20), Czech Republic (19), Sweden (15), The Netherlands (15), etc. Roughly speaking 66% came from Europe, 17% from the Americas, 8% from the Far East and 9% from other countries.

The fifteen plenary lectures were presented at the conference. The remaining 683 papers were arranged in 25 tracks and 35 special sessions with 303 and 380 papers, respectively. The papers of the tracks have been contributed from open call, while the respective organizers have solicited the papers for special sessions. Both tracks and special sessions fall into two categories, namely Fracture of nanomaterials and nanostructures and Engineering materials and structures with 88 and 595 papers, respectively.

The review and contents of the tracks is given as follows.

Nanomaterials and Nanostructures (B. TRACKS)

B1. Nanomaterials and Nanostructures
1T1. Fracture and fatigue of nanostuctured materials
1T2. Failure mechanisms

[1)] Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

1T4. Fatigue and Fracture of MEMS and NEMS
1T7. Thin films
1T9. Failure of nanocomposites
1T10. Other
B2. Engineering Materials and Structures
2T1. Physical aspects of fracture
2T2. Brittle fracture
2T3. Ductile fracture
2T4. Nonlinear fracture mechanics
2T5. Fatigue and fracture
2T8. Polymers and composites
2T11. Fracture mechanics analysis
2T13. Probabilistic approaches to fracture mechanics
2T14. Computational fracture mechanics
2T15. Experiments; fracture mechanics
2T16. Creep fracture
2T17. Environment assisted fracture
2T18. Dynamic, high strain rate or impact fracture
2T19. Damage mechanics
2T21. Concrete and rock
2T22. Sandwich structures
2T23. Novel testing and evaluation techniques
2T26. Structural integrity
2T28. Mesofracture mechanics
2T32. Micromechanisms in fracture and fatigue

Special symposia-sessions (C. TRACKS)

C1. Nanomaterials and Nanostructures

1. Fracture and Fatigue at the Micro and Nano scales (H. D. Espinosa & Isaac Daniel)
2. Nanoscale Deformation and Failure (Min Zhou)
3. Deformation and Fracture at the Nano Scale (N.R. Moody & D.F. Bahr)
4. Reliability and Failure Analysis of Electronics and Mechanical Systems (Ouk Sub Lee)
5. Multiscaling in Molecular and Continuum Mechanics - Scaling in Time and Size from Macro to Nano (George C. Sih)
6. Cracks in Micro- and Nanoelectronics (B. Michel) 43.Interfacial Fracture in Composites and Electronic Packaging Materials (C.T. Sun and T. Ikeda)

C2. Engineering Materials and Structures

1. Fracture and Fatigue of Elastomers (Claude Bathias & Emin Bayraktar)
2. Integrity of Dynamical Systems (Katica (Stevanovic) Hedrih)
3. Modelling of Material Property Data and Fracture Mechanisms (Robert Moskovic)
4. Micromechanisms in Fracture and Fatigue (Jaroslav Pokluda & Reinhard Pippan)
5. Interface Fracture and Behavior of Joints (Leslie Banks-Sills)
6. Computational Fracture Mechanics (Ted Belytschko) 14.Cohesive Models of Fracture (W. Brocks)
7. Environment Assisted Fracture (Giovanna Gabetta & Wolfgang Dietzel & Hryhoriy Nykyforchyn)
8. SIM, Philosophy, Instrumentation and Analysis (W. D. Dover)
9. Fracture of Biomaterials (Jie Tong)
10. Structural Integrity Assessment in Theory and Practice (Stefan Vodenicharov & Stojan Sedmak)
11. Critical Distance Theories of Fracture (David Taylor)
12. New Investigations on Very High Cycle Fatigue of Materials (Herwig Mayer & Stefanie Stanzl-Tschegg)
13. Deformation and Fracture of Engineering Materials (Chi T. Liu)
14. Materials Damage Prognosis and Life Cycle Engineering (Robert P. Wei & Gary Harlow & Anthony Ingraffea & James Larsen)
15. Mixed-Mode Fracture (Mike Gosz)
16. Fracture Mechanics Characterization of Wood (Stefanie Stanzl-Tschegg)
17. Short Fatigue Crack Growth under Multi-axial Loading Conditions (Y. Murakami and A.J. McEvily)
18. Integrity of gears (Damir Jelaska)
19. High Temperature and Thermomechanical Fatigue (Richard W. Neu & Sreeramesh Kalluri & Hans J. Maier)
20. Impact Failure of Laminated and Sandwich Composite Structures (R. AW Mines)
21. Mesofracture and transferability (Guy Pluvinage)
22. Damage in Composites - Damage Development in Composite Materials & Structures - Models of Prediction (Costas Galiotis)
23. Aging Aerostructures (Spiros Pantelakis)
24. Residual Stress and its Effects on Fatigue and Fracture (A.G. Youtsos & P.J. Withers)
25. Computational Modeling of Multiphysics Degrading Systems (CMMDS) (John Michopoulos)
26. Scaling and Size Effects (Zdenek P. Bazant & Milan Jirasek)
27. Multiple cracking and delamination (R. Goldstein and R. Massabo)

