Fatigue accumulation in oscillating thermoelastoplastic structures with hysteresis part I (modelling)

Michela Eleuteri

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EQUADIFF13 - Prague, August 29th, 2013

Plan of the talk

- Theory of hysteresis operators powerful tool for solving mathematical problems in various applications (solid mechanics, material fatigue, ferromagnetism, phase transitions)

Elasto-plastic oscillations of beams and plates with material fatigue

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- Main modeling assumption: proportionality between fatigue rate and dissipation rate
- Influence of energy dissipation (due to material softening on the damage increase) taken into account - fatigue accumulation accelerated - a singularity (material failure) may develop in finite time
- Account also for *decreasing fatigue rate* (phase parameter χ)
- Discuss thermodynamic consistency of the model with a proper choice of the evolution equation for the fatigue parameter m

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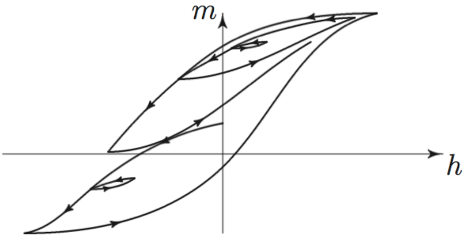
Hysteresis: a rate-independent memory effect

- **Hysteresis:** a rate-independent memory effect (multidisciplinary character)



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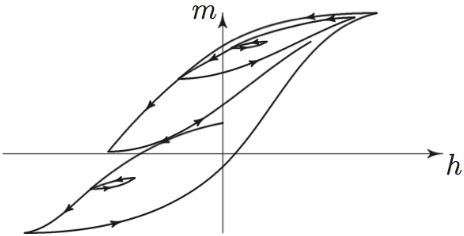

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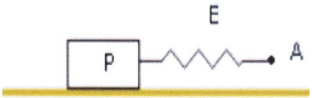
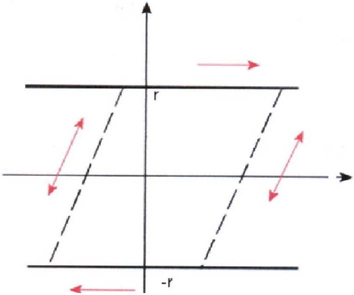
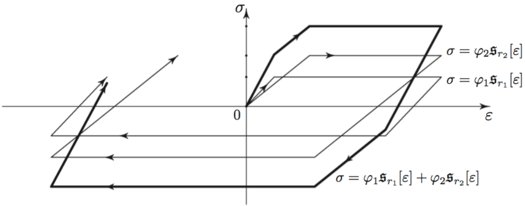
The stop and the Prandtl-Ishlinskii operators







A classical hysteresis-type model for 1D elastoplasticity

- Introduced by L. Prandtl and A. Yu. Ishlinskii (extensions to the multidimensional case are possible)
- The relation between (one-dimensional) strain ε and stress σ is given in the form of the so-called Prandtl-Ishlinskii operator

$$\sigma = \mathscr{P}[\varepsilon](t) = \int_0^\infty \mathfrak{s}_r[\varepsilon](t)\,\varphi(r)\,\mathrm{d}r$$

  for all $\varepsilon \in W^{1,1}(0,T)$. Here $\varphi > 0$ is a nonnegative weight function not known a priori and $\mathfrak{s}_r$ represents the **one-dimensional elastic-ideally plastic element or stop operator**, with the threshold $r > 0$
- Prandtl-Ishlinskii description of elastoplasticity: a superposition of infinitely many stop operators having different thresholds (very imaginative and easily understood) BUT engineers very often prefer classical engineering approaches like the three-dimensional von Mises or Tresca models
- Motivation: the disadvantage that the weight function φ **is not known a priori** and must be identified

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New theory of oscillating elastoplastic beams and plates

