Materials Physics and Mechanics 28 (2016) 106-109 Received: December 10, 2015

A MODERN EXPERIMENTAL-THEORETICAL APPROACH TO RATIONALLY DESIGNING NOVEL TECHNOLOGICAL OBJECTS

A.Yu. Кonstantinov[1,2*]

[1]Research Institute of Mechanics, Lobachevsky State University of Nizhni Novgorod,

Prospekt Gagarina (Gagarin Avenue) 23, Nizhny Novgorod, 603950, Russia

[2]Scientific Research Institute for Mechanical Engineering named after V.V. Bahirev,

Sverdlova 11a, Dzerzhinsk, Russia

*e-mail: constantinov.al@yandex.ru

Abstract. The paper presents a general methodology for solving problems analyzing strength of dynamically loaded structures, beginning from their development, substantiation and using experimental schemes of obtaining data on dynamic deformation and failure of materials of various physical nature up to the construction of reliable verified defining equations.

1. Introduction

Nowadays the necessity of using numerical modeling at early stages of designing novel technological objects is not questioned. Mathematical modeling, apart from shortening the design time, allows one to optimize substantially the structure being designed, as it becomes possible to analyze a considerably larger number of possible designs (including geometry, materials, coupling methods) and working conditions, as compared with the experimental approach. It is noteworthy that numerical methods and modern computational resources make it possible to analyze accurately enough complex systems of mathematical equations describing processes in a structure under the effect of various factors, to describe the behavior of materials using complex nonlinear mathematical models, as well as to take into account various geometrical and physical singularities. Thus, it can be stated that the accuracy of a numerical solution is mainly determined by the accuracy of the input data, one of the most important components of which being mathematical models of material behavior. To equip and verify phenomenological models of behavior, an ample database on dynamic material properties is required.

There exist practically no standardized testing methods or industrial stands or equipment for dynamically testing materials. Dynamic deformation diagrams are currently constructed using a number of most popular methodologies: pile driver tensile and compression tests, cam plastometer, Kolsky and Tailor methods [1, 2]. Some other methodologies more rarely used to this end are those using ring specimen distribution, Ilyushin and Lensky methodology based on the theory of propagation of one-dimensional elastoplastic waves and distribution of residual stresses along the length of the specimen, etc.

It can be stated that dynamic properties of a number of conventional materials, to say nothing about novel ones, are poorly studied. As a result, the above mentioned critical objects are often designed using static properties (or data on available foreign analogues), leading to irrational design of structures subject to impact loading. In this respect, the development of instrumental and methodological means for dynamic tests, as well as comprehensive study of the dynamic behavior of structural materials under various conditions appears to be a very timely issue, whereas compilation of a databank on dynamic properties of structural materials as a function of strain rate, temperature, intensity and history of impact-wave loading is of a paramount importance.

2. Experimental and theoretical approach to studying the dynamic behavior of materials

Construction of reliable models of deformation and failure of materials of various physical nature in a wide range of loading conditions (strain rate, temperature, stressed state type) is a complex issue. It is made up of vast experimental studies of representative samples for obtaining material characteristics (basic experiments), the analysis of the obtained data for finding the relations of these characteristics with the loading parameters, the description of the obtained relations using mathematical models and, finally, the verification of thus constructed defining relations using numerical modeling methods and realistic tests (test experiments). This process is schematically presented in the form of a diagram shown in Fig.1.

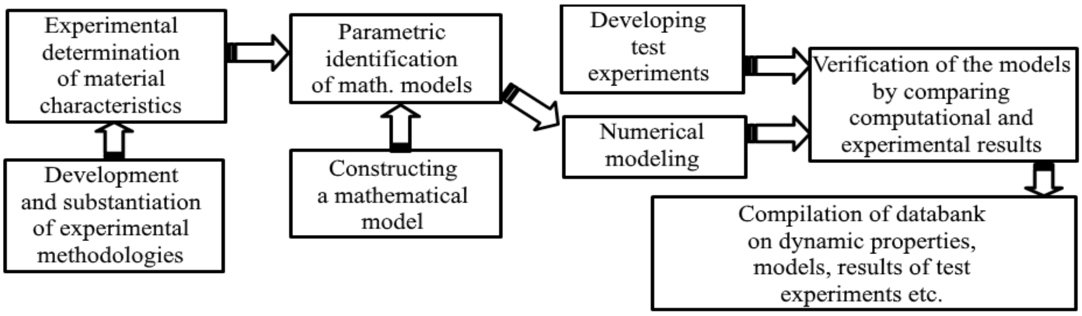

Fig.1. A scheme of a complex approach to studying the dynamic deformation and failure of materials.

3. Methods of experimental investigation

Currently, Kolsky method is the most widely used way of determining the characteristics of materials under dynamic loading [3]. To determine the characteristics of materials loaded in dynamic tension, various modification of this scheme are used [4, 5].

