P. M. S. T. de Castro, Universidade do Porto, Portugal

Lecture #1 (of 2) for Salerno University BSc students, 22-24 May 2023

An Introduction to Linear Elastic Fracture Mechanics

Abstract

A 50 minutes introduction to Linear Elastic Fracture Mechanics is presented. The presentation presupposes familiarity with basic mathematical analysis and mechanics of materials, but no previous knowledge of fracture mechanics. Historical context is mentioned, and basic contributions of stress analysis of solids in the presence of cracks are highlighted. Westergaard solution based upon the use of complex variable is presented in detail so that the derivation of the equations for elastic stress and displacement near the tip of cracks is fully understood. The concept of stress intensity factor K_I (I meaning mode I) is presented, and its role in fracture mechanics assessments - $K_I > K_c$ implying fracture - is mentioned. The equivalence between stress intensity factor and energy approaches, as presented by George Irwin, is demonstrated. The use of the stress intensity factor concept in modelling fatigue crack growth and circumstances related to the pioneering contributions of Paul Paris are mentioned.

Takeaways

- Linear Elastic Fracture Mechanics (LEFM) does not involve any attempt to ellucidate the fundamental details of the fracture process at atomic level. Instead, it relies upon the elastic stress field near a crack tip (characterized through the stress intensity factor K) to make predictions of behaviour. At the conditions of interest - temperature etc. - , if K is greater than a critical value characteristic of the material K_c, then fracture (*i.e.*, crack extension) is predicted.
- Through time two schools of thought emerged, one based upon the use of K, and another based on the concept of strain energy release rate G. It is thanks to George Irwin that the equivalence of both concepts was established: if you know K_c you also know G_c, and *vice versa*.
- Paul Paris and colleagues were the first to appreciate that fatigue crack growth (FCG) could be modelled based on the range of values of K (ΔK) of a cracked solid subjected to cyclic loading. FCG rate is the same for a given material and conditions (environmental, etc.), irrespective of the particular structure being examined, since what matters is the value of ΔK.
- The Paris law applies to a region of the ΔK domain. FCG rates spanning the entire range from threshold to final failure are typically described by a sigmoidal curve.
- Hopefully the talk will stimulate participants to further explore the field of Fracture Mechanics, of which this presentation is intended as an ‘appetizer’.

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Lecture #2 (of 2) for Salerno University BSc students, 22-24 May 2023

Fatigue Case Studies

Abstract

The 50 minutes presentation will focus on lessons learned through engineering failure analyses performed in a variety of contexts. The first case involves the failure of a axle shaft of the bogie of a train. The usual monitoring of the integrity of the axle boxes through temperature measurements is mentioned. The importance of periodic examination of axles for crack initiation is emphasised, and the relative importance of increasing toughness, or decreasing initial crack size (through improved non-destructive inspection resolution) is discussed on the basis of Fracture Mechanics concepts.

The next two cases are not based on Fracture Mechanics, and instead use classical fatigue analyses and concepts. The first involves the failure of a shaft of a heavy duty fatigue testing machine, which failed by fatigue. The case illustrates the importance of stress concentration particularly in cyclic loaded components (even a fatigue testing machine may fail by fatigue!). The second case involves the analyses of a spring, and will serve to illustrate how it is possible to gather relevant fatigue information in the presence of a bare minimum of data.

Takeaways

- Initial crack size as a feature of the resolution of the non-destructive inspection system used.
- From Fracture Mechanics knowledge, but also from plain common sense, if you need to guarantee the largest number of cycles (or 'life') of a component or structure, two relevant measures can be considered – (i) increase the toughness of the material, so that for the same external loading larger size cracks might be tolerated, and (ii) reduce the initial crack size, in order to benefit from slow growth associated to low ΔK and early FCG. Using the Paris law, this presentation illustrates that the increase in life is substantially greater reducing initial crack size (approach ii) rather than increasing toughness (approach i).
- The importance of stress concentrations in fatigue behaviour of mechanical components cannot be overemphasised.
- Basquin law and some basic procedures to model high cycle fatigue (HCF) behaviour in the presence of mean load are illustrated in the talk.

