A Brief Review of Expertises and Applications of Experimental Mechanics in Italy

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ABSTRACT

Italian researchers have certainly provided important contributions to the field of Experimental Mechanics (EM). The pioneering work on analysis of failure mechanisms with strain gages and optical interferometry techniques are nowadays still cited. Over the years, Italian experts of EM proposed innovative approaches thus improving procedures and tools in the EM field. In view of this, the present paper reviews the current state of Experimental Mechanics in Italy with particular attention to issues such as optical and thermal NDT, characterization of material behavior and properties, monitoring and preservation of art wells, industrial applications, biomechanics and biomedical engineering. As is clear, the present review does not pretend to cover the whole spectrum of EM applications in Italy. However, the authors aim to provide basic information on the most important research lines and to address readers to the Italian centers/groups specialized in each particular field.

INTRODUCTION

The Experimental Mechanics (EM) community is diffused all over Italy. From the stand point of professional education, Experimental Mechanics plays a considerable role in the instruction of highly qualified people. Mechanical and aeronautical engineers have to take at least one undergraduate course of about 80 hours where measurement theories and techniques are presented to students along with their practical applications. Furthermore, a requirement for pursuing doctoral degrees is to take advanced courses of Experimental Mechanics. In view of this, there is no engineering school in Italy without EM specialists and instructors. A rather quick estimate would result in some 500 academics and collaborators working everyday in the EM field. On the other side, Italians have been often considered “speculative individuals” rather than “practical people”. However, application of experimental techniques to complicated problems brought up by industry is very common. For instance, automotive industry analysts are very active in studying structural behavior under impact. Besides, railway industries put much effort in trying to improve passengers safety and comfort. Moreover, aircraft industries and biomedical firms are continuously testing new materials.

The progress in Experimental Mechanics as well as the most recent industrial applications of EM are discussed every year in the meeting of the Italian Society for Stress Analysis (AIAS). The excellent reputation of the AIAS meeting - held from 30 years - is confirmed by the fact that an average number of 200 papers is presented every year together with many contributions from other countries including US and Japan. Outstanding EM experts give plenary lectures and are awarded with the AIAS honorary fellowship. Abstracts are reviewed by two independent referees. Paper rejection rate is high in order to ensure excellent quality of contributions. On September 2004, the AIAS meeting will take place together with the ICEM12 conference. The latter is the meeting of the European Association for Experimental Mechanics. Besides the contributions usually submitted to the AIAS meeting, the scientific committee of the ICEM12 received about 400 papers from some 45 countries. Such a large number of papers required ICEM12 committees to organize 25 specific sections.

The above arguments justify the attempt of this paper to review the very recent developments and current trend of Experimental Mechanics in Italy. In particular, we will focus our attention on the following issues:

- Optical NDT;
- Thermal NDT;
- X-rays and acoustic inspection;
- Material characterization and reverse engineering;
- Composite materials;
- Fatigue and fracture;
- Coatings and nanomechanics;
- Biomedical engineering;
- Industrial applications (automotive, railway, electronics).

The activities carried out in each field mentioned above will be shortly described in the rest of the paper. Readers will be provided with a comprehensive list of technical papers published in referenced journals. Research centers active in each particular field will be also indicated in the paper.

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OPTICAL NDT

Italy has an outstanding tradition in Optics since the work of scientists like Righi, Occhialini and Ronchi. Theoretical knowledge has been transferred to engineers making them able to use interferometric techniques and photoelastic effect for non-destructive testing (NDT) of materials and structures. The leading research centers in Italy are: Polytechnic Institute of Bari (Politecnico di Bari), University of Cagliari, University of Calabria, University of Catania, University of Palermo, two universities in Roma: “La Sapienza” and “Roma III”. Besides universities, considerable activities have been carried out at the ENEA (Italian Agency for Innovative Energy Sources) research center of Frascati (Roma) and the Laser Center (Centro Laser) of Valenzano (Bari). In these centers, speckle interferometry, moiré, and photoelasticity are applied every day to a wide variety of problems.

In particular, researchers at the University of Calabria attempted to establish a precise correspondence between speckle de-correlation and displacement fields [1]. Another group at Roma “La Sapienza” focused on the use of white light speckle taking care of maximizing cross-correlation [2-3]. Speckle NDT is generally acknowledged as particularly suitable for composite materials or in general for all those components which involve complications in testing. For this reason, speckle interferometry has been utilized at the Bari Polytechnic Institute for measuring thermal strains in electronic components [4] or at the ENEA Frascati for measuring dynamic displacement fields [5]. Interestingly, the EM group in Bari was able to measure strains and shape of components with one single set-up properly designed. Theoretical aspects connected with processing of speckle patterns have been also addressed [4]. Polytechnic Institute of Bari, ENEA Frascati and University of Calabria utilized speckle interferometry in the reverse engineering problem of material identification [6-9]. More details on this aspect will be presented in the “*Material characterization*” section.

