Direct FEM approach to design-by-analysis of pressurized components

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The elastic strain range of pressure vessels and piping is rather small already in normal operation. Severe thermal loads or other residual stresses may push stress further into the plastic range locally. Therefore, all relevant design codes consider plastic deformation of ductile materials using the concepts of limit and shakedown analysis for design-by-formulae (DBF) or for stress assessment [2]. This current design practice rests on simplifying assumptions for geometry, loading and constitutive equation. It is restrictive and over conservative for complex structural problems.

A first improvement is achieved by the finite element method (FEM) and inelastic analyses [3]. The allowable mechanical and thermal loads are obtained from a stress assessment. This indirect design-by-analysis (DBA) route has been developed in the 60th and after countless discussions the inherent problems of stress criteria may not be overlooked [12]. As a second option, the direct DBA route of the new European unfired pressure vessels standard [4] proposes the use of limit and shakedown analysis to compute the load carrying capacity [5]. Implicitly, this possibility is also available with other modern codes such as [11]. Plastic design cannot be based on stress assessment, because there is no stress to bound the plastic range from failure domains. Therefore direct DBA considers the characteristic development of plastic strains and deformations towards structural failure [5]:

- Instantaneous collapse by unrestricted plastic flow at limit load (gross plastic deformation).
- Incremental collapse by accumulation of plastic deformations over subsequent load cycles (ratchetting, progressive plastic deformation).
- Low Cycle Fatigue (LCF) by alternating plasticity.
- Plastic instability of slender compression members (buckling).

Limit and shakedown analyses deal with these failure modes (except buckling) directly [6], [7], [8]. Although being simplifying methods, they are exact theories of classic plasticity, which do not contain any restrictions or assumptions other than sufficient ductility of the material. The direct limit and shakedown analysis approach computes the load carrying capacity or the safety factor independently of the details of material behaviour and of the generally unknown load history.

We propose to make limit and shakedown analysis available to the designer as an optional module of his or her FEM software. For this purpose static theorems are formulated in terms of stress. They define safe structural states giving an optimization problem for safe loads.

Static limit load theorem:

An elastic-plastic structure will not collapse under monotone loads if it is in static equilibrium and if the yield function is nowhere violated. The maximum safe load is the limit load.

Static shakedown theorem:

An elastic--plastic structure will not fail with macroscopic plasticity under time variant loads if it is in static equilibrium, if the yield function is nowhere and at no instance violated, if the plastic deformation rates tend to zero, and if the plastic dissipation is bounded. The maximum safe load domain avoids ratchetting and LCF by elastic shakedown.

We have implemented limit and shakedown analysis into the general purpose FEM program PERMAS [9] employing a subspace technique which can handle very large optimization problems [6], [7], [8]. Limit and shakedown analysis compute the allowable loads directly from the allowable stress. For two-parameter loading the allowable load range for a structure can be represented in an interaction diagram (e.g. Bree-diagram [1]). As a simple example we investigate a thin tube under internal pressure and thermal loading (one and two-parameter loading). The results are shown in the following interaction diagram:

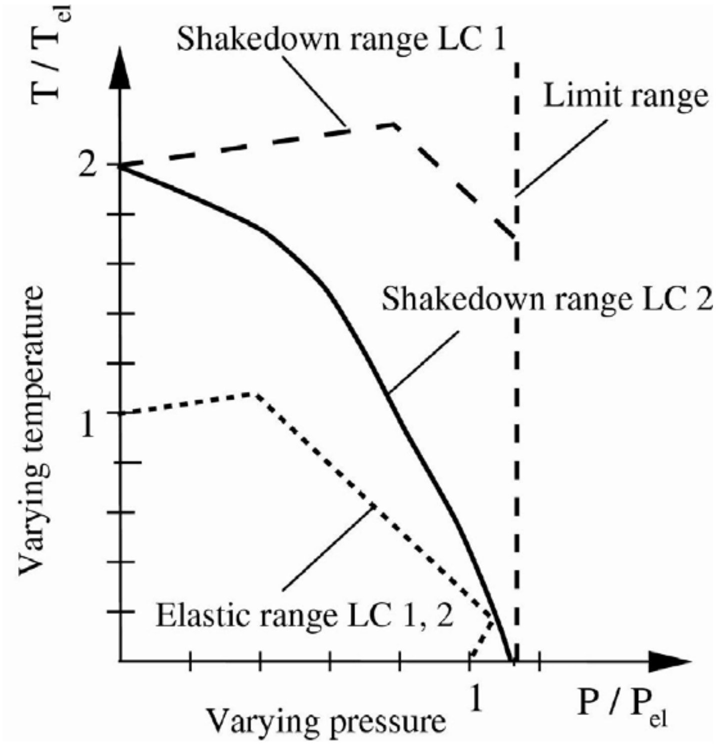

Fig.1: Interaction diagram of a thin tube for one and two-parameter loading (load cases LC 1, LC 2)

Once the plastic actions have decayed in the first load cycles, there is no difference between elastic and shakedown behaviour. Obviously, the shakedown range is an important extension of the useful operation regime beyond the elastic domain. Similarly, shakedown analyses of pipe junctions [6], [8] or limit analyses in fracture mechanics [10] are presented.

As the new approach deals directly with the failure modes, the results give better insight for the designer into the structural behaviour under all possible mechanical or thermal actions, the safety margins and the possibilities for design or operation improvement. The designer obtains direct information about the allowable loads from limit and shakedown analysis. The new FEM module allows any complexity of structure and loading at costs and at simplicity that compares favourable with standard elastic FEM analyses. Current developments concentrate on extensions towards nonlinear kinematic hardening and reliability analysis.

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