Characterisation and Parameters Identification of Materials Constitutive and Damage Models: From Normalised Direct Approach to Most Advanced Inverse Problem Resolution

Eric Markiewicz, Bertrand Langrand

▶ To cite this version:

Eric Markiewicz, Bertrand Langrand. Characterisation and Parameters Identification of Materials Constitutive and Damage Models: From Normalised Direct Approach to Most Advanced Inverse Problem Resolution. 11th International Symposium on Plasticity and Impact Mechanics, IMPLAST 2016, Dec 2016, New Delhi, India. pp.33-40, 10.1016/j.proeng.2016.12.016 . hal-03666667

HAL Id: hal-03666667

https://hal-uphf.archives-ouvertes.fr/hal-03666667

Submitted on 31 Aug 2022

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 173 (2017) 33 – 40

Procedia Engineering

www.elsevier.com/locate/procedia

11th International Symposium on Plasticity and Impact Mechanics, Implast 2016

Characterisation and parameters identification of materials constitutive and damage models: from normalised direct approach to most advanced inverse problem resolution

E. Markiewicz[a,*], B. Langrand[b]

[a] *University of Valenciennes, LAMIH UMR CNRS 8201, F-59313 Valenciennes Cedex 9, France*
[b] *Onera–The French Aerospace Lab, Aeroelasticity and Structural Dynamics Department, F-59014 Lille Cedex, France*

Abstract

The paper aims at providing an overview of the research activities performed from the two past decades at the authors laboratory, in the field of the materials characterisation under dynamic loadings (i.e. from 10^{-3} s^{-1} to 10^{+3} s^{-1} for structural crashworthiness and impact applications) and the parameters identification to model their constitutive behaviour and damage. The different testing devices to load the material sample on the expected strain rate range are presented and discussed first, including the different experimental measurement techniques applied to analyse the stress - strain curves. From the normalised direct approach, two different numerical approaches, based on inverse problem resolution techniques, are introduced and discussed: the well-know Finite Element Model Updating method and the most advanced one based on the Virtual Fields Method, that enables to take the full advantages of full-field measurement techniques, such the Digital Image Correlation method. Applications for different materials and models, viscoplastic and damage, are given to support these advanced methods, including the dynamic strength of riveted and welded assemblies.

Peer-review under responsibility of the organizing committee of Implast 2016

Keywords: Dynamic loading ; Material behaviour ; Parameter identification ; Inverse approach ; Full-field measurement ; Virtual fields method

1. Introduction

The characterisation of material properties is very challenging especially when the number of material parameters governing the constitutive equations is significant. This is particularly true when considering anisotropic materials and/or strongly nonlinear constitutive laws, for example, in viscoplasticity or damage theories. Different normalized tests are necessary to fix the parameters of the material models. They are used in this case as statically determined tests because the mechanical fields are assumed (i.e. uni-axial tension) and expected homogeneous over the specimen gauge length. Material parameters are obtained with tests in one loading direction while constitutive equations are defined among all strain and stress tensors components; and tests exploitation is anyway limited to small levels of strain

---

[*] Corresponding author. Tel.: +33-327-511-302 ; fax: +33-327-511-317.
E-mail address: eric.markiewicz@univ-valenciennes.fr

Peer-review under responsibility of the organizing committee of Implast 2016
doi:10.1016/j.proeng.2016.12.016

because of the plastic localisation. Consequently, a large number of tests are required when complex behaviours are involved. For example, many tests have to be performed at constant strain-rate to identify viscoplastic models and/or at different stress triaxiality ratio and Lode angles for damage or failure models.

The limitations of the statically determined approach can be bypassed with the statically undetermined approach that considers no hypothesis on the kinematic fields, their homogeneity and/or the loading conditions. The most widespread approach is the Finite Element Model Updating (FEMU) method. Finite element (FE) simulations are iterated until constitutive parameters leading to the best match between FE computations and experimental measurements is found. Many FEMU methods do not require strain field measurements but other approches have been developed to take advantage of their treatment. Among them, the Virtual Field Method is based on the principle of virtual work (PVW) that expresses the global equilibrium of a solid of any shape. One of the main advantages of the VFM compared to FEMU methods is that it does not require to build a numerical model of the test, including the boundary conditions. In fact, provided convenient virtual displacement fields, the VFM can be carried out knowing only the resultant of applied loads. In addition, the characterisation with the VFM of linear constitutive laws is based on the resolution of a linear system of equations and is consequently no time-consuming, whereas FEMU methods always require costly iterative computations of FE models.