Moiré techniques are the other “milestone” of optical engineering. Grating projection methods (Projection Moiré) emerged as a standard tool for monitoring art wells. The emphasis in preserving art wells is justified by the tremendous richness in artistic treasures of Italy. University “Roma III” in Roma and University of L’Aquila are very active in this field. Fringe projection methods have been used in order to contour artworks (i.e., statues and vases) [10-12]. Besides moiré, laser scan systems developed at the ENEA center of Frascati proved themselves able to reconstruct complex geometries at a good level of detail. Recently, the Bari Polytechnic Institute started a new research line aimed to develop multi-view projection moiré techniques along with mathematical models able to match the different views.

Fringe projection and other types of moiré had a number of industrial applications: surface profiling and roughness measurements [13-15], analysis of aeronautical components, analysis of weldments (holographic moiré, see Ref. [16]), stresses in shell-shaped doors (reflection moiré, see Ref. [17]).

A special mention must be done for the applications of moiré to microscopy. Researchers at the University of Parma checked on the applicability of moiré interferometry and microscopic magnification to the visualization of the heterogeneous nature of the plastic strains in a polycrystalline material. Also, sensitivity of measurements to grating thickness and fringe/structure localization has been investigated. [18-19]. Measurements in the microscopic range have been also conducted by the Polytechnic Institute of Bari in cooperation with the Illinois Institute of Chicago. However, moiré was replaced by electronic holographic interferometry in order to measure strains at the interface between matrix and particles in reinforced particle composite materials. [20]

Researchers of the University of Palermo have significantly contributed to developing modern photoelasticity. They combined phase-shifting with true color imaging technology in order to minimize the interaction between isoclinic and isocromatic fringes [21]. Besides this, phase stepping effectiveness was improved by taking care of the quarter-wave plate errors unavoidably introduced by manufacturing [22]. Further analyses aimed to choose opportunely either phase stepping strategies and the polariscope design in order to have full field automatic evaluation of the quarter wave plate error [23-25]. Integrated photoelasticity with automatic fringe analysis has been also applied by researchers at University of Calabria in order to measure residual thermal stresses in optical fiber pre-forms. Traditional compensation methods have been combined with phase-stepping and a correction procedure accounted for the fact that the trajectories of light rays inside pre-forms are not straight lines [26].

Optical techniques have been utilized also to build measuring devices such as speckle velocimeters [27-28], laser triangulation devices for measuring sheet thickness [29]. Advanced sensors like fiber Bragg gratings allowed to measure strains in the dynamic and static range within a precision of 1 $\mu\varepsilon$. [30]

Besides practical application of optical techniques, significant work has been done in developing numerical techniques for processing the data gathered experimentally. Also in this case, many engineering schools in Italy acquired considerable expertise. For instance, people at University of Cagliari coded algorithms for automatic processing of interferometric fringes [31-32]. University of Palermo has already been cited as far it concerns the application of phase-stepping to photoelasticity. Finally, Bari Polytechnic Institute developed algorithms for fringe unwrapping based on cellular automata [4].

THERMAL NDT

Although thermal NDT methods was introduced much more recently than interferometry or photoelasticity, their use is a very common practice in Italy. The most important centers are the National Research Center (CNR) at Padova, University of Napoli “Federico II”, Bari Polytechnic Institute and University of Catania. Thermal methods are certainly superior over optical NDT methods as far as it concerns detection of internal damages.

Thermal methods allow accurate measurement of material properties such as diffusivity [33-34]. However, the fact that any perturbation of the thermal field corresponds to some in-homogeneity or defect made the use of thermal methods attractive in many fields of practical engineering. In particular, Infra-Red Thermography (IRT) has been used for structural engineering for detecting flaws in buildings [35]. Other applications concerned the comprehensive testing of art wells such as valuable paintings [36, 38-39] or ancient buildings [37]. A study carried out at the University of Napoli [40] compared different thermographic techniques (pulse thermography, lateral heating thermography, lock-in or modulated thermography and pulse phase thermography) employed to detect the flaws created artificially. It was found that pulse thermography is easy and fast to use for information about the state of the art treasures, but data may be affected by non-uniform heating and local variation of thermal emission; the lateral heating can help to overcome interference effects due to non-uniform heating but it is more troublesome to use. When the evaluation regards rare art treasures, lock-in thermography seems to be the only response since it is able to operate within very low increase of surface temperature; this technique is also able to give information about the material composition. The pulse phase thermography may be used to detect more in depth flaws but it needs higher temperature increase with respect to the ambient temperature and so it is recommended to control, before testing, the temperature sensitivity of the artefact.

IRT has been also used for detecting hidden corrosion in metals. A dedicated 3D numerical model of heat transfer solved the direct thermal problem and simulated the test [41-42]. Numerical models where neural networks are used as defect classifiers have been also developed in order to handle the high degree of uncertainty in defect class boundaries due to several factors, such as the noise in the measurement, the uneven heating of the target object and the anisotropies in its thermal conductivity [43].

