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Stability of the Low-Cycle Deformation of Structures

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Abstract

The need to analyze the stability of low-cycle processes of deformation is stimulated by the transition from strength criteria in terms of allowable stresses to the analysis of limit states of structures and risk criteria . It is proposed to separate the solution of this problem for the four main types of a low-cycle deformation. The deformation properties of the material are qualitatively different to those process types. This leads to qualitative and quantitative differences in both the unstable processes and their consequences. Possibilities and methods of the analysis and those providing a desired durability of structures also become different.

Keywords: stability; progressive buckling; low cycle deformation; shakedown; alternating flow; incremental collapse; thermal cycling.

The main characteristics of low-cycle deformation processes are [1-6] inelastic strain increment $\Delta\varepsilon_{ij}$ and the strain amplitude $\delta\varepsilon_{ij}$ per cycle with period T:

$$\Delta\varepsilon_{ij} = \int_0^T \dot{\varepsilon}_{ij} d\tau, \quad \delta\varepsilon_{ij} = \frac{1}{2}\left[\max_{\tau} \varepsilon_{ij} - \min_{\tau} \varepsilon_{ij} - \Delta\varepsilon_{ij}\right], \quad 0 \le \tau \le T, \quad i, j = 1,2,3. \tag{1}$$

where ε_{ij} – components of inelastic strain tensor, τ – time, upper dot denote derivative with respect to time.

The characteristics $\Delta\varepsilon_{ij}$ and $\delta\varepsilon_{ij}$ vary during a structure adaptation in first loading cycles. Damages and displacements, accumulated during this running-in stage, are usually small, but can play the role of disturbances in

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subsequent deformation process. Next stage, followed by the adaptation, is stable operation, characterized by relatively small variation of $\Delta\varepsilon_{ij}$ and $\delta\varepsilon_{ij}$, and then the structure goes to pre-fracture and fracture.

There are four types of low-cycle deformation after the adaptation, depending on the ratio of $\Delta\varepsilon_{ij}$ and $\delta\varepsilon_{ij}$:

- elastic shakedown with $\Delta\varepsilon_{ij} = 0$, $\delta\varepsilon_{ij} = 0$;
- alternating plasticity $\Delta\varepsilon_{ij} = 0$, $\delta\varepsilon_{ij} \neq 0$;
- incremental collapse (progressive accumulation of strains and displacements) with $\Delta\varepsilon_{ij} \neq 0$, $\delta\varepsilon_{ij} = 0$э
- combined deformation with $\Delta\varepsilon_{ij} \neq 0$, $\delta\varepsilon_{ij} \neq 0$.

The limit special case of incremental collapse is a limit equilibrium, in which small increment of a load results in large increment of inelastic strains and displacements.

A large number of works is devoted to analysis of stability of elastic structures [7-20]. Stability of cyclic inelastic deformation processes has not been studied so detail.

Three kinds of processes in which $\Delta\varepsilon_{ij} \neq 0$ or $\delta\varepsilon_{ij} \neq 0$ form a group of low-cycle processes. The transition from estimation of structure strength based on allowable stresses to estimations, based on limit state analysis and subsequent safety (risk) estimations demands stability analysis of the low-cycle processes. The process of deformation is considered unstable if a small change in input parameters (external actions, material properties, geometric characteristics of the structure) leads to large changes in values $\Delta\varepsilon_{ij}$ or δεij, or to a qualitative change in the distribution of these quantities through the structure volume, causing the structure shape changes.

It is obvious that the state of limit equilibrium is unstable by definition. The derivative of the residual displacement with respect to load tends to infinity for any continuation of the deformation process. At this time the process of deformation itself is in the branching point with an infinite number of possible continuations. A simple illustration is plastic deformation of a rod with formation of a necking at arbitrary weakened cross-section or rotation of the rod cross-sections without tension under compression. In the absence of geometric hardening the limit equilibrium state immediately precedes the fracture with the fragmentation of the structure.

Incremental collapse differs from the limit equilibrium: inelastic strains at each time moment of a cycle are incompatible and therefore are usually small. These strains become compatible only at the end of cycle, remaining small. The instability of the process appears in the form of the structure shape changes (distribution of residual displacements increments per cycle), different from the main continuation of the process. A typical example is progressive buckling of axisymmetric structures under symmetric thermal loads (Figure 1).

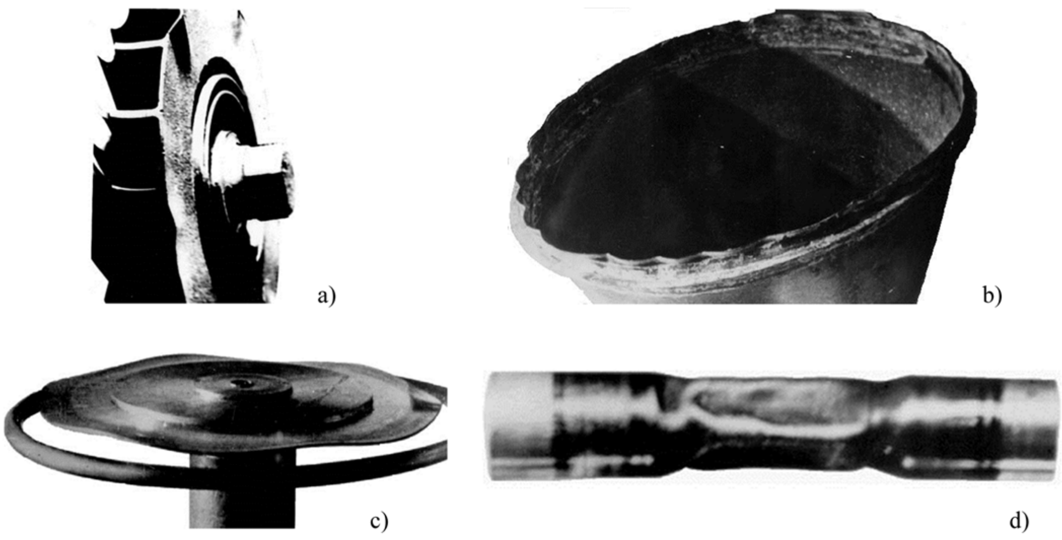

Fig.1. Non-axisymmetric deformation of axisymmetric structures under cyclic axisymmetric thermal loads: a) turbine wheel, b) rocket heat shield, c) round plate, d) cylindrical shell.