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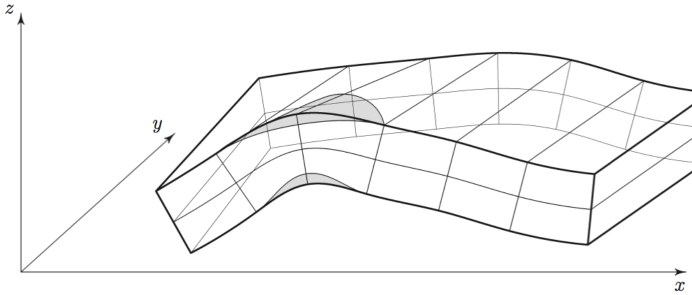

A plate section with grey plasticized zone.

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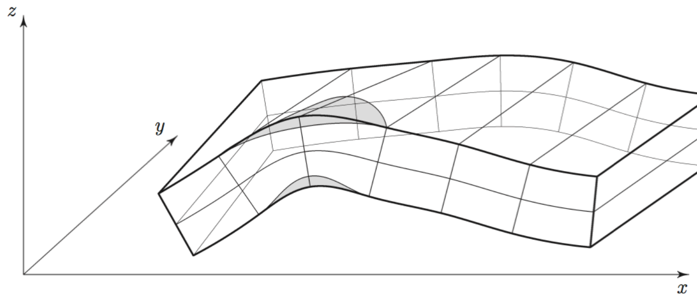

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Motivation for material fatigue

- Plastic deformations lead to energy dissipation and material fatigue, manifested by material softening, heat release, material failure in finite time
- Very important: take into account the effects of energy exchange and estimating the lifetime of oscillating thermoelastoplastic structures under material fatigue
- **Aim:** develop a thermodynamically consistent theory of oscillating thermoelastoplastic plates under material fatigue (dynamic approach - different from literature)
- The resulting system from the theory developed by Krejčí & al:

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\begin{aligned}
\partial_{tt} w - \partial_{tt}\Delta w + \mathbf{D}_2^* \sigma &= g\,, \\
\sigma &= \mathbf{B}\varepsilon + \int_0^\infty \mathfrak{s}_{rZ}[\varepsilon](t)\,\varphi(r)\,\mathrm{d}r \\
\varepsilon &= \mathbf{D}_2 w
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- We introduce $\theta > 0$ (absolute temperature) and $m(x,t) \geq 0$ (material fatigue)

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- We introduce $\theta > 0$ (absolute temperature) and $m(x,t) \geq 0$ (material fatigue); **aim:** get an evolution equation for m consistent from the thermodynamic point of view

Evolution equation for the fatigue

- **Main assumption:** proportionality between rate of fatigue $\partial_t m$ and

$$\begin{aligned}\mathscr{D} &= \langle \sigma, \partial_t \varepsilon \rangle - \partial_t \theta \mathscr{S}[\theta, \varepsilon] - \partial_t \mathscr{F}[\theta, \varepsilon] \\ &= -\frac{1}{2} \langle \mathbf{B}'(m)\varepsilon, \varepsilon \rangle \, \partial_t m + \int_0^\infty \langle \partial_t(\varepsilon - \mathfrak{s}_{rZ}[\varepsilon]), \mathfrak{s}_{rZ}[\varepsilon] \rangle \, \varphi(\theta, r) \, \mathrm{d}r\end{aligned}$$

  where $\mathscr{F}$ is the **specific free energy** and $\mathscr{S}$ is the **specific entropy**
- Justified by the so-called **rainflow method for cyclic fatigue accumulation** in uniaxial processes (counts closed hysteresis loops in the loading hystory - mechanism of energy dissipation)
- In multiaxial loading processes? Experimental measurements at the point of material failure: strong temperature increase, manifested by energy dissipation peak (temperature tests are in engineering practice for damage analysis in high frequency regimes (e.g. in aircraft industry))

$$\left(\frac{1}{C(\theta)} + \frac{1}{2} \langle \mathbf{B}'(m)\varepsilon, \varepsilon \rangle \right) \partial_t m = \int_0^\infty \langle \partial_t(\varepsilon - \mathfrak{s}_{rZ}[\varepsilon]), \mathfrak{s}_{rZ}[\varepsilon] \rangle \, \varphi(\theta, r) \, \mathrm{d}r$$

- $\mathbf{B}'(m) \leq 0$ softening $\Rightarrow$ **singularity!** Material failure in finite time!

