IMEKO TC15 - Experimental Mechanics - Proceedings of the
11th Youth Symposium on Experimental Solid Mechanics
Brasov, ROMANIA, 2012, May 30-June 2

EXPERIMENTAL STRESS ANALYSIS SYLLABUS AND COURSE DESIGN

A. FREDDI[1], G. OLMI[1]

Abstract: *According to tradition, an Experimental Analysis Course has the task of presenting the main methods of experimental analysis in the awareness that stress and strain are responsible for a variety of phenomena of structural failures of modern artefacts, which are due to several causes such as load estimates, insufficient stress analysis and lack of data on materials. The discipline was created as a selection of tools for finding results when analytical solutions did not formerly exist, but today it has the new task of clarifying the limitations of analytical theories, of validating numerical results, of building the fundaments of phenomenological theories and simulations and of allowing reliability and life extension estimations especially in case of incomplete data and badly posed problems.*

Key words: *Experimental Stress Analysis, Course Syllabus, Task*

1. Introduction

The experimental method is essentially the mathematical/logical treatment of empirical data. According to a sentence of a philosopher of science [16]: *Since the time the science was born, hypothesis as well as experiment have mathematical meaning because the reality is expressed in mathematical terms, since they are reduced to physical parameters which must be measured (not qualitative)......*

In agreement with the authors' experience, the syllabus of a course of Experimental Stress Analysis (ESA) must include the following points [5], [6], [8]:

- presentation of the main methods with their characteristics and limits
- selection of the most suitable methods to achieve the main objectives of structural engineering
- selection of the applications of the methods to paradigmatic examples to show and to test them with laboratory activity.

The following philosophy inspired the selection of the methods: year after year, the activity developed in that time in the Laboratory was taken advantage of and attention was paid to unusual problems of strength of materials, not generally dealt with in other courses, but useful as a basis for good mechanical design.

Active exercises with no more than 6-8 students together, were devoted to [12]:

- strain gage mounting and connection to bridges
- building and calibration of a six-degree of freedom loading cell
- static and fatigue tests on universal machines
- strain measurements in components
- brittle lacquer use to favour strain gage application

[1] Department of *Industrial Engineering*, University of Bologna

- plane and 3-D photoelastic and holographic interferometry applications
- fracture mechanics tests on small and large CT specimens
- visit to the Biomechanics Lab. with the application of several techniques to bones and prostheses (strain gauges, photoelastic coating, Digital Image Correlation systems).
- writing of a technical report.

Just to correctly compare theoretical and experimental methods, some lectures must be devoted to the concepts of accuracy, precision and resolution of every experimental method, treated as measurement instruments. This opens the door to the statistical approach to the discipline, not only to descriptive aspects but also to the inference capability of statistics that makes it possible to perform prevision for the future, i.e. to support reliability previsions.

The second part of the Course is devoted to the main applications of Exp. Str. Analysis to the great chapters of structural mechanics, selected according to the authors' experience:

- Static loads
- Impact loads
- High Cycle Fatigue
- Low Cycle Fatigue
- Fracture Mechanics
- Residual Stress

Of course, many other topics are relevant in understanding the behaviour of structural components, but the syllabus was inspired by effective research work on the main phenomena and causes of industrial cases of failure [5]. This analysis of service failure of Hitachi products in the 1970s reports the following statistics of phenomena of failure [9]:

- fatigue (59.8 %)
- static fracture and creep (13.4%)
- brittle fracture (10.3%)
- buckling and ex. deformation (8.9 %)
- wear and fretting (4.0%)
- corrosion (3.6%).

2. Applications of Experimental stress Analysis to Statics

2.1. Contact problems

The Theories of Boussinesq, Hertz and Saint Venant are excellently illustrated with optical methods, especially with photoelasticity. The experiment shows some side-effects that the elementary theory generally neglects, Figure 1.

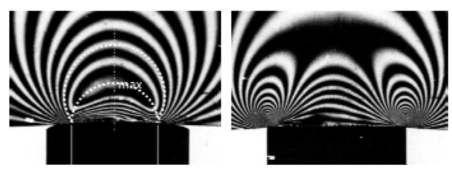

Fig. 1. *At low level the theory is perfectly respected but at higher load discontinuities appear.*

Additional help is offered by using the Wedge method to represent the tangential stress distribution in beams of several shapes, when a discontinuity introduces concentration of the contour lines of the membrane surface, Figure 2.