Invited plenary lectures

1. *Deformation and Fracture at the Micron and Nano Scales* (E. C. Aifantis)
2. *Statistical Mechanics of Safety Factors and Size Effect in Quasibrittle Fracture* (Z. P. Bazant and S.-D. Pang)
3. *Nanoreliability – Fracture Mechanics on the Way from Micro to Nano* (B. Michel)
4. *Fracture Mechanics and Complexity Sciences* (A. Carpinteri and S. Puzzi)
5. *Failure of Composite Materials* (I. M. Daniel)
6. *Interactions of Constrained Flow and Size Scale on Mechanical Behavior* (W. W. Gerberich, W. M. Mook, M. J. Cordill and D. Hallman)
7. *Space Shuttle Columbia Post-Accident Analysis and Investigation* (S. McDanels)
8. *The Role of Adhesion and Fracture on the Performance of Nanostructured Films* (N. Moody, M. J. Cordill, M. S. Kennedy, D. P. Adams, D. F. Bahr and W. W. Gerberich)
9. *Assessment of Weldment Specimens Containing Residual Stress* (K. M. Nikbin)
10. *MEMS: Recent Advances and Current Challenges* (R. J. Pryputniewicz)
11. *Fracture, Aging and Disease in Bone and Teeth* (R. O. Ritchie and R. K. Nalla)
12. *Laboratory Earthquakes* (A. J. Rosakis, K. Xia and H. Kanamori)

13. *A Historical Retrospective of the Beginnings of Brittle Fracture Mechanics - The Period 1907-1947* (H. P. Rossmanith), and
14. *Dynamic Crack Propagation in Particle Reinforced Nanocomposites and Graded Materials* (A. Shukla)
15. *Spatial and Temporal Scaling Affected by System Inhomogeneity: Atomic, Microscopic and Macroscopic.* (G. C. Sih).

VTI presentation

Marinko Ugrčić, Stevan Maksimović, and Zijah Burzić from the Military Technical Institute (VTI) presented their own papers as well as the papers of their absent colleagues.

It is believed by the authors that, among all the papers communicated during the Symposium, the following ones deserve special attention of the readers from the Military Technical Institute.