The paper aims at providing the scientific community a synthesis of the research activities performed from the two past decades at the LAMIH Laboratory of the University of Valenciennes and at the DADS Department of the Onera, in the field of the materials characterisation of metallic materials under dynamic loadings (i.e. from 10^{-3} s^{-1} to 10^{+3} s^{-1} for structural crashworthiness and impact applications) and the parameters identification to model their constitutive behaviour and damage. The different testing devices to load the material sample on the expected strain rate range are presented and discussed in Section 2, including the different experimental measurement techniques applied to analyse the stress - strain curves. Different numerical methods available to identify/optimise the parameters of the material viscoplastic and damage models are presented in the Section 3. The normalised direct approach is briefly presented and two different numerical approaches, based on inverse problem resolution techniques are discussed: the well-know FEMU method and the most advanced one based on the VFM. Applications for different materials and models are given to support these advanced methods, including the dynamic strength of riveted and welded assemblies.

2. Experimental devices for material characterisation over a large range of strain rates

Measurements. Stress-strain curves are analysed based on experimental measurements: load cells to analyse the stress ($\sigma = F/S_0$), extensometers ($\varepsilon = \Delta L/L_0$), strain gages, ... for the strains. The measurement range of the strain gauge is limited to 0.15 - 0.2 at most, while the optic sensor can deliver elongation until the specimen failure whatever the applied displacement rate. However, the elongation of the specimen is irrelevant for material characterisation after plastic location, because the strain are heterogeneous over the gage length.

The development of full-field measurement techniques now gives easy access to heterogeneous mechanical fields. These techniques, such as digital image correlation (DIC), Moiré and speckle interferometry and grid methods, provide a very large amount of experimental data. In addition, full-field techniques allow to focus on specific areas of measurement (e.g. zones of strain localisation), which may be used to improve the accuracy of the identification. The DIC technique is a popular method for full-fields strain measurements. Strains are measured at a discrete set of points i, uniformly distributed according to a user-defined mesh (step size initially equal to δ). Each point is located at the center of a subset of pixels (facets or Zone of Interest, ZOI).

Hydraulic jack enables to test materials under tensile and/or compressive loads and over a large range of displacement rates, from 0.0001 m.s^{-1} to 20 m.s^{-1}. The relation between the specimen gauge length L_0, the prescribed displacement rate V and the rate of strain $\dot{\varepsilon}$ is given by $\dot{\varepsilon} = V/L_0$. By varying the displacement rate prescribed to the specimen, this experimental facility makes it possible to test the strain rate dependency of materials other a wide range of strain rates.

However, these testing machines hardly maintain their maximum capability in terms of velocity when the applied load reaches its maximum level because the hydraulic power is limited. To keep the displacement rate constant, it is necessary to reduce the specimen cross section S_0 to decrease the applied load. To reach high strain rates at moderate displacement rates, the gauge length L_0 is reduced. These are the main reasons why the specimens used for dynamic testing do not satisfied the standards. The specimens geometry is obviously designed and validated to avoid any geometric and scale effects on the experimental responses.

Experimental devices are used to grip the specimen and to apply the displacement rate. A load cell implemented in the device is pre-loaded (compression), the release of the pre-load enabling to measure the force time history when the specimen is subjected to a tension. However, this kind of devices has to be carefully designed in terms of dynamic response and especially mechanical natural frequencies because of the oscillatory phenomena which perturb the measure. To reach the highest possible first natural frequencies of the system, the masses, stiffness, gaps and pre-load are optimised to avoid digital filtering under moderate strain rates. For greater strain rate, the digital filtering can be used over a well-known frequency range without cutting the mechanical response (especially the elastic response). For high stiffness materials like metals, that kind of testing machine can cover a strain rate range from $10^{-2}\,\mathrm{s}^{-1}$ to $200\,\mathrm{s}^{-1}$.