Lock-in thermography has been utilized for evaluating aspects of industrial interest such as inclusions of spurious materials in both carbon-epoxy and glass-epoxy, impact damage and delaminations occurring around holes during drilling in carbon-epoxy, bonding improvements in Certran((R)) after plasma treatments and steel modifications after welding. [44] Thermal barrier coatings sprayed on aeronautical turbine blades have been analyzed using pulse phase thermography [45]. Processing techniques were compared in terms of their ability to detect de-laminations between the blade and the coating. Polytechnic Institute of Bari and University of Lecce used thermography for detecting defects in composite material sandwich structures [46]. Ability to detect porosity in composite aeronautical structures has been also analyzed [47]. Further investigations on detection of defects in composite materials are presented in [48]. Finally, thermal NDT has been used in other problems such as inspection of glasses for illumination devices [49] and adhesive layers [50].

An interesting application of thermography is concerned with fatigue [51-52]. The thermal NDT group at the University of Catania proposed the following approach. Based on the analysis of the temperature of the external surface during the application of cyclic loading, it is possible to evaluate the dynamic behavior of an element and to determine the fatigue limit. The methodology does not need any particular testing machine and proved itself able to provide reliable results by using a very limited number of specimens in a very short time. The methodology also yields information on the energy retained by the specimen and mechanical components. The procedure mentioned above makes not necessary to determine highly specialized parameters (K_I, J-integral) and often too closely linked to the micro-mechanics of the material, downgrading the engineering aspects of the problem and its design definition. Finally, the whole fatigue curve can be determined. Refs. [53-54] present the results of the joint research program carried out by the Polytechnic Institute of Bari and University of Lecce. The analysis of fatigue damage is approached in terms of dissipated energy. The method has been applied to studying the fatigue behavior of aluminum alloys.

It should be also noticed that advanced sensors have been developed. Refs. [55-56] presented an equipment able to measure simultaneously strain and temperature with an electrical resistance strain gage powered by an ac signal and connected to a strain indicator by means of thermocouple wires. The experimental validation of the method showed that the effect of cross-talk between the two signals is insignificant. The sensor has been built at Roma “La Sapienza”.

X-RAYS AND ACOUSTIC INSPECTION

Polytechnic Institute of Torino hosts a research group particularly active in the X-ray and acoustic NDT. A recent example of application of X-rays to diagnostics of industrial components is given in Ref. [57]. An appropriate X-ray diffraction procedure has been developed in purpose to measure residual stress on samples with high curvature radius. High-strength hot worked coil springs for car suspensions (wire diameter d=12 mm) have been analyzed. Different methods of X-ray measurement area limitation have been compared, taking into account the measurement errors, for the determination of stress in one and in three directions. After the identification of the irradiated area limits for plane samples, further limits have been identified due to the sample curvature (torsion bar). Samples have been loaded so that the stress state could be determined by strain gages and by X-ray measurement independently.

The acoustoelastic effect, i.e. the stress dependence of the propagation velocity of ultrasonic waves in deformed elastic media, is of great interest as a non-destructive tool in the determination of applied and residual stresses. Rayleigh ultrasonic waves (RUW) penetrate the material to a depth of approximately one wavelength. For this reason, RUW allow to measure sub-surface stress fields induced in pieces after cold-working or heat treatments. A device to take the measurements has been constructed with one transmitting and two receiving probes at fixed distance coupled to the material surface by means of springs. The probes are commercial piezoelectric transducers. The surface wave is detected by the said two receivers through two steel elements of different shapes (wedges, cylinders, cones). The two signals from the receiving transducers are fed to a digital oscilloscope and are mathematically correlated to determine their phase shift. Different correlation methods are examined. The system has been calibrated by measuring the acoustoelastic effect in a beam subjected to four point bending with known loads. [58] In a subsequent study, two independent experimental techniques for measuring the acoustoelastic effect on a sample of AL6082-T6 aluminum alloy were tested and compared: a non-contact technique using acoustic microscopy and a contact technique using two point wedges as receivers. The results confirm the validity of the measurements and of the techniques employed. [59]

Ultrasonic guided waves have been utilized by researchers of University of Palermo to detect thinning defects simulating hidden corrosion in thin aluminum plates. It was found that mode cutoff measurements provide a qualitative detection of thinning defects, while frequency shift measurements allow quantification of thinning depth. Measurement of the mode group velocity can be also used to quantify thinning depth. Similarly, thinning length can be determined by mode time-of-flight measurements. [60] The same group carried out non-destructive inspection of adhesively bonded lap joints by using ultrasonic guided (plate) waves. Thin aluminum joints with dimensions typical of aircraft fuselage and wing panels were analyzed with respects to different types of bond defects, disbonded regions and regions of poorly cured (low-cohesive-strength) adhesive. It appears that proper choice of the vibrating mode structure, in terms of crosssectional displacement distributions, maximizes the sensitivity of the inspection to the presence of the low-cohesive-strength bond [61]. Further studies on three different bond states in aluminum joints, namely a fully cured adhesive bond, a poorly cured adhesive bond, and a slip bond are presented in Ref. [62].

