

Theoretical and numerical modeling of instability criteria (localization, necking, wrinkling): application to sheet metal forming

The research project proposed through this PhD thesis lies within the general framework relating to the prediction of instability phenomena. These phenomena manifest themselves most often in presence of thin or sufficiently slender structures. A twofold approach is proposed - theoretical and numerical - in order to develop effective prediction tools based on state-of-the-art finite element structural simulations. The applications of these developments are very important, particularly in metal forming processes in relation with the prediction of sheet metal defects. The latter may have various forms, which have themselves different physical origins: plastic strain localization in the form of shear bands (material instabilities), wrinkling or buckling (geometric/structural instabilities) or necking observed on the formed parts (coupling between material and geometric instabilities). The common consequence to all these aspect defects is to cause the formed parts to be rejected, which is very detrimental for many industrial sectors (automotive, packaging, aerospace etc), in terms of cost and delay. Therefore, the predictive capability, with sufficient accuracy, of these phenomena, which are limiting factors in sheet metal forming, is of primary concern for many mechanical industries.

Although stability and bifurcation issues in solids and structures have been tackled by a number of researchers for decades, the advent of new grades of high-strength steels keeps this research topic still very active. In order to enhance the degree of reliability of prediction models (criteria and indicators), it is necessary to improve the current development of finite element (FE) software packages by enriching them with the latest theoretical advances in the field. The aim of this project is thus to contribute to improving the predictive capabilities of sheet metal defects, in particular for new materials, by simultaneously focusing attention on the following aspects:

- Theoretical and numerical modeling of reliable and validated criteria for the prediction of localized and diffuse necking,
- Critical evaluation and review of structural instability criteria for elasto-plastic and visco-plastic solids in view of the recent advances in the field,
- Implementation of these material and structural instability criteria into FE simulation programs in order to build effective tools for the prediction of sheet metal defects.

More specifically, the tasks that need to be conducted within this PhD project are described in what follows:

- I. The first important theoretical development is concerned with the prediction of local defects in sheet metal forming. Various approaches, based either on bifurcation analyses (loss of uniqueness of rate equilibrium equations) or on linearized perturbation techniques (stability of the fundamental solution), have led to the formulation of existing prediction criteria. Examples of rigorous approaches for the prediction of these phenomena are the Rice localization criterion [1] (loss of ellipticity) or the Hill bifurcation criterion [2] (positiveness of second-order work). Concurrently, engineer-type approaches are widely used in the industry for the prediction of forming limits. The Marciniak-Kuczynski model [3] as well as the maximum force criteria, introduced by Considère [4] and subsequently extended by Swift [5], are examples of such simplified approaches. The first task would be to reformulate these local criteria within a unified approach and to evaluate them on the prediction of diffuse and localized necking (see [6, 7]). These criteria will then be compared for classification purposes: the goal being to establish relationships between theoretical and more pragmatic (simplified) approaches. This comparison will also allow an in-depth understanding of these instability phenomena and will help to select the most relevant criteria. For rate-sensitive (elasto-visco-plastic) materials, alternative criteria will be investigated based on stability theory of non-stationary solutions and taking into account the non-autonomous character of the governing differential equations.

II. The second important fundamental development concerns the geometric instability (buckling) of structures. To this end, the theoretical foundations of stability for visco-elastic, visco-plastic or elasto-plastic solids will be revisited. The key idea is to investigate the problem, no longer in terms of equilibrium stability or bifurcation from fundamental path, but rather as a stability problem of the quasi-static evolution (see, e.g., [8, 9]). This is more consistent whenever equilibrium states do not exist (case of viscous solids). For elasto-plastic solids, the obtained criterion [10, 11] is shown to be more conservative than that given by the flow-theory tangent modulus of plasticity (see Hill [2]), and seems to be close to the one given by the deformation theory of plasticity. On the other hand, it is well-known that the criterion based on flow theory of plasticity overestimates the critical buckling loads, which are found to be more realistic using the deformation theory of plasticity. Therefore, the criteria obtained by means of stability analysis of quasi-static evolutions may conciliate these buckling approaches and provide a more founded justification to the use of the deformation theory of plasticity. These resulting criteria will be implemented into FE software packages and evaluated for comparison purposes with both approaches: flow theory and deformation theory of plasticity.

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Laboratory: LEM3 (Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux), UMR CNRS 7239.

Web site: <http://www.lpmm.univ-metz.fr>

Team: Computational Mechanics.

Head of the team: Michel POTIER-FERRY.

Supervisor: Farid ABED-MERAIM.

Email: farid.abed-meraim@ensam.eu

Collaboration with other partners during the PhD:

In France: M. POTIER-FERRY (LEM3, Université de Lorraine).

Application:

Please send application form and materials to Mr. Yvon VELOT

→ yvon.velot@ensam.eu