Hopkinson Pressure Bar was first suggested by Hopkinson as a way to measure stress pulse propagation in a metallic bar. Later, Kolsky refined Hopkinson's technique by using two Hopkinson bars in series, now known as the split-Hopkinson pressure bar (SHPB), to measure stress and strain. Later modifications on that same principle of analysing elastic waves have allowed performing tensile testing (SHTB) and shear testing.

Although there are various set-ups and techniques currently in use for the SHPB, the underlying principles for the test and measurement are the same. The specimen is placed between the ends of two straight bars, called the incident and the transmitted bars, respectively. At the end of the incident bar, a stress wave is created which propagates through the bar toward the specimen. For compression tests, a projectile (striker) impacts the free end of the input bar, to generate a compression longitudinal incident wave. This wave is referred to as the incident wave, and upon reaching the specimen, splits into two smaller waves. One of which, the transmitted wave, travels through the specimen and into the transmitted bar, causing plastic deformation in the specimen. The other wave, called the reflected wave, is reflected away from the specimen and travels back down the incident bar. Strain gages on the bars are used to measure the pulses caused by the waves. Assuming deformation in the specimen is uniform, the stress and strain can be calculated from the amplitudes of the incident, transmitted, and reflected waves.

However, the length of the striker is generally limited due to technological reasons (mass, friction effects, high pressure). As a consequence, the duration of the pulse generated by the impact is limited and do not allow to characterize high ductility materials up to fracture at moderate strain rates around $200\,\mathrm{s}^{-1}$ which correspond to the upper limit of hydraulic jacks previously presented. To overcome this limitation, the pre-stretched bar technique, first proposed by Albertini for tensile tests, is an alternative technique that allows specimens to be loaded up to fracture, thanks to greater duration times than those generated by striker impact. The incident bar is partly pre-stretched. This ensures the storage of elastic energy which is abruptly released when the brittle fracture of a fuse occurs [1]. The elastic wave propagates with a constant duration time depending on the length of the pre-stretched part along the input bar and loads the specimen up to failure.

The complementary use of hydraulic jacks and various declensions of Hopkinson bars allows to characterize the dynamic behaviour of materials over a large range of strain rates, from $10^{-2}\,\mathrm{s}^{-1}$ to $5000\,\mathrm{s}^{-1}$ without any gap [2].

At last, the mechanical tests aforementioned assume that the strain and strain rate are homogeneous over the gauge length and that the stress is uni-axial. These hypothesis are not fulfilled when a strain location develops in the specimen. Most of the experimental devices used for material testing consists in applying uniaxial tension or compression, at constant rate of strain, monotonously until the specimen rupture.

3. Identification of material elasto-viscoplastic constants

The direct approach for material parameter identification assumes that all boundary and initial conditions of the mechanical system (i.e. specimen, experimental device and set-up) are well-known and that the only unknown parameters are the material constants. The approach considers the experimental results as the state variables of the mechanical system that is completely described through the Solid Mechanics theory.

With this approach, the true tensile strain, ε_t, and stress, σ_t, are analysed according to the measurements (the engineering tensile strain, ε, and stress, σ) by the relation (1). The elastic strain, ε_t^e, is computed following Hooke's law for an isotropic uni-axial behaviour, i.e. $\varepsilon_t^e = \sigma_t / E$. The plastic strain, ε_t^p, is obtained assuming the classical strain partition, i.e. $\varepsilon_t^p = \varepsilon_t - \varepsilon_t^e$. The offset yielding point (0.2%) is conventionally (not physical) considered at last. The experimental data expressed in terms of true stress vs. plastic strain diagrams are then considered to identify the parameters of viscoplastic model. However, due to the different hypothesis linked to the testing procedure, this approach can only be used as long as strains are homogeneous (before plastic localisation) and is inappropriate when dealing with ductile damage models.

$$\varepsilon_t = \ln(1+\varepsilon) \text{ and } \sigma_t = \sigma(1+\varepsilon) \tag{1}$$