- *Modelling of the surface cracks and fatigue life estimation* (K.Maksimović, VTI, Belgrade, S.Maksimović, VTI, Belgrade, V.Nikolić-Stanojević, Faculty of Mechanical Engineering, Kragujevac)
  Part-through cracks such as corner or surface cracks are among the most common cracks in structural components. The paper focuses on developing analytic expressions for the stress intensity factor (SIF) for the surface crack in 3-D solid type structural components and crack growth. Traditionally, damages in structural components are assumed to have an elliptic shape and are loaded with cyclic loads and load spectra. The propagation of semi-elliptical surface initiated fatigue cracks has been considered. Analytical model for the stress intensity factors, derived in this work, was used for crack growth analyses and fatigue life predictions. Semi-elliptic surface cracks frequently initiate and grow in the vicinity of high stresses, stress concentrations, thermal stresses and other non-linear stress fields. Accurate stress intensity factors for such cracks are necessary for reliable prediction of fatigue crack growth rates or fracture. The slice synthesis approach was used here for the computation of surface flaw stress intensities. To validate the analytic derived stress intensity factors for semi-elliptic surface cracks finite element method was used. The propagation of semi-elliptical surface initiated fatigue cracks has been considered. Analytic model for the stress intensity factors, derived in this work, is used for crack growth analyses and fatigue life predictions. Good agreement between the developed analytic expressions for the stress intensity factors and numerical results based on finite element method were obtained.
- *Clock mechanism as base of artillery safety and arming devices* (M.Ugrčić, Military Technical Institute, Belgrade)
  A theoretical analysis was conducted and a mathematical model of the motion of safety and arming device consisting of a rotor (drive gear), two pairs of involute gears and pallet was established. Mathematical model, developed on the basis of the equations of the dynamics of rigid material system and impact mechanics, includes differential equations of motion for coupled and free motion, as well as the phase of impact. On the basis of the mathematical model of the motion of the safety and arming device, the program code SADFOR for resolving the differential equations of the motion of the clock mechanism and numerical simulation of its function was developed. Some calculation results with variation of the significant parameters of the clock mechanism construction, due to its optimization as well as the arming time performed, are shown. The results of experimental testing of the real model of the mechanism construction, that satisfies all functional characteristics as well as the safety performance, confirming the quality of the developed method, was also given.
- *Fatigue life estimation of notched structural components: Computation and experimental investigation* (S.Maksimović, VTI, Belgrade, Z.Burzić, VTI, Belgrade, K.Maksimović, VTI, Belgrade)
  This work considers the analytical/numerical methods and procedures for obtaining the stress intensity factors and predicting the fatigue crack growth life for cracks at notched structural components. Many failures in aircraft structures are due to fatigue cracks initiating and developing from fastener holes at which there are large stress concentrations. Stress intensity factor (SIF) solutions are required for assessing the fracture strength and residual fatigue life for defects in structures or damage tolerance analysis recommend to be performed at the stage of aerospace structure design. Many efforts have been made during the past two decades to evaluate the stress intensity factor for corner cracks and for through the thickness crack emanating from fastener holes. A variety of methods has been used to estimate the SIF values, such as approximate analytical methods, finite element (FE), finite element alternating, weight function, photo elasticity and fatigue tests. In this paper, the analytical/numerical methods and procedures were used for obtaining the SIF and predicting the fatigue crack growth life for cracks at attachment lugs. Single through crack in the attachment lug analysis was considered. For this purpose analytic expressions were evaluated for SIF of cracked lug structures. For validation of the analytic stress intensity factors of cracked lugs, FEM with singular finite elements was used. Good agreement between computation and experimental results for fatigue life of the cracked lugs was obtained. The strain energy density criterion was used to determine the crack trajectory or angle of crack propagation in a thin shell with cracks emanating from two riveted holes.
- *Failure analysis of layered composite structures: Computation and experimental investigation* (S.Maksimović, VTI, Belgrade)
  A geometric nonlinear finite element method based on the von Karman-High Order Shear Deformation Theory (HOST) is used to study the first-ply failure behaviour as well as the post buckling behaviour of laminated type composite structures. For this purpose and for the investigation of the failure responses improved 4-node layered shell finite elements are used. The finite element formulation is based on the third order shear deformation theory with four-node shell finite elements having eight degrees of freedom per node. The first-ply failure of laminates and the onset of delaminating in the process of first-ply failure computation are some of the features incorporated in the geometric nonlinear formulation. The load-displacement curves for different types of graphite/epoxy laminates are obtained. Stresses are computed in order to determine the first-ply failure of the mentioned axially compressed laminated composite structure based on the maximal strain failure criterion. In this procedure, post buckling and failure behaviour of axially compressed flat and curved composite panels are investigated numerically and experimentally. Compu-tational

results for buckling loads of compressed panel responses using linear and geometrically nonlinear analyzes are compared with experiments. The effects of stacking sequences on initial failure load are investigated.