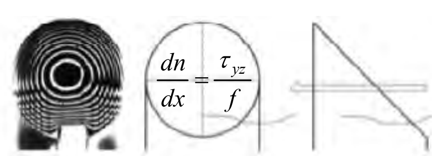

Fig. 2. *The membrane analogy through photoelastic fringes (M. Nisida, A. Kuske).*

2.2. Local non-linearity

Locally overcoming the elastic limits can be visualized and measured by the classic method of Photoelastic Coating and by the

Digital Image Correlation method. The Strain Gauges can be employed only if the gradient of strain is com patible with the gage grid dimension. Figure 3 shows the yield point in a sp ecimen with a discontinuity, an application to a static loading of a rod bar and the behaviour of the stress concentration factor that, beyond the elastic limit, divide into two different values for stress and for strain concentration.

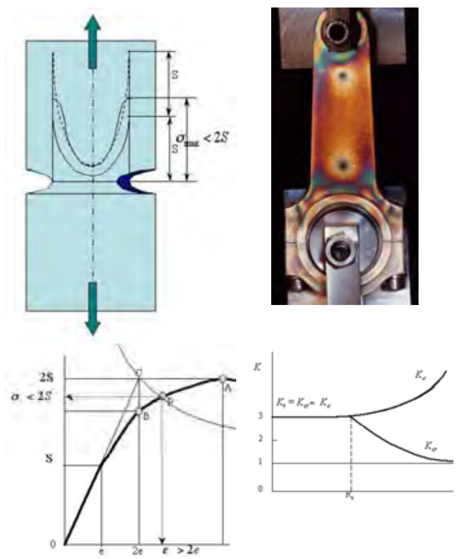

Fig. 3. *Beyond the elastic limit the relationship between loads and stress is no longer linear and the stress concentration factor divides into stress and strain concentration factors.*

3. Impact theory and stress waves

The impact theory is on e of the most attractive developments of the theory of elasticity but only the experiment approach clarifies the meaning of stress waves vs. sound waves. An easy experimental apparatus [2] can be built through a photoelastic bench with a flas h, an open camera recording source and an electronic circuit to delay the instant of the impact to the instant of recording of the wave. Figure 4 shows th e image sequence at different time intervals with respect to the impact of a bullet, shot by compressed air against the border of a flat plate and distribution of the orders of isochromatics.

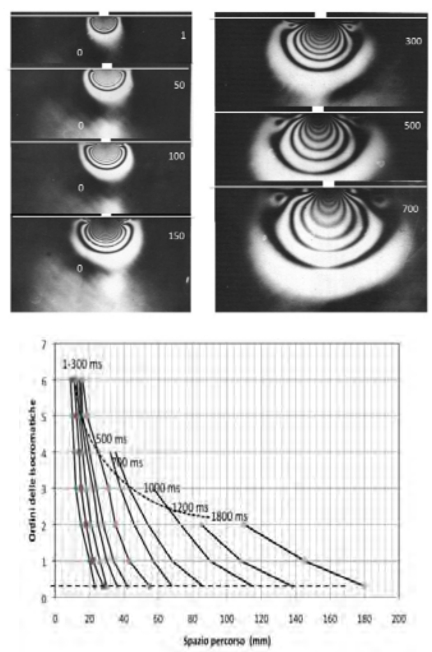

Fig. 4. *Photoelastic images of stress waves at times from impact (in ns) and distribution of the orders of isochromatics along the symmetry line of the plate at different time intervals .*

4. High Cycle Fatigue

The main contribution of the methods of ESA in supporting a p henomenological theory of fatigue at high number of cycles is given by the illustration of the role of the dynamic advantage due to the cyclic local loadings at the root of a ge ometrical discontinuity. According to the classic theory, the effect of the stress concentration factor K_t is mitigated by the sensitivity factor $\eta = f(material)$, depending on the local accommodation of the micro-plasticity, and the real effect is represented by $K_f < K_t$. For non-saintvenantian bodies and, in general, for a wider availability of data for different materials, the support factor *n* approach seems more valuable and general, Figure 5. The support factor depends on the material as well as the relative stress gradient (RSG) in the critical point

The RSG can be evaluated numerically or experimentally with optical methods better than by strain gages, Figure 6.

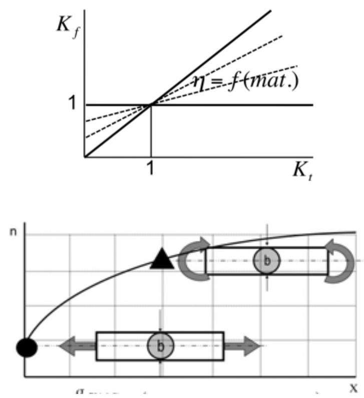

Fig. 5. *Comparison between the classic material sensitivity factor approach and the support factor approach*

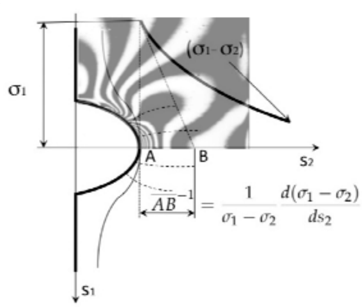

Fig. 6. *The relative stress gradient calculation from isochromatic pattern.*

According to the authors' opinion, the n-curve can be better estimated extrapolating from 3 values instead of 2, as in Figure 6. The following Figure 7, [13] shows an example of the n-curve, determined for a Titanium Alloy through new approach.