The material model parameters are commonly identified using an optimisation software (e.g. Symplex or Conjugate Gradient methods, genetic algorithm). The criterion or cost function can be defined by the least error square method (2). In this relation, σ_{num} and σ_{exp} are the numerical stress obtained with a given material model (e.g. the Johnson-Cook model) and experimental stress considered in the cost function. $\bar{z}$ is the unknown vector (material parameters), ε_p is the cumulative plastic strain, $\dot{\varepsilon}$ is the strain rate and N_d is the number of experimental data points. Bounds can also be considered for each parameter. The optimisation process ends if the value of the criterion reaches zero ($f = 0$) or if the criterion doesn't not decreased with the iterations. This is common when the experiments are scattered or when the boundary conditions are not well-known (e.g. sliding in the gripping area), or when the selected material model can not predict all the experimental data over the plastic strain and strain rate ranges obtained during the experimental campaign. Global convergence is expected regardless of the initial set of parameters $\bar{z}_0$. However, some optimisation methods can converged to local minima because the cost function is non-convex.

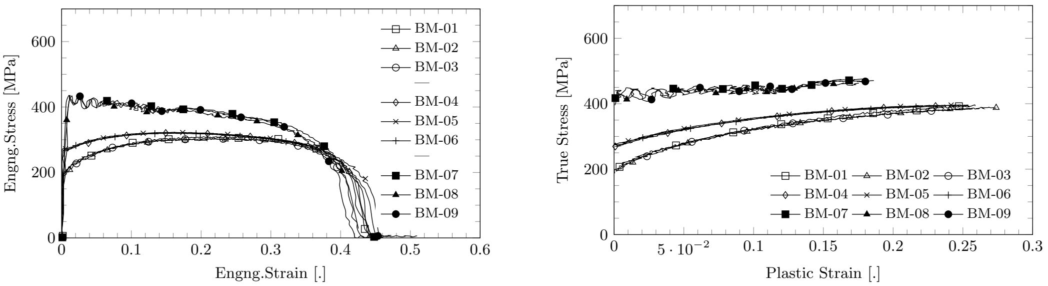
$$f(\bar{z}) = \sum_{N_d} \left(\frac{\sigma_{num}\left(\bar{z}, \varepsilon_p, \dot{\varepsilon}\right) - \sigma_{exp}\left(\varepsilon_p, \dot{\varepsilon}\right)}{\sigma_{exp}\left(\varepsilon_p, \dot{\varepsilon}\right)} \right)^2 \tag{2}$$

Application examples of this method concern the characterisation of the viscoplastic behaviour of a high strength steel at different temperatures [3] and of a mild steel [4]. The parameters of a Johnson-Cook and a modified Krupkowsky viscoplastic models were identified for the high strength steel and mild steel materials respectively. Fig. 1 presents the experimental responses obtained for the mild steel at different strain rate using an hydraulic jack. The tests 1-3, 4-6 and 7-9 were performed at 0.005 $\mathrm{s^{-1}}$, 0.6 $\mathrm{s^{-1}}$ and 80 $\mathrm{s^{-1}}$ respectively. The diagrams obtained at the highest strain rate exhibit the natural frequency of the experimental device that influenced the force time history. Here, the strains were measured by both strain gages and an optical sensor. Fig. 1 show engineering strains, measured by an optical sensor, greater than 0.4 but the plastic localisation occurs near 0.2 (depending on the strain rate). The data in the strain range $[0.2, 0.4]$ were consequently unused/lost for the characterisation of the material properties. The material model parameters were identified using an optimization software developed by the authors [5]. Several constitutive viscoplastic models were tested to model the strain rate sensitivity of the materials. The modified Krupkowsky viscoplastic model (3) best fitted the hardening profile and was consequently chosen. The parameter vector to be identified for this model was: $\bar{z} = \{K, \varepsilon_0, n, \dot{\varepsilon}_{ref}, a, b, c\}$. The average error between the experimental data and the viscoplastic models was under 1% for most of the tests considered in the optimisation process. The error between the models and the experiments was maximum or minimum at yielding and especially for the tests performed at 80 $\mathrm{s^{-1}}$ due to the high frequency oscillations.

$$\sigma = KX^a \left(\varepsilon_0 X^b + \varepsilon_p\right)^{nX^c} \quad \text{with} \quad X = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}} \tag{3}$$

The classical procedures of identification of material parameters require to perform several normalised tests (e.g. tensile tests) to fit the model with experimental data. The exploitation of these tests is usually statically determined, i.e. it assumes that the mechanical fields (in particular strain and strain-rate) are homogeneous over the specimen's region of interest. Yet, such a hypothesis is obviously violated as soon as plastic localisation (e.g. necking) occurs in the material. The tests exploitation is limited to small levels of strain, before localisation. Moreover, material parameters are determined with tests in one direction of loading. Consequently, a large number of tests are required when complex behaviours are involved. For example, several tests have to be performed at constant strain-rate to characterise the strain-rate sensitivity of a material.