Ultrasonic refractometry improved the traditional ultrasonic methods for measuring the stress level in materials by means of acousto-elasticity. The technique consists of relating the variations in wave propagation velocity to variations in the angle of refraction at the interface with a second medium. Researchers of the University of Firenze measured longitudinal wave velocity changes due to uniaxial stress in aluminum and steel specimens [63]. Experiments showed the effectiveness of the technique for stress measurement. Furthermore, it is possible to isolate the effects of stress on velocity from the possible effects of temperature.

MATERIAL CHARACTERIZATION AND REVERSE ENGINEERING

Experimental identification of mechanical properties of orthotropic materials is a complicated reverse engineering problem entailing several tests each of which requires *ad hoc* setups. Moreover, each test specifically designed for determining a given elastic constant should be run always serially in order to reliably determine the value of that elastic constant on a statistical basis. Finally, because of anisotropy, non-homogeneity and internal defects of the material, different testing procedures may even result in significantly different values of the same elastic constant. On the other hand, theoretical/analytical models and numerical techniques are certainly much cheaper than experimental techniques in terms of required equipment but they are often based on highly idealized conditions that may be openly in contrast with the real behavior of the material. Moreover, analytical formulations can usually model only a limited set of loading and/or boundary conditions. It appears that an efficient material characterization procedure should determine all the elastic constants by performing a very limited number of experimental tests. *Hybrid techniques* that minimize the difference between experimental and numerical data by means of optimization algorithms where elastic constants are included as design variables certainly satisfy such a requirement and are actually getting more and more common in practical engineering. As is clear, a suitable hybrid technique will require: (i) a simple experimental set-up which allows accurate and non-invasive full field measurements; (ii) a robust and reliable optimization procedure able to converge to the target values of elastic properties regardless of load type, initial guess on elastic constants, boundary conditions, etc. In view of this, the experimental mechanics group at the Bari Polytechnic Institute proposed a hybrid procedure for characterization of composite materials where *Phase Shifting Electronic Speckle Pattern Interferometry* (PS-ESPI) and *Simulated Annealing* (SA) are combined together in order to minimize the difference between the displacement field gathered experimentally and its counterpart obtained with finite element analysis. [9]

Although other material identification techniques process strain values, it should be noticed that strain determination involves numerical differentiation of the displacement field obtained experimentally. However, since the displacement field measured by optical methods will be locally smoothed over a set of pixels close to the location where the value of strain is to be computed, strains might not be correctly estimated. In such a case, the entire identification procedure could fail. In addition, strain based material identification procedures lead to write energy balance equations which may require the knowledge of several strain components (for instance, in a 2-D case we need to know ε_x and ε_y under the very limited hypothesis that the cross derivatives $\partial u/\partial y$ and $\partial v/\partial x$ of the x, y displacements do not play any role in the structural response). Determination of in-plane strain components with experimental set-ups based on the Michelson's interferometer principle is a rather well established practice. Hung and Wang built in the middle 1990s a dual beam shearometer for measurement of in-plane strains thus overcoming the limitation of classical shearography which allowed analysts to measure only derivatives of out-of-plane displacements. However, shearographic evaluation of each strain component implies changing the illumination direction. This may be openly in contrast to the requirements on simplicity, repeatability and accuracy of the experimental part included in a hybrid procedure for material identification.

The feasibility of the procedure has been tested in the identification of an 8-ply woven reinforced fiberglass-epoxy laminate utilized as substrate for printed circuit boards. Specimens under 3-point-bending have been considered in the experimental tests in order to minimize rigid body motions and thus to prevent speckle pattern de-correlation. The results obtained indicate that the in-plane behavior of the laminate is well characterized. In fact, the residual error on computed displacements was less than 3%.

Researchers of University of Calabria at Cosenza focused their attention on designing experimental set-ups suitable for material identification [7-8] while modal component identification have been carried out at the ENEA-Frascati center.

Another aspect investigated was how experimental techniques can be used in order to speed up the design process. For instance, a research group at the Bari Polytechnic Institute used the powerfulness of Photoelasticity in 3D stress analysis of a generically complex model in combination with Stereolithography (SL) that allows us to build samples in a very fast and precise way. In was found that SL can be utilized to build models for photoelastic analyses, provided that the properties and features of the material tested are suitable for the analysis. The strength point of the procedure is that serial models are no longer required. As is known, in a step-by-step design process, usually a series of models must be built before coming to the final configuration of the structure. While in the case of cast models this may be unaffordable in terms of time and cost, combining photoelasticity and SL is clearly the answer to the problem. The proposed approach has been applied to the design of a complicated engine bracket. It was found that the stress distribution determined with 3D photoelasticity is in good agreement with FEM predictions. Details are given in Ref. [125]