4. Defining relations and identification methods

In the most popular empiric defining relations used in numerical modeling, the yielding surface radius is represented with a strain ε, strain rate $\dot{\varepsilon}$ and temperature T function:

$$\sigma = f(\varepsilon, \dot{\varepsilon}, T).$$

More often, a simplified additive or multiplicative form of this function is used. In most models, high-rate hardening and thermal softening effects are considered to be independent and are represented with separate multipliers:

$$\sigma = f_1(\varepsilon)\, f_2(\dot{\varepsilon})\, f_3(T).$$

A detailed review of mathematical models for problems of high strain-rate deformation is presented in [6]. As a rule, function f_1 represents a linear combination of power and/or exponential functions of ε. Various forms of thermal multiplier f_3 are introduced. The most widely-used model in dynamic calculations is Johnson-Cook model. Several versions of the multiplier accounting for the strain rate effect in Johnson-Cook model are given.

To evaluate the warming-up of the material in plastic deformation the following relation is used:

$$\Delta T = \frac{\beta W_p}{\rho c_p},$$

where ΔT is increment of temperature of the material, W_p is plastic deformation work, ρ is density, c_p is specific heat of the material, β is part of mechanical energy transformed into heat (β=0.9 for adiabatic deformation, β=0 in isothermal case). The transfer from isothermal to adiabatic deformation mode in different materials takes place at different strain rates. However, when analyzing work [6], it can be concluded that, beginning from the strain rate of 10 s^{-1} the material is deformed adiabatically. Mathematical models for coefficient β as a function of strain rate $\beta = f\left(\dot{\varepsilon}\right)$ can also be found in [6].

A natural method of identifying empiric defining relations is the direct method, where experimental data obtained in various loading conditions are described by an analytical model (solving the approximation problem) [7]. However, in case of complex distributions of stress and strain fields in the active area of the specimen, as well as of the history of these values, the identification process can be effected using numerical modeling methods.

5. Verification of defining relations

As in the identification of mathematical models the data of “simple” experiments (homogeneous and uniaxial stressed state, constant strain rate and temperature) is used, it is required to test the effectiveness of defining relations in realistic working conditions of structural units. Due to the complex geometry of such elements and to the wide variety of load distributions and histories, the stressed and strained state in them is neither homogeneous nor uniaxial, whereas the strain rate can vary substantially in the process of loading. To verify the adequacy of models, special test experiments were developed (Fig.2) [7], which, on the one hand, are simple enough and allow for an unambiguous interpretation of the results and numerical representation without any simplifications, and, on the other hand, the stressed state in such tests, as well as the history of loading parameters, differ from those in basic experiments. The presented schemes for registering processes in specimens use the measuring bar technique, which gives additional information for comparing with the results of computational (virtual) experiment.

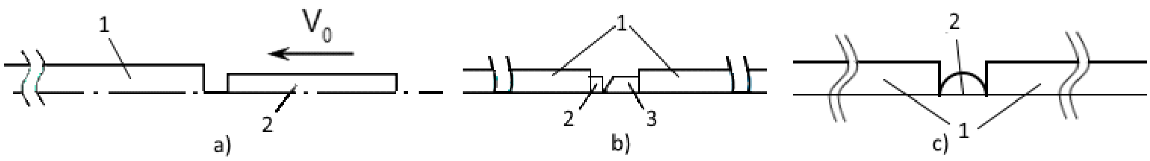

Fig. 2. Schemes of verification experiments: a) modified Taylor test, b) dynamic indentation, c) dynamic diagonal compression of an elastoplastic specimen.

In Fig. 2: 1 are measuring bars, 2 is specimen, 3 is disposable indenter.

6. Conclusions

At present, obtaining reliable mathematical models of materials for predicting the behavior of structures under impact or explosive loading is a highly important issue. Using a complex approach incorporating the development, substantiation and implementation of methodologies of basic tests, obtaining experimental data on high strain-rate deformation and failure of materials, identification of mathematical models, conducting specialized test experiments and verification of mathematical models by comparing the results of realistic and numerical experiments appears to be the most promising way.

Acknowledgments

Theoretical part of research was supported by the Russian Science Foundation (grant No. 15-19-10032). The experimental study was done with financial support from RFFI (Projects 15-38-20759_mol_a_ved, 14-08-00197A).

References

[1] M.A. Golderman, E.D. Habrovickaya, L.D. Molokova // *TsNIITEI Instrumentation TC-7* **1** (1981) 1.

[2] J. Klepaczko, In: *New Experimental Methods in Material Dynamics and Impact, Trends in Mechanics of Materials*, ed. by W.K. Nowacki, J.R. Klepaczko (Warsaw, 2001), p. 223.

[3] A.M. Bragov, A.K. Lomunov // *International Journal of Impact Engineering* **16(2)** (1995) 321.

[4] O. Nicholas // *Experimental Mechanics* **21(5)** (1981) 177.

[5] E. Cadoni, M. Dotta, D. Forni, A. Meda, G.A. Plizzari, In: *DYMAT*-2009 (9th International DYMAT Conference, Brussels, Belgium, 7-11 September 2009), p. 809.

[6] D. Stark-Seuken, *Ermittlung und Beschreibung der Fliekurven von Karosserie-werkstoffen bei hohen Dehnraten*. Dr.-Ing. Thesis (RWTH Aachen University, 2000).

[7] A.Yu. Konstantinov, *Experimental and numerical investigation of behavior of constructional materials under dynamic loading*, PhD Thesis (Nizhny Novgorod, 2007).