These drawbacks can be avoided by dealing with heterogeneous kinematic fields, with no hypothesis on their nature anymore (i.e. statically undetermined approach). The measurement of heterogeneous mechanical fields provides



(a) Engineering stress-strain diagram

(b) True stress-strain diagram

Fig. 1. Experimental characterisation of the viscoplastic behaviour of a mild steel [4].

very rich experimental data and allows to extract more information from a smaller number of tests. In particular, the heterogeneity of strain-rate can lead to a sufficient involvement of viscoplastic material parameters in the specimen response to attempt their identification in a reduced number of tests. The development of full-field measurement techniques now gives easy access to heterogeneous mechanical fields. These techniques, such as digital image correlation (DIC), Moiré and speckle interferometry and grid methods, provide a very large amount of experimental data. In addition, full-field techniques allow to focus on specific areas of measurement (e.g. zones of strain localisation), which may be used to improve the accuracy of the identification. The Finite Element Model Updating (FEMU) method is a widespread statically undetermined approach to identify material constants and the VFM is a more advanced approach that takes the full advantage of the full-field strain measurement methods.

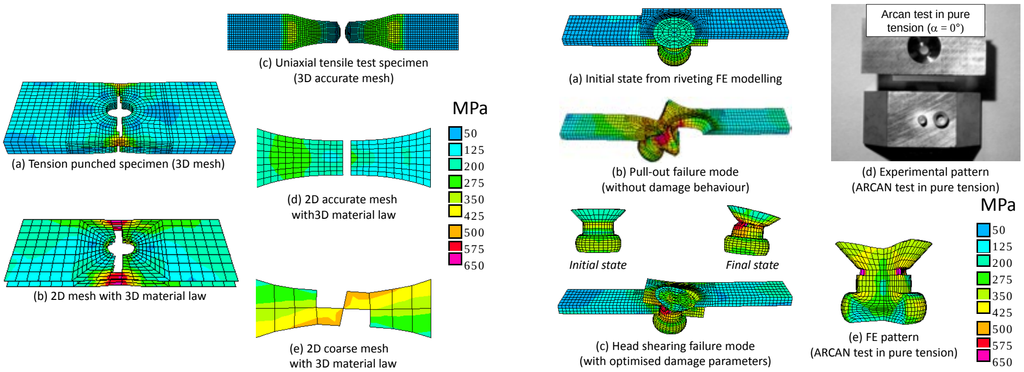
The Finite Element Model Updating (FEMU) method consists in determining the value of parameters of an FE model in order to reproduce a given known state. It is commonly used to identify material parameters. Iterative FE simulations are processed until constitutive parameters leading to the best match between FE computations and experimental measurements are found. The material model parameters are also identified using an optimisation software. Similarly to relation (2), the cost function can be also defined by the least error square method. In relation (4), d_{exp} is the experimental data considered in the optimisation process and d_{num} is the corresponding numerical data produced by the FE software with a given set of material parameters $\bar{z}$.

$$f(\bar{z}) = \sum_{N_d} \left(\frac{d_{num}(\bar{z}) - d_{exp}}{d_{exp}} \right)^2 \tag{4}$$

Generally, FEMU method considers the discrepancy between known and predicted quantities (e.g. loads for FEMU-F methods) or displacement fields for FEMU-U methods. Note that many FEMU methods (FEMU-F methods in particular) do not require field measurements. All FEMU methods are sensitive to mesh discretisation and modelling errors. In particular, boundary conditions have to be perfectly known and modelled. Convergence issues are also encountered with the FEMU method.