COMPOSITES AND OTHER ADVANCED MATERIALS

Besides the inspection procedures based on thermal NDT, experiments on composite materials concerned a multitude of aspects. University of Cagliari presented a first generation X-ray microtomograph for analysing defects in composite materials is described and characterized [64]. Residual stresses in composite laminates were also evaluated

by means of a moiré interferometric hole drilling procedure calibrated numerically [65]. It should be noticed that University of Cagliari is very active in the field of composites and holds every year an important conference on the topic.
In the late 1990s, investigations on the thermoelastic effect in composites have carried out for the first time at the University of Catania [66]. The sensitivity of fatigue strength to quick ageing has been also analyzed [67]. Researchers in Bari measured internal deformation of laminates by using strain gauges inserted between laminate layers before polymerization in the oven [68]. A scanning laser acoustic microscope analysis was performed to check whether the embedding technique caused problems of delamination between the gauges and the layers of composite and between the layers. Tensile, bending and inter-laminar shear stress tests served to assess the feasibility of embedded strain gauges to measure internal deformation in laminate composites. Results were in good agreement with theoretical values obtained from simple calculations. Again in Bari, hybrid junctions made of sandwich panels connected by fasteners have been investigated in detail; the ageing effect was also studied [69-70]. More recently, the relationship between mechanical properties and manufacturing has been analyzed [71].
The material engineering group at the University of Trento studied crack propagation mechanisms in a short glass fibre reinforced composite at various temperatures in the range from 32 to 60 °C. Under static and fatigue loads, creep crack speed resulted initially decreasing till a minimum value, and then gradually increasing up to instability and fracture. [72-73]. Researchers from University of Napoli investigated on the corrosion mechanisms of fibers in reinforced concrete. University of Palermo studied the non-linear elastic contact problem of a pin-loaded laminate: finite elements results and speckle interferometry measures were in fairly good agreement [74-75].

Studies on advanced materials are of great importance for aerospace structures. Bari Polytechnic Institute is involved in a program on characterization and testing of braided composites. The industrial partner is the Alenia Aeronautics, the most important aircraft industry in Italy. The activity includes also impact and fatigue tests. The final objective is to find the composite material with the most suitable construction for the new transonic cruiser currently designed by the Boeing Company and the Alenia Aeronautics. Collaborations are activated also with French aerospace industries in order to study materials for solid lubrication in rocket engines [126].

The Italian Center for Researches in Aerospace (CIRA) in Capua (near Napoli) designed and developed a fiber optic sensor system to measure reflection coefficient at the interface between the fiber optic and the resin during a curing process. The study was motivated by the fact that the curing process determines the chemical and physical properties of a reacting resin. Among these, the optical properties strongly correlate with the structural features of the developing polymeric network. By monitoring changes of the refractive index, it is possible to analyze the polymerization of thermoset resin. Considerable work has been developed till the present days [76-80]. The material testing branch of Alenia Aeronautics (Foggia), cooperated with CIRA on the program summarized above. The University of Napoli and University of Messina and CNR Napoli also are involved in the program. Finally, the CIRA agency also activated a program on innovative materials for hot-structures which if utilized in reusable launch vehicles together with SiC would improve tremendously the performance of thermal shields currently available.

FATIGUE AND FRACTURE

Fatigue life prediction and fracture mechanics are very important because their modeling afffects design methodologies. Several research centers in Italy work in this field: University of Padova, University of Napoli, University of Catania, University of Palermo, the three Polytechnic Institutes of Bari, Milano and Torino. In particular, researchers at University of Padova carried out extensive investigations on multiaxial fatigue and low-cycle fatigue using thermography and strain gages. In Padova, analysts spent considerable effort in developing methodologies based on infrared thermography for the fast assessment of high-cycle fatigue strength of conventional and composite materials. Besides Padova, University of Napoli also studied multi-axial fatigue with special concern on full-scale testing of aircraft structures. As is mentioned in the “Thermal NDT” section, University of Catania developed a model where plastic deformation energy has been put in relationship with temperature: the data gathered with thermo-cameras were correlated to results of measurements carried out with other methods such as speckle interferometry and acoustic emission. In addition, cracks were analyzed with optical methods and neural networks based algorithms were utilized in order to predict crack propagation. Photoelastic investigations aimed to determine stress intensity factors (K_I, K_{II} and K_{III}) were carried out at Politecnico di Milano. Finally, fatigue and fracture of composite materials and hybrid joints made of composite material and metals were extensively analyzed in the recent years at the polytechnic institutes of Milano and Bari.

In general, fatigue life prediction involves analyzing data gathered from a large number of tests. In the last decade, different research groups in Italy attempted to organize experimental data in fashion of diagrams which might help designers to make realistic prediction on fatigue life without carrying out long tests. This approach has been followed at the University of Padova where some 750 fatigue data reported in the literature or obtained by several laboratories have been processed on a statistical basis [81]. All data are pertinent to friction and bearing-type aluminum butt splice bolted joints. In spite of the fact that a large number of factors could theoretically influence the fatigue behavior and the failure modes of the joints (yield stress of the plates, type of bolts, bolt pattern, bolts to member ratio, nominal load ratio, surface finishing, plate thickness and so on), it resulted that all data fall within a very reduced number of scatter bands whose reference values are related to different probabilities of survival and can be hence used for establishing trends, planning future research and for design purposes. These results were utilized later in order to assess the behavior of the AA356-T6 cast alloy [82]. More investigations on aluminum alloys have been carried out at the Polytechnic Institute of Torino. [83-84]
Researchers at the University of Palermo focused their attention on components and structures subjected to random fatigue, i.e. to cyclic loading whose amplitude varies in an essentially random manner [85-86]. They related directly fatigue cycle distribution to the power spectral density (PSD) by means of closed-form expressions that avoid expensive digital simulations of the stress process. It came out that the statistical distribution of fatigue cycles depends on four parameters of the PSD and the methods proposed in the literature provide reliable results only in particular cases.