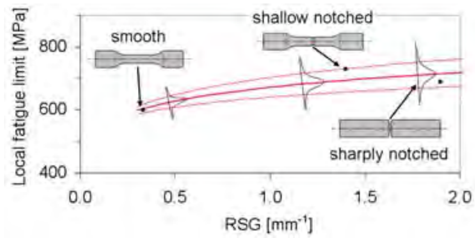

Fig. 7. *The new n-curve for a Titanium Alloy (TI-6AL-4V) obtained by three types of specimens loaded in bending.*

5. Low Cycle Fatigue

The most relevant contribution of ESA to low cycle fatigue (LCF) understanding is due to the use of strain gages as sensors in the conduction of strain controlled tests. The results have totally changed the interpretation of the fatigue life at high levels of deformation. In order to summarize this result in a few pictures, let us show the torsion testing of a shaft of different diameters, Figure 8. The main difference is in the direction of the crack that is at 45 degrees in torque controlled tests and along the direction of the maximum value of shear stress in shear controlled tests. A further contribution is described in Figure 8c). With the use of strain gages directly mounted at the root of a notch, a prediction of the local damage can be performed, monitoring the local strain (1), finding the corresponding value of stress in a reference specimen of the same material without a notch (2), and reconstructing the sequence of the local hysteresis loops (3) and the relative fatigue damage in the notch, [11]. Finally, several examples of LCF tests with full details on the experimental set-up and on novel procedures for strain control and data processing are contained in [14].

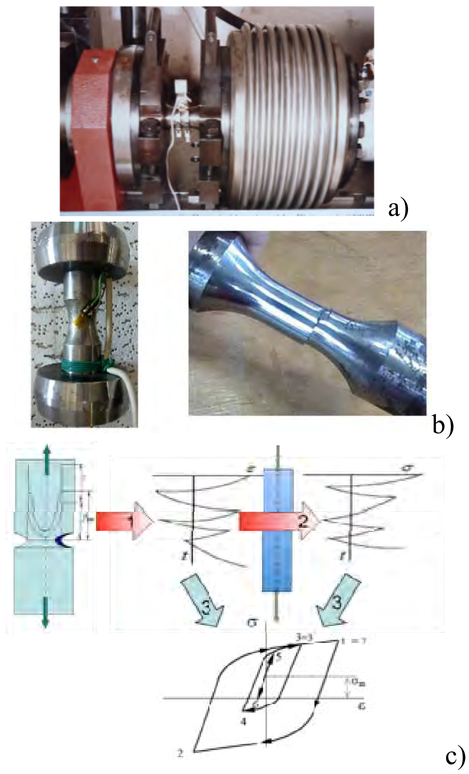

Fig. 8. *a) Shear controlled torsion tests. b) Torque controlled torsion and shear-controlled tests. c) Damage analysis.*

6. Fracture Mechanics

The first experimental validation of the approximate theory of the *Stress Intensity Factor* K_I is clarified in Figure 9. Only the series development with higher degree matches the experimental form of contour line of th e maximum shear stress . The experimental determination of K_I can be done through Strain gages [10], Photoelasticity and Holographic Interferometry [3] as well as through Digital Image Correlation methods.

Finally, Figure 10 summarizes the use of 3D-Photoelasticity and Strain gages in the estimation of Stress Intensity Factor.

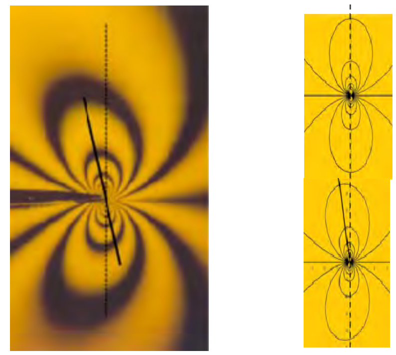

Fig. 9. *First and second order approximation (lower) of the shear stress compared with an experiment*