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Lecture #1 (of 5) for Salerno University MSc students, 22-24 May 2023

Fatigue in Aeronautics

Abstract

In his many books Henri Petrosky explains very elegantly the role of failure in the progress of engineering. Aeronautical engineering is not an exception, and some failures had a seminal role in the progress of design practice and regulations. Brief reference will be made to failures as those of Comet aircraft in the fifties or, later, to the Aloha Boeing 737 1988 accident (Aloha Airlines Flight 243, April 28), as these were game-changing events. The philosophy and practice of damage tolerance will be discusssed in detail in this presentation. Materials for aerostructures and fabrication methods, including the consequences of residual stresses, will be mentioned. Notwithstanding the increasing use of carbon fiber composites, particularly in large passenger aircraft, most civil aircraft flying everyday still use riveted Al alloy structures. Thus the behaviour of these structures will be discussed, and the role of induced residual stresss explained. The talk presupposes some familiarity with Fracture Mechanics concepts.

Takeaways

- Provided adequate periodical inspection plans are designed, and repairs are timely made as required, design for damage tolerance implies that the aerostructure can fly safely for very long times.
- Aiming ar lightweight structures motivates the search for materials with high strength and toughness, which is a combination hard to achieve since usually high strength is associated with low toughness.
- Although large cracking of fuselage is an highly uncommon accident, this still occasionaly occcurs as shown by the Southwest Airlines Boeing 737-300 accident on April 1, 2011.
- The role of residual stresses in the behaviour of mechanical components is highlighted and students are expected to get a engineering appreciation of the subject – benefits and eventual harm to be expected from residual stresses.

P. M. S. T. de Castro, Universidade do Porto, Portugal

Lecture #2 (of 5) for Salerno University MSc students, 22-24 May 2023

Mixed-mode Fracture. Part I

Abstract

As an introdution to the problem of mixed-mode fracture, the case of an inclined crack in a plate remotely loaded by an uniform remote tensile stress will be analised. The plate with an inclined crack was the first mixed-mode problem to get the attention of researchers, and the work of Fazil Erdogan and George Sih on britttle fracture of PMMA is now a classic feature of all Fracture Mechanics books (see *e.g.* David Broek's 'Elementary Fracture Mechanics' Kluwer, 1982, or Emmanuel Gdoutos' 'Fracture Mechanics - an Introduction', 3rd ed, Springer, 2020). Brittle materials are ideal test cases for validating models of fracture behaviour, and in particular for prediction of crack propagation path. This will be illustrated by experiments on three- and four-point bend PMMA specimens. The development of the extended finite element method (X-FEM) makes it possible to address in a convenient way the problem of crack path prediction. X-FEM addresses shortcomings of FEM when dealing with cracks, through enriching with discontinuous functions the solution space. The application of X-FEM to the above mentioned PMMA experiments will be presented.

A further step consists in modelling fatigue crack growth (FCG) in mixed-mode conditions. Early work involved CT ('compact tension') specimens modified with holes; this quickly became a popular topic for researchers, perhaps because of the ease of generating experimental data for comparison and validation of the X-FEM models. Limitations are the usually low values of K_{II} by comparison with K_I , implying that the behaviours revealed by these studies concern just a small part of the possible combinations K_I, K_{II} that can be foreseeen. In the next talk of this series, mixed-mode FCG testing with other specimen types that enforce large values of K_{II} will be discussed.

Takeaways

- Fazil Erdogan and George Sih gave a key contribution to the field of mixed-mode fracture with their ground-breaking 1963 paper on brittle fracture of PMMA (polymethyl methacrylate) plates with inclined cracks. This is a pioneering presentation of the important problem of the direction of crack propagation.
- X-FEM addresses shortcomings of FEM when dealing with cracks, enriching with discontinuous functions the solution space.
- The widespread study of mixed-mode behaviour on the basis of tests on CT ('compact tension') specimens modified with holes has a limitation which consists on the common preponderance of mode I in the studies.

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Lecture #3 (of 5) for Salerno University MSc students, 22-24 May 2023

Mixed-mode Fracture. Part II

Abstract

The CTS ('compact tension shear') specimen introduced by Hans Richard *et al.* is frequently found in experimental mixed-mode fracture studies. The advantages and shortcomings of this specimen will be discussed in the talk, in the context of its use in the study of the fatigue crack growth (FCG) behaviour of the steel of a high speed train wheel. The fatigue behaviour of this steel is discussed in detail, particularly as regards the characterization of near-threshold values. The CTS specimen makes it possible to characterize the direction of crack propagation for a range of initial mixed-mode situations. It is observed that very quickly the crack path is rearranged so that predominantly mode I conditions prevail in the test.