This method was extensively applied for the identification of isotropic hardening model parameters [6–8] and Gurson damage model parameters [9,10] of various materials from joints, shock absorbers and also human bones. For riveted joints made of aluminium alloys, experiments were performed on a specimen with a hole to generate heterogeous strain fields to characterise the damage model of the plate and on a single lap riveted joint specimen for the model of the rivet (Fig. 2). Strains were measured at different positions of the plate with strain gages and the force was also measured during the tests. Force and local strains responses were considered in the cost function. The damage models were identified in different steps because the parameters were highly coupled. For the damage model of the rivet material, the FEMU method was performed considering the riveting process in the FE simulations. The identified damage parameters were also tested for different specimens and FE types (Fig. 2).

The Virtual Field Method (VFM) is dedicated to the treatment of full-field strain measurements. It is based on the principle of virtual work (PVW) that expresses the global equilibrium of a solid of any shape (5). The several integrals



(a) AA2024T351 (b) AA7050

Fig. 2. FEMU method for the identification of Gurson damage models of aluminium alloys [9].

stand for the virtual work of acceleration, volume external forces (body forces), surface external forces and internal forces, respectively. In relation (5), ρ is the material density, $\vec{\gamma}$ the acceleration field, $\vec{f}$ the body forces vector acting on V, $\vec{T}$ the stress vector acting on S_f. $\bar{\sigma}$ is the Cauchy stress tensor; $\bar{\varepsilon}^*$ is the virtual strain tensor derived from the kinematically admissible virtual displacement, $\vec{u}^*$. One of the main advantages of the VFM compared to FEMU methods is that it does not require to build a numerical model of the material test. Provided convenient virtual displacement fields, the VFM can be carried out knowing only the resultant of applied loads (the boundary conditions haven't to be known exactly). In addition, the characterisation with the VFM of linear constitutive laws is based on the resolution of a linear system of equations and is consequently no time-consuming, whereas FEMU methods always require costly iterative computations of FE models.

$$\int_V \rho\vec{\gamma}.\vec{u}^* dV = \int_V \vec{f}.\vec{u}^* dV + \int_{S_f} \vec{T}.\vec{u}^* dS - \int_V \bar{\sigma} : \bar{\varepsilon}^* dV \tag{5}$$

Due to low mass of usual tensile specimens, body forces (i.e. here only weight) can be neglected and the external virtual work, w^*_{ext}, only takes surface forces applied on S_f into account. The acceleration field is commonly assumed to remain equal to zero under quasi-static loading conditions and also under dynamic conditions when the inertia effects remain weak. As a consequence, the relation (5) of the PVW is greatly simplified in:

$$\underbrace{\int_{S_f} \vec{T}.\vec{u}^* dS}_{w^*_{ext}} = \underbrace{\int_V \bar{\sigma} : \bar{\varepsilon}^* dV}_{w^*_{int}} \tag{6}$$

The VFM allows the characterisation of material models of behaviour thanks to the resolution of the PVW. Material parameters are introduced into relation (6) through the expression of the stress tensor, $\bar{\sigma}$. Indeed, stresses are linked to measured strains by constitutive equations. Knowing the specimen's geometry, the applied loads and determining an appropriate virtual displacement field, the only unknowns of relation (6) are the material parameters to be identified. The PVW theoretically enables the VFM to deal with all types of constitutive equations, linear or not, and all types of loadings, provided strain fields are measurable.

When dealing with nonlinear constitutive equations (plasticity, viscoplasticity, damage . . .), there is generally no closed-form solution linking stress and strain tensors and it is not possible to express directly the material constants using relation (6). The identification with the VFM therefore relies on the minimisation of a cost-function, f, that expresses the distance between w^*_{int} and w^*_{ext} (i.e. gap to equilibrium), as a function of the vector of unknown material parameters, $\bar{z}$. As proposed for the previous methods, the cost function can be also defined in a least-square sense by relation (7).