University of Bologna utilized the Design of Experiment (DOE) technique to analyze the residual stress state and to investigate the fatigue life improvement of nitriding steel subjected to thermal and mechanical treatment. Nitriding treatments have been performed on several specimens which have been subsequently shotpeened, varying the main parameters controlling the process. The design of experiment method has been accomplished in order to evaluate the influence of the main shot-peening parameters on the distribution and values of the residual stresses close to the surface, and also in order to estimate the influence of these parameters on fatigue resistance. [87-88]

An important field of investigation is the prediction of fatigue behavior of welded structures. As well known, fatigue performance of welded joints is worse than that of un-welded specimens. Such a behavior comes from the very complex interaction of different factors. However, official standards like the Eurocode 3 that generally err on the conservative side and force designers to over-dimension structures with obvious cost and weight penalty. The WELFARE Local Strain Method (WElding FAtigue REsistance) proposed by Pappalettere et al. [89-90] works very well in fatigue strength predictions of structural steel welded joints of different geometry (angular, cruciform, T and butt welded joints), subjected to different load ratio R. Polytechnic Institute of Bari and University of Lecce are extensively using the WELFARE method [127-128]. WELFARE is based on two important considerations which are inherent to local strain method:

(i) two identical stress fields result in identical damages in a given material, even if they are produced by different global conditions of load and geometry;
(ii) it is possible to describe the material damage by means of some characteristic parameters of critical zone stress, independent from the global geometry of the joint and from the type of load but however dependent from the cord geometry that influences significantly the stress state of the critical zone.

The method assumes as representative parameter of the stress–strain field in the critical zone the local amplitude of strain ε_a measured with strain gages. The ε_A parameter, correlated with the number N of cycles to failure, allows to build fatigue life curves ε_A - N. From these curves, drawn for joints of different geometry and different values of load ratio R, it is possible to extrapolate the value ε_A of the local strain at $N=2 \cdot 10^6$ cycles. The limit strain amplitudes ε_A are subsequently reported into a hemi-logarithmic diagram and plotted versus the load ratio R so to obtain the ε_A-R limit curves. The main advantage of WELFARE is the direct measurement of the strain field intensity close to the weld bead. Hence, all factors certainly affecting the strain field at the weld toe but also difficult to be computed numerically can be now determined easily: global geometry of the joint, misalignments and distortions, local weld toe geometry, plasticization, load type. The only effect that the ε_a parameter is not able to capture is the influence of residual stress field after thermal welding cycle. However, this issue is being currently addressed. [129]

Further work on welded structures has been done in Padova [91].

In the last year, University of Parma studied in detail elastoplastic behavior induced by notch [92] and fracture of bonded specimens [93]. The three-dimensional nature of the local constraint at a notch root for elastic or elastic-plastic behavior was confirmed along with the fact that stress concentration factor ratio from the mid-plane and the surface is practically insensitive to the actual sigma-epsilon relationship when the nominal stress becomes equal to the yield stress. Fatigue crack growth tests conducted on double cantilever beam bonded specimens served to characterize adhesives for structural applications. The tests were conducted in lab air at two different load ratios, R = P-min/P-max, and at two different loading frequencies, f.

COATINGS AND NANOMECHANICS

Bari Polytechnic Institute and University of Lecce carried out an intense activity on mechanical characterization of coatings in cooperation with the ENEA research center on materials in Brindisi. In particular, high velocity oxy-fuel thermal spray coating technique [94-95] has been investigated with regard to the residual stresses which can grow in the coating and in the coated material. The hole-drilling strain-gage method served to measure stresses. Different preheating temperatures of the specimen surface and the influence of the thickness coating have been tested. Statistical analyses excluded the influence of the interaction of these variables. While the preheating temperature affected dramatically the measured strain, the effect of the variation of the thickness of the coating resulted secondary. Residual stress evaluated at the set of most favourable conditions were about as the yield stress of the material. No evidence of coating-substrate interface singularity was found.