The equivalent stress is a powerful concept in Mechanics of Materials, as illustrated by the Tresca and von Mises yield criteria. These make it possible to analyse a multiaxial problem on the basis of a uniaxial concept – the uniaxial yield strength, in the case of studies concerning yielding. In mixed-mode FCG situations, FCG rate is usually described by a version of the Paris law, where instead of K_{I} an equivalent K_{eq} is used. Several approaches are mentioned in the literature and the presentation will discuss shortcomings involved in definitions of K_{eq}.

If the interest is focused on FCG under mixed-mode situations, and given the limitation of the CTS specimen, recourse to other specimens should be foreseen. Among these the asymmetrically loaded 4-point bend specimen was used in a test campaign on AA 6082-T6. The tests made it possible to identify the direction of crack propagation for a wide range of initial K_I, K_{II} combinations, and show experimentally the near 90º direction obtained for the pure mode II situation. Limitations of the present approaches will be discussed, and a possible way forward proposed.

Takeaways

- The CTS specimen allows for practical testing for determination of FCG direction starting from a range of K_I, K_{II} mixities. However, quickly after this initial stage of crack propagation, the crack assumes a near mode I situation.
- How to perform a test for FCG threshold determination.
- In the presence of K_{I}, K_{II} and eventually K_{III}, there are several criteria for defining an equivalent K_{I} stress intensity factor (K_{eq}). The several definitions of K_{eq} can present substantial differences among them.
- The asymmetrical 4-point bend specimen allows for FCG and unstable crack propagation under mixed-mode for a wide range of mixities.

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Lecture #4 (of 5) for Salerno University MSc students, 22-24 May 2023

Case Studies in Fracture Mechanics

Abstract

Residual stresses, existing in the absence of external loads and resulting of mechanical processes causing deformation, may have a major influence in the fatigue and fracture behaviour of materials and structures. Tests of fatigue crack growth (FCG) of CT (compact tension) specimens cut from steel weldments will be presented, highlighting an apparent much higher resistance to FCG than the base material. The detailed analysis of residual stress of the weldments, carried out using the contour method, made it possible to understand the behaviour of the specimens, consisting of a closure effect induced by residual stress. Once this was quantitatively taken into account, it was possible to identify the true FCG of the specimens, closer to the base material data. The experimental technique for residual stress assessment (contour technique) will be presented and discussed. In a second part of the talk, the International Institute of Welding (IIW) rules for welded structures subjected to fatigue loading will be presented. These rules specify that no R effect (R=min. load/max. load) should be considered in these structures, *i.e.* SN data for different R values is undistinguishable. Yield stress level residual stresses are asssumed by IIW, and therefore all load cycles will hava $\sigma_{max}=\sigma_{yield}$, irrespective of its R value. A case study of a failed component of a welded connection of a kiln shell of an expanded clay factory will be presented and discussed.

Takeaways

- What are and how to measure residual stresses. The contour method invented by Michael Prime at Los Alamos National Laboratory.
- Effects of residual stresses in FCG of welded structures.
- IIW rules for fatigue loaded welded structures.
- As a sideline of the talk, the design of kiln shells with a gear crown, accounting for large variation of temperature, will be noted.

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Lecture #5 (of 5) for Salerno University MSc students, 22-24 May 2023

Engineering and Society

Abstract

This talk - the last of a series of seven talks at the University of Salerno in May 2023 - deals with the societal context where engineering practice takes place, and is of a rather different nature than the other six talks, that were all concerned with technical engineering problems. A quick overview of recent and historical data concerning GDP and GDP per capita will be followed by a quick discussion of some similarities between Italy and Portugal as regards evolution of the educational attainment level of their populations. Some correlation is suggested between the level of human capital, particularly as concerns the educational attainment level, and the economy performance. Further to the human capital, a key ingredient for economic growth is the innovation potential of the society, and models of innovation process will be briefly discussed. Attention to the UN 17 sustainability goals gives the background for the necessary evolution, and precursors as the Club of Rome report 'The Limits to Growth' will be recalled. The role of quality of institutions in enabling or impeding economic growth will be mentioned, with particular reference to justice systems and corruption.

Takeaways

- Economic trends; Portugal and Italy.
- 'Atlas of Economic Complexity' (Harvard Univ.) and the 'Observatory of Economic Complexity' (MIT).
- Educational attainment. Skills and career paths.
- Human capital and its constraints on economic growth.
- Innovation models. Moore's law. Kondratiev waves.
- The 17 Sustainable Development Goals (SDGs) and the UN 2030 Agenda for Sustainable Development.
- The Club of Rome and 'The Limits to Growth'.
- Role of institutions. Justice.