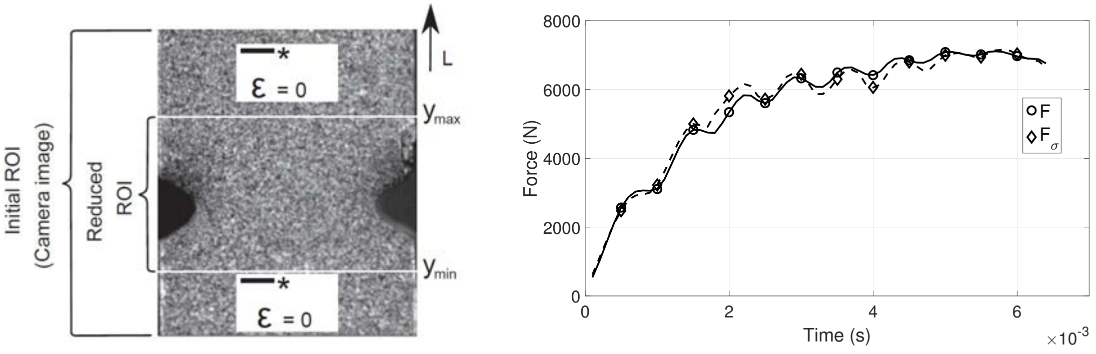
$$f(\bar{z}) = \left(\frac{w^*_{int}(\bar{z}) - w^*_{ext}}{w^*_{ext}}\right)^2 \tag{7}$$

The actual stress fields, $\bar{\sigma}$, must be known to express the internal virtual work, w^*_{int}. Mechanical quantities, including stress fields, are computed from full-field strain measurements by return-mapping algorithms [11,12]. In practice, time history of strain fields is measured on a finite number of time steps t_k, spread over the time period $\left[t_0, t_f\right]$. Moreover, for the majority of available experimental techniques (e.g. DIC), the strain fields are actually analysed over the solid surfaces and strains through the thickness are not always available. Plane stress conditions are consequently assumed in most applications. For the computation of the internal virtual work, w^*_{int}, the volume of the Region of Interest (ROI), V_{ROI}, is divided in several sub-domains of volume V_i, external surface S_i and thickness e_i around each point of measurement i. The plane stress hypothesis allows first to consider that mechanical fields are homogeneous through the thickness of each sub-domain V_i. It is also assumed that they are uniform over each surface S_i. Consequently, mechanical fields are computed by the return-mapping algorithm at each time step and in each sub-domain V_i from strains measured at point i. The internal virtual work is therefore computed using a discrete approximation of the integral by relation (8).

$$w^*_{int} \approx \sum_i \bar{\sigma}^i\left(\bar{z}, t_k\right) : \bar{\varepsilon}^{*i} e_i\left(t_k\right) S_i\left(t_k\right) \tag{8}$$

A great advantage of the VFM is that it does not required to model precisely boundary conditions and in particular the exact repartition of loading on S_f. Indeed, as the expression of the PVW is valid for any kinematically admissible virtual field, one can choose a virtual field co-linear to the load resultant. The external virtual work is therefore expressed directly from the load resultant, F, which is measured during experiments.

The VFM was applied to the parameters identification of an isotropic hardening model of an aluminium alloy [11] and of the Johnson-Cook viscoplastic model of a titanium alloy [12]. For the identification of the Johnson-Cook viscoplastic model parameters, quasi-static and dynamic experiments were performed on notched specimens and the strain fields were measured with the DIC technique (Fig. 3(a)). The parameters were identified in two steps: first the parameters of the quasi-static isotropic hardening model using the quasi-static experiments and then the viscoplastic parameters of the model using the dynamic experiments. The parameters were identified with two different optimisation approaches (Symplex and CMAES). Both algorithms delivered the same parameter values. The force response in Fig. 3(b) obtained with the identified parameters matched very well the high frequency oscillations observed on the experimental dynamic measurement without any modelling the experimental device (the load cell being implemented in the lower holder). This dynamic response would be very tricky to predict with the FEMU method or to model with the direct approach presented before. The identified parameters were also validated by comparison with other experiments performed on different notch specimens.



(a) Camera image and reduced region of interest

(b) Dynamic force response

Fig. 3. VFM for the identification of Johnson-Cook viscoplastic model parameters [12].

As a first attempt, the VFM was also applied to identify simultaneously the plastic and damage parameters of a coupled elastoplastic damage model (Lemaitre) of a mild steel using simulated data [13]. A FE model of two different specimen geometries was computed to generate the strain fields and the force responses. The Symplex method failed to identify the damage model parameters because the parameters were highly coupled and the cost-function was non-convex. The CMAES algorithm succeeded the parameter identification. The influence of the specimen geometry was also discussed. Specimen geometries leading to confined damaged areas and moderate damage rate, like perforated specimens, seem more suitable to identify coupled elastoplastic-damage models with the VFM.