In a subsequent investigation [96], zinc selenide (ZnSe), barium fluoride (BaF2) and silver (Ag) single layer and multilayered thin films were deposited by thermal evaporation onto cantilevered substrate Si(100) with native oxide, near room temperature in high vacuum. The macroscopic strain in the film during and after deposition was determined from the change in electrical resistance of a strain gauge glued at the substrate back surface. The intrinsic component of the strain was obtained by subtraction of the apparent thermal component, obtained by measuring the strain in the heating phase of the deposition process. During the deposition, the strain in the film shows a general trend regardless of the growth parameters: initially it is negative with a linear behaviour, then reaches a broad minimum value and increases towards an asynthetic value after vacuum cooling. After deposition ends, residual strain analysis indicates tensile in-plane strain for all the investigated samples. When a multilayer BaF_2/ZnSe/Ag/Si(100) is deposited continuously, the evolution of the features of the strain is different for the several layers, but it is same for the corresponding single layers. The BaF_2/ZnSe interface strain can be related to the discontinuities in strain measured, during the process associated with the formation of the interface itself. These discontinuities were evaluated for both BaF_2 on ZnSe and ZnSe on BaF_2.

Polytechnic Institute of Bari and Laser Center of Valenzano (Bari) started a research program for measuring residual stresses in thin silicon films. This objective will be achieved by using reflection moiré.

Physicists from the University of Milano focused their attention on mechanical properties of diamond, like diamond carbon and CrN thin films. Hardness was controlled by different growth temperatures. Investigations on tribologic behavior at the nano-scale was also carried out by means of X-ray photoelectron spectroscopy and atomic force microscopy. [97-99] It was found that for the CrN films, the changes in the friction coefficient can be traced back to variations of the Young modulus. More generally, for all samples investigated and in wearless regime, the nanoscopic friction coefficient is directly linked to the Young modulus. Another interesting study on mechanics of nanocomposite materials has been carried out by researchers of University of Palermo [100-101]. Multi-wall carbon nanotubes (MWCNTs) have been modeled in order to predict buckling and post-buckling behavior. The numerical model has been validated by comparing simulations of deformation with molecular dynamics results available in the literature and to high-resolution images from experiments. The proposed approach successfully predicted the experimentally observed wavelengths and shapes of the wrinkles that develop in bent MWCNTs, a complex phenomenon dominated by inter-layer interactions.

BIOMEDICAL ENGINEERING

Biomedical applications are gathering more and more the attention of the Italian engineering community. In fact, bio-mechanics centers have been established all over the country from north (Milano and Torino polytechnic institutes) to south (Catania). The main research fields are: determination of stresses at the bone-prosthesis interfaces, prediction of fatigue life of bone implants, testing of new materials, *in-situ* contouring of dental elements, simulation of mandible cavity and mandibular functions, simulation of vascular and breath circulation with particular attention to fluid-structure interactions. Characterization of biological tissues by means of optical techniques is the most recent research program operated by the Polytechnic Institute of Bari and the University of Basilicata. Reverse Engineering methods including Rapid Prototyping are widely utilized to build models for preliminary and/or numerical analysis. Using these techniques allows to overcome the difficulties in carrying out measurements on living human beings as well as the complications in modeling. Outside academies, the Laser Center in Valenzano (Bari) is a nationally acknowledged research center where stereo-lithographic devices are utilized for the purposes mentioned above.

The University of Catania tested a centrifugal track for runners. The principal advantage of this track is to increase the forces on athlete during the run with an effect very similar to that of an "artificial gravity", so the athlete can develop more muscle power [102]. National Research Council and University of Bologna developed devices for measuring interface forces between cement and prosthesis [103]. Numerical and experimental techniques were integrated in order to predict the behavior of femoral and stem prostheses. Partial cementing was adopted since it ensures the primary stability necessary to allow bone in-growth on the cement-free surfaces. [104-105]

Finite element (FE) models can be used for pre-clinical testing of bio-medical devices against the damage accumulation failure scenario. To accurately predict mechanical failure, the models should accurately predict stresses and strains. This should be the case for various implants. In [106], two FE models of composite hip reconstructions with two different implants were validated relative to experimental bone and cement strains. The objective was an overall agreement within 10% between experimental and FE strains. Finite elements were also used in the University of Trento for testing composite dental posts [107]; material properties used in the numerical analysis have been derived from experimental tests. Very recently, the Bari Polytechnic Institute and the Medicine School of the University of Bari analyzed a new generation of composite posts which proved to be clearly superior over other dental restoration techniques. This conclusion is supported by *in-vitro* fracture tests as well as by finite element analysis.

The proper integration of numerical and experimental model is a very critical issue in bio-engineering. An excellent example is reported in Ref. [108]. Researchers of Roma “La Sapienza” and clinical experts designed a device for evaluating the mechanical behavior of plastic Ankle-Foot Orthosis. The apparatus allows: (a) the evaluation of AFO stiffness in sagittal and frontal planes; (b) the conduction of semi-automatic trials; and, finally, (c) a global accuracy associated to the AFO stiffness values always less than 4%. The device may be of great help to handle children affected by hemi-plegia.