- *Determination of J_R-curve by two points method* (I. Blačić, VTI, Belgrade, V. Grabulov, VTI, Belgrade)
  New approach for crack resistance curve is proposed in the paper and the possibility of its application investigated. The approach is based on *JR* description by polynomial function with two coefficients. For determining the coefficient, two pairs of values of *J* integral and crack extension Δa are necessary. One of them is determined experimentally at the end of the experiment. It is accepted that the second pair of values belongs to the blunting line, but in addition to this assumption, certain criteria are required. The paper considers establishing of additional criteria for determining the second pair for values of *J* integral and crack extension Δa.
- *Monitoring of stress-strain state of boiler during pressure test (*J. Kurai, CertLab, Pancevo, Z. Burzić, VTI, Belgrade, N. Garić, VTI, Belgrade, M. Zrilić, Faculty of Technology and Metallurgy, Belgrade, B. Aleksić, VTI, Belgrade)
  In order to extend the capacity of steam production, a new boiler of 110 t/h has been installed in the Oil Refinery Pančevo. Misalignment had been revealed after assembling the tube 13, produced from St 35.8/I steel. During assembling, tube 52 in the boiler upper part, made from the same steel, had been distorted and plastically deformed due to local overloading. Additional testing was specified in inspection procedure for boiler acceptance in order to assess its "fitness-for-purpose", enabling to evaluate the stress and strain state of the damaged zones before, during and after proof pressure test by cold water. This testing was performed from the outer side. Residual stresses were measured by hole drilling method in the regions of the damaged tubes. Stress level was determined by strain gauges in the specified regions of the drum and damaged tubes, and acoustic emission was monitored during proof pressure test. By this testing, boiler initial state ("zero state") before service was defined as well. The level of residual stresses was 44% of yield strength around tube 52. It was about 39% of yield strength in HAZ and BM of tube 13 welded joint, and reduced to about 32% after the proof test, indicating some local plastic deformation developed at the sites of stress concentration. The stress calculated from micro strains measured by strain gauges during the pressure test was elastic in all locations in tubes and boiler drum, with the maximum value of 99.3 MPa in boiler drum and 66 MPA at tube 52. The elastic behaviour was confirmed by acoustic emission. The performed testing and analysis allowed suggesting the acceptance of the boiler as "fit for purpose", with no further action necessary.
- *Loading rate effect on fracture resistance of HSLA steel welded joints* (V. Grabulov, VTI, Belgrade, I. Blačić, VTI, Belgrade, A. Radović, Faculty of Technology and Metallurgy, Belgrade, S. Sedmak, Faculty of Technology and Metallurgy, Belgrade)
  Three testing methods of different loading rates (impact test, explosion bulge test and fracture mechanics tests) had been applied for fracture behaviour evaluation of base metal and welded joints, produced by metal manual arc welding. Basic properties of weldments and transition temperatures (50% Charpy impact energy and nil ductility drop weight test temperature) were also assessed as a part of weld ability testing. The results, obtained for the base metal, weld metal and heat-affected-zone were analyzed. The results of application of the given methods to Yugoslav version of HY 100 type steel and SUMITEN 80P, produced in Japan, are presented. This enabled to assess the effect of the loading rate on fracture resistance of the welded joint of these high strength low alloyed steels for pressure vessel application. It was concluded that the applied testing methods do not exclude each other, since they produce complementary results, helping to understand fracture behaviour of the welded joints as an important part of the global weld ability assessment better.
- *The effect of welding procedure of microalloyed steel on fatigue crack growth* (Z. Burzić, VTI, Belgrade, S. Sedmak, Faculty of Technology and Metallurgy, Belgrade, V. Grabulov, VTI, Belgrade, M. Burzić, NIC, Užice, M. Manjgo, MF, Mostar-BiH, V. Gliha and T. Vuherer, MF, Maribor-Slovenia)
  The application of high strength steels developed for welded structures highly stressed by impact and variable loading and for low temperatures depends on the properties of critical regions of the welded joint. Samples for investigation had been prepared by metal manual arc welding (SMAW) and CO_2 gas shielded welding (MAG). In addition to strength, toughness and crack resistance of the welding joints also have to be confirmed by testing. Impact testing of notched Charpy specimens had been used for impact energy determination. The reduction in impact properties of the weld metal and heat-affected-zone (HAZ) compared to the base metal were quantified. Applying CRACKTRONIC system, developed by RUMUL for pre-cracked specimen testing, crack growth rate was defined. This enabled obtaining fracture mechanics parameter in a form of stress intensity factor range ΔK, induced by variable loading as dependent of crack extension for one cycle, da/dN. It has been found that the behaviour of the base metal is superior to that of weld metal and HAZ, but the differences are not significant.
- The organizer has published the Proceedings of the 16th European Conference of Fracture – *Fracture of Nano and Engineering Materials and Structures*, edited by Professor E. E. Gdoutos and printed by Springer (Netherlands). The Proceedings include a CD containing the full 698 papers presented at the Conference.

Furthermore, due to the expected care and enormous efforts of Professor Katica S. Hedrih from the Faculty of Mechanical Engineering of the University of Niš, the *Booklet of Abstracts, Minisymposium - Integrity of Dynamical Systems* (Theory, Applications and Experiments) was published. The Booklet contains the abstracts of the invited/contributed papers concerning the phenomenology, analogy, nonlinear oscillations and chaos, stability, clock models of structures: paradigms of nonlinear phenomena, noise and fracture dynamics, theory of stress and strain state of deformable bodies, damage in structure, models of different materials, control oscillations of active structure and fracture, applications and experiments.

Special events

Besides the superb technical program, the participants of the symposia enjoyed the majestic city of Alexandroupolis with its unique beaches and beautiful scenery, the areas of historical interest and archaeological importance of the

prefecture of Thrace, and one-day excursions.

Alexandroupolis, the capital of Evros Region, holds the leading position in the geographical area of Eastern Macedonia and Thrace. Historical records say that in 334 BC, in this region near the sea, Alexander the Great founded a city that was later depopulated. In the 19th Century, the Russians, who conquered the land, rebuilt the city. When the region became part of the Greek state, in 1920, the city was named Alexandroupolis. Today, it is the capital of the prefecture and a modern well-planned city, placed along the banks of the Evros River.