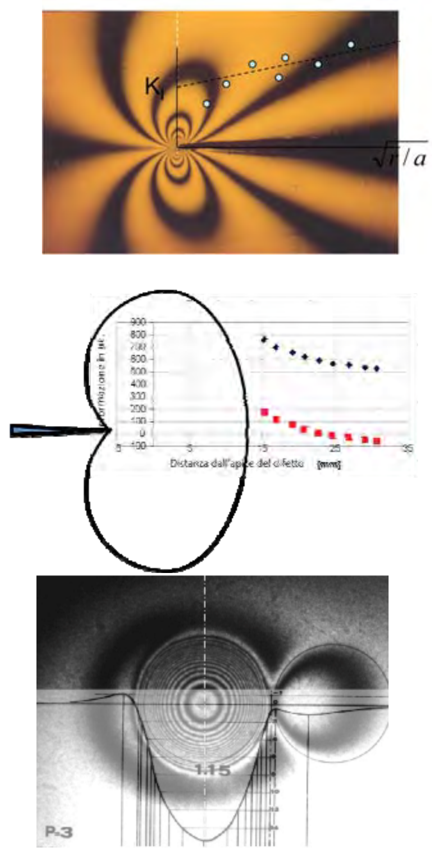

Fig. 10. *Derivation of Stress Intensity Factor from Photoelastic fringe pattern, from Strain gages and Holography.*

7. Application to Orthopaedic Biomechanics

A wide possibility of application of ESA to Biomechanics has led to a sensitive development and improvement of orthopedic surgery [4]. Just limiting the presentation to the main topics, it is worth mentioning the characterization of long bones and stability of cemented hip stems through tests on implantable materials and biomaterials, on simple structures and on prosthesis implant.

8. Conclusions

Far from declining in the time of modern numerical simulations, Experimental Stress Analysis offers invaluable conceptual tools for developing modern applied sciences [1], [7]. As a celebrated researcher said [15]: *"Modern science is fast-moving and no laboratory can exist for long with a program based on old facilities. Innovation and renewal are required to keep a laboratory on the frontiers of science and only if it remains on the frontiers will it have a long-term future. .... It is important that these resources be made available even in times of tight budgets…."*

References

1. Doyle, J.F.: *Modern Experimental Stress Analysis*. J. Wiley, 2004.
2. Freddi, A.: *Esperimenti di fotoelasticità dinamica.* Report Inst. Appl. Mecc. Bologna University,1975.
3. Freddi, A.: *Integrity Assessment of Large Forgings Containing Defects: A Fracture Mechanics Approach*. In: Int. J. Mat. & Prod. Tech., Inderscience Ent. Ltd. Geneve, 1987.
4. Freddi, A., Cristofolini, L.: *Preclinical biomechanical validation of hip prosthesis.* In: Proc. of XII School of Biomechanics, Politechnik of Wroclaw, 1994.
5. Freddi, A.: *Handouts of the Course of Experimental Stress Analysis.* Engineering Faculty, (in italian) Bologna University, 2010.
6. Freddi, A.: *Some Reflections upon the Design by Experiment of Mechanical Structures*. In: Proc. of Konstruktionsmethodik für Fahrzeug-konzepte, Braunschweig, 2010, p. 159-176).
7. Laermann, K.-H.: *Inverse Problems on Experimental Structural Mechanics*. Shaker Verlag Aachen, G.R., 2008.
8. Lazzarino, L.: *Prolusione* al III Convegno AIAS, Bologna, 1975.
9. Ohchuda, H.: *Analysis of Service Failures of Hitachi Products (1970-1975),* Hitachi Company Report, Tokyo, 1979.
10. Olmi, G., Freddi, A.: *Crack initiation and propagation in a press column under compressive load*. In: Archiwum Budowy Maszyn. **52** (2005), p. 323-340.
11. Olmi, G., Freddi, A. *Experimentelle Spannungsanalyse an einer Asphalt-fräsmaschine bei der Montage und im Betrieb.* In: Messtechnische Briefe. **2/2007** (2007), p. 2-15.
12. Olmi, G., Freddi, A.: *Il Corso e il Laboratorio di Meccanica Sperimen-tale nel CDLS in Ing. Meccanica a Bologna*. In: Proc. of the AIAS Nat. Conf., Ed. Cuzzolin, 2007.
13. Olmi, G., Freddi, A.: *Resistenza a fatica della lega Ti-6Al-4V con e senza trattamento di pallinatura*. In: GEF 2012, Bologna University, 2012.
14. Olmi, G.: *LCF experiments on turbogenerator steels and a new method for defining confidence bands*. In: JTE **40** (2012), No. 4.
15. Richter, B.: *Autobiography*. Nobel in Physics, 1976., see his Website.
16. Severino, E.: *Storia della Filosofia*, Rizzoli Ed., 1970.