Finally, Refs. [109-110] present a series of recent studies on implants carried out in Bologna. Polymethylmethacrylate (PMMA) bone cement with barium sulphate added was confirmed to have a reduced fatigue strength when compared with plain PMMA, no detrimental effect was found for the addition of gentamicin sulphate to radiopaque PMMA [109]. Since the success of prostheses is highly dependent upon load transfer and bone stresses, implantation strains and strain under load were measured separately by a suitable procedure: the reflective photoelastic coating was applied to the femur after stem press-fitting. Application of external loads (e.g. to simulate a physiological activity) resulted in fringe patterns indicating the effect of the external load alone. Implantation strains are measured independently, after load removal; the stem is extracted and stresses are released, causing a new fringe pattern. The method was used to investigate the stress pattern caused by press-fitting of two cementless hip stems and that caused by a load applied to the implanted femora. Differences in press-fit pattern and load transfer were successfully detected between the two designs [110].

Resins for dental restorations reinforced by glass fibers have been characterized in Trento also in terms of their thermo-mechanical properties. In particular, long term effects of aging in water on physical properties have been studied [111]. The stresses generated during the light curing of resin composites and the effect of the stress relaxation after the polymerization were investigated at the University of Napoli by using a micro-strain technique [112]. Three different classes of composites were tested: traditional composites, condensable composites and flow composites. The experimental results showed that the plasma cure induces a lower shrinkage stress than the halogen cure and the relaxation time of the condensable materials are shorter than the traditional ones.

INDUSTRIAL APPLICATIONS

Experimental techniques have been used in railway and automotive industry in order to improve passenger safety and comfort. Researchers of the University of Firenze addressed issues such as sound absorption [113] and exact determination of forces exchanged by the wheel and the rail [114]. The latter is of primary importance in governing the amount of noise and vibration. Strain gages mounted on the wheel web and axle cannot determine the high-frequency content of the contact force. In addition, the spatial variability of input-output transfer functions makes it difficult to estimate the contact force by simple inversion of the point frequency response function. These problems were solved as

follows: (i) the track must be characterized precisely for a finite length by the analysis of the time series of several impacts supplied with an instrumented hammer; (ii) the response of the rail must be simulated by a random force acting on the system while the variability of the transfer function must be accounted by distributing the force on adjacent elements; (iii) the simulated response must be compared to the rail acceleration measured for the passage of several trains. It has thus been possible to reconstruct the 1/3 octave power spectrum of contact forces with a simple and stable iterative procedure. Remarkably, forces reconstructed from different sensors were found to be practically the same for a given wheel. Further investigations reported in [115] proved that the wheel noise emission depends on the lateral position of the contact patch area on the wheel tyre. Results of a test programme held on the ETR500 Italian high-speed train are shown. Thanks to a special device mounted under the axle box comprising a microphone and a windshield, it has been possible to measure the wheel noise continuously up to 300 km/h in tangent track and in curves.
The contact between wheel and rail in terms of contact area size and pressure distribution has been extensively analyzed also by researchers of the University of Cagliari [116-118]. Ultrasonic scan was used. Finally, Polytechnic Institute of Torino focused on resistance to high speed frontal impact of composite foam sandwich structures [119].

Excellent structural behavior under impact is obviously a primary requirement in automotive industry. University of Cagliari, Polytechnic Institute of Torino, University of Firenze, University of Roma “La Sapienza” have been very active in this field during the last six years. Particular emphasis has been put on composite materials [120-121] and structural foams [122]. Tests on glass fiber-epoxy matrix laminates were carried out according to ASTM norms [123]. More recently, the effect of laminate thickness has been investigated as far as it concerns carbon fiber-epoxy matrix laminates [124].

Testing of electronic devices is of great importance since these components are commonly employed in a multitude of objects utilized every day. Product development in electronic industry is characterized by the short time-to-market and high-reliability requirements. Improved design methods and advanced modelling techniques are therefore required to support package design selection and to arrive at lifetime prediction algorithms for failure prevention. However, uncertainties on material properties make it difficult to come up to reliable analytical/numerical models. For instance, strains and stresses produced by Joule’s heating effect could be captured by thermo-mechanical models only if these are calibrated by experiments. Polytechnic Institute of Bari utilized moiré and speckle interferometry for measuring thermal strains in electronic components. Speckle interferometry proved itself able to monitor the behavior of chips during the transient phase of Joule’s heating. Remarkably, combined deformation and shape measurements of electronics were carried out by using just a single set-up. Another research line just started concerns the analysis of residual deformations induced on chips by the welding process. Co-operations with nationally relevant industries manufacturing electronic components will be activated in the very near future.

CONCLUSIONS

This paper reviewed the expertise and most recent applications in the field of Experimental Mechanics in Italy. From the arguments developed in the manuscript it came out that Italian experts are very active in every sector of EM and carry out very advanced researches. This statement is supported by the over 120 referenced journal papers published from the end of 1990s to the present date. EM schools and research groups in academy are rather uniformly diffused over the entire territory of Italy. Remarkably, Italian academic institutions and nationally relevant research centers are in deep connection with industrial partners of international relevance. This is certainly the ideal condition for having Italy as the host of the meeting of the European Association for Experimental Mechanics.

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