The mouth of the Evros River is an important wetland, with rare species of birds and other animals, where it is not permitted to hunt. There are therapeutic springs in the region, near the village of Loutros, 14 km from Alexandroupolis.

During the Symposium very interesting excursions to the Dadia forest reserve and Soufli, Didimotiho and Orestiada, Evros Delta, Xanthi, Porto Lagos, Fanari, and the island of Thassos were successfully organised. It was a great occasion to visit the Byzantine castle, Byzantine church of S. Ekaterini, the Armenian church of St. George and the post–Byzantine churches of Athanassios the Great, the folklore and ethnological museum and the town and enjoy the delicious local cuisine, swimming, the sandy beaches and the traditional Greek hospitality, as well.

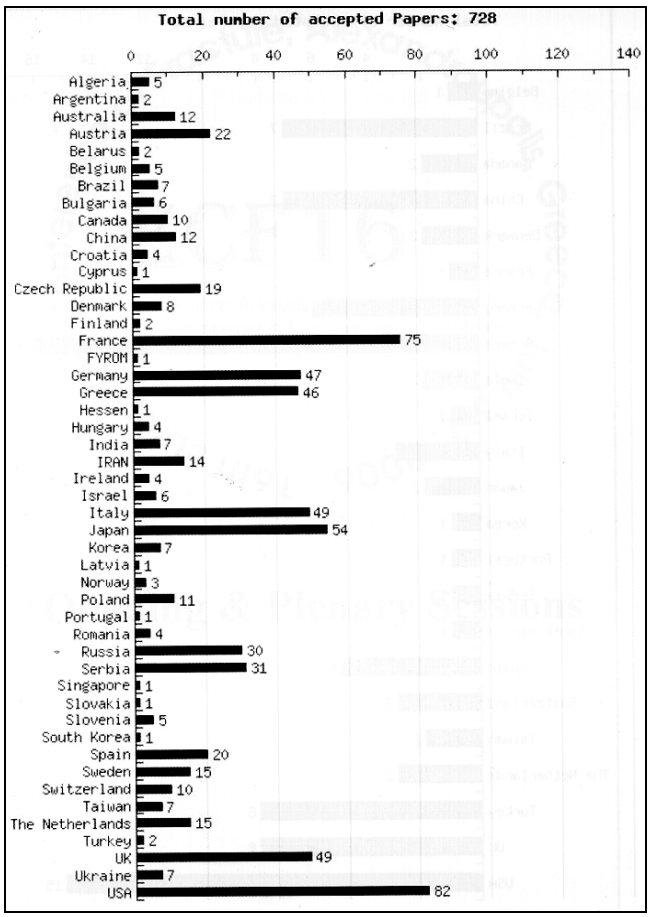
Special exhibitions were organised from 10:00 to 19:00 on Monday, Tuesday, Wednesday and Friday. Two exhibitors, *Instron* and *Springer* have presented their own very rich programs. *Instron* is a leading provider of testing equipment for the material testing, and structural testing markets. *Instron*'s products test the mechanical properties and performance of various materials, components and structures in a wide array of environments. *Springer* is one of the most renowned scientific publishing companies in the world. Its publications cover subjects ranging from the natural sciences, mathematics, and engineering and computer science to medicine and psychology.

Organization

The organization of the Symposium and the above mentioned social events was immaculate, mainly due to the permanent care and enormous efforts of Professor Emmanuel E. Gdoutos and his tireless collaborators and senior students from the Faculty of Mechanical Engineering as well as the Department of Electrical and Computer Engineering of Engineering Democritus University of Thrace at Xanthi.

Conclusion

The Conference provided an extraordinary opportunity for the participants to meet and discuss recent advances in *Fracture of Nano and Engineering Materials and Structures*. During this Conference new ideas and research results in many domains of structural design with respect to failure of materials and structures were presented. Practical and scientific contributions in the domains of analytic and computation methods in fracture mechanics analyses, improved mechanical properties with respect to fatigue lives, computation and test methods in fatigue life estimations were also presented.



Comparative review of participants at ECF 16 per country (from official Conference Program)

The main conclusion that can be drawn from the lectures presented at the Conference is that *Fracture of Nano and Engineering Materials and Structures* has gained in extent, as far as theoretical end experimental methodology and applicability are concerned.

Received: 11.10.2006.

Šesnaesta evropska konferencija o lomu

Шеснадцатая европейская конференция о изломах

La 16ième conférence européenne sur la fracture