4. Conclusions

An overview of the research activities done by the authors in the field of the materials characterisation under dynamic loadings and the parameters identification to model their constitutive behaviour and damage has been presented. Experimental devices for which the complementary use allows to continuously cover a large range of strain rate are highlighted. Direct and inverse approaches dedicated to materials parameters identification are introduced. A special attention is paid on the promising virtual fields method which allows to take the full advantages of full-field measurement techniques.

Acknowledgements

The authors are grateful to the European Union, the “Hauts de France” regional council, the CISIT research program (www.cisit.org), and the French Ministries of Defence and of Research for their financial support of the joint laboratory DRSC (Crashworthiness and Fast Structural Dynamic) with the participation of Onéra, the university of Valenciennes and the National Center for Scientific Research. The authors are also indebted to the PhD students, some became academic researchers, and particularly S. Blanchard, G. Haugou, N. Leconte, P. Mahelle, and D. Notta-Cuvier, for their contributions to the development of the various applications presented in this overview.

References

[1] G. Haugou, N. Leconte, H. Morvan, Design of a pre-stretched tension hopkinson bar device: Configuration, tail corrections, and numerical validation, Int. J. of Impact Engineering 97 (2016) 89–101.

[2] G. Haugou, E. Markiewicz, J. Fabis, G. Gary, Contribution to the definition of a partial overlapping plastic strain rates domain for moderate loadings–application to tensile testing on metallic materials, Int. J. of Crashworthiness 9 (2004) 187–194.

[3] B. Langrand, N. Leconte, A. Menegazzi, T. Millot, Submarine hull integrity under blast loading, Int. J. of Impact Engineering 36 (2009) 1070–1078.

[4] E. Markiewicz, B. Langrand, N. Leconte, J. Fabis, T. Dupuy, A methodology for the viscoplastic behaviour characterisation of spot-weld heat affected materials, Journal of Materials Processing Technology 238 (2016) 169–180.

[5] B. Langrand, P. Geoffroy, J.-L. Petitniot, J. Fabis, E. Markiewicz, P. Drazetic, Identification technique of constitutive model parameters for crashworthiness modelling, Aerospace Science and Technology 3 (1999) 215–227.

[6] E. Markiewicz, B. Langrand, E. Deletombe, P. Drazetic, L. Patronelli, Analysis of the riveting process forming mechanisms, Int. J. of Materials and Product Technology 13 (1998) 123–145.

[7] E. Markiewicz, P. Ducrocq, P. Drazetic, An inverse approach to determine the constitutive model parameters from axial crushing of thin-walled square tubes, Int. J. of Impact Engineering 21 (1998) 433–449.

[8] F. Chaari, E. Markiewicz, P. Drazetic, Identification of the spongy bone mechanical behavior under compression loads: numerical simulation versus experimental results, Int. J. of Crashworthiness 12 (2007) 247–253.

[9] B. Langrand, E. Deletombe, E. Markiewicz, P. Drazetic, Characterisation of dynamic failure for riveted joint assemblies, Shocks and Vibrations 7 (2000) 121–138.

[10] E. Markiewicz, P. Ducrocq, P. Drazetic, G. Haugou, T. Fourmentraux, J. Y. Berard, Material behaviour law identification for the various zones of the spot-weld under quasi-static loadings, Int. J. of Materials and Product Technology 16 (2001) 484–509.

[11] S. Blanchard, B. Langrand, J. Fabis, E. Markiewicz, Identification of plastic behaviour parameters from strongly heterogeneous strain field, in: SEM–XIth International Congress & Exposition on Experimental and Applied Mechanics, Orlando (USA), 2008.

[12] D. Notta-Cuvier, B. Langrand, E. Markiewicz, F. Lauro, G. Portemont, Identification of johnsoncook's viscoplastic model parameters using the virtual fields method: Application to titanium alloy ti6al4v, Strain 49 (2013) 22–45.

[13] D. Notta-Cuvier, B. Langrand, F. Lauro, E. Markiewicz, An innovative procedure for characterising a coupled elastoplastic damage model of behaviour using the virtual fields method, Int. J. of Solids and Structures 6970 (2015) 415–427.