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$$\left(\frac{1}{C(\theta)} + \frac{1}{2}\left\langle \mathbf{B}'(m)\varepsilon, \varepsilon \right\rangle \right) \partial_t m = \int_0^\infty \langle \partial_t (\varepsilon - \mathfrak{s}_{rZ}[\varepsilon]), \mathfrak{s}_{rZ}[\varepsilon] \rangle \, \varphi(\theta, r) \, \mathrm{d}r$$

- $\mathbf{B}'(m) \leq 0$ softening $\Rightarrow$ **singularity!** Material failure in finite time!

Evolution equation for the fatigue

- **Main assumption:** proportionality between rate of fatigue $\partial_t m$ and

$$\begin{aligned}\mathscr{D} &= \langle \sigma, \partial_t \varepsilon \rangle - \partial_t \theta \mathscr{S}[\theta, \varepsilon] - \partial_t \mathscr{F}[\theta, \varepsilon] \\ &= -\frac{1}{2}\left\langle \mathbf{B}'(m)\varepsilon, \varepsilon \right\rangle \partial_t m + \int_0^\infty \langle \partial_t (\varepsilon - \mathfrak{s}_{rZ}[\varepsilon]), \mathfrak{s}_{rZ}[\varepsilon] \rangle \, \varphi(\theta, r) \, \mathrm{d}r\end{aligned}$$

  where $\mathscr{F}$ is the **specific free energy** and $\mathscr{S}$ is the **specific entropy**
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- **Motivation:**
  - possibility to account also for decreasing fatigue rate (in view of engineering applications)
  - the material can be partially repaired by local melting
- **How to achieve this goal:**
- Phase transition equation in the form of melting-solidification law

$$\alpha \chi_t \in -\partial_\chi \mathscr{F}[\varepsilon, \theta, \chi] \qquad \chi \in [0,1]$$

$\chi_0 \in [0,1]$ some initial condition, $A(x,t) := \int_0^t \frac{1}{\alpha} \left(\frac{L}{\theta_c}(\theta - \theta_c) \right)(x,\tau)\, d\tau$

$(\chi_t - A_t)(z - \chi) \geq 0$ for all $z \in [0,1]$

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$$\boxed{\chi \in \mathfrak{s}_{[0,1]}[\chi_0, A]}$$

$\mathfrak{s}_{[0,1]}$ is a shifted stop

Thermodynamical consistency

- If we introduce $\mathscr{F}[\varepsilon,\theta,\chi]$ **specific free energy**, $\mathscr{S}[\varepsilon,\theta,\chi]$ **specific entropy** and $\mathscr{U}[\varepsilon,\theta,\chi]$ **internal energy** we are able to show that the first and second principles of thermodynamics are satisfied

$$\frac{\partial}{\partial t}\mathscr{U}[\varepsilon,\theta,\chi] + \mathrm{div}\,\mathbf{q} = \langle\sigma,\varepsilon_t\rangle \qquad \text{(energy conservation)}$$

$$\frac{\partial}{\partial t}\mathscr{S}[\varepsilon,\theta,\chi] + \mathrm{div}\,\frac{\mathbf{q}}{\theta} \geq 0, \qquad \text{(Clausius-Duhem inequality)}$$

- **Evolution equation for m:**

$$(C+\mathscr{K}[m,\theta,\varepsilon])\,m_t = -h(\chi_t) + \mathscr{D}[m,\theta,\varepsilon]$$

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$$\mathscr{D}[m,\theta,\varepsilon] := \int_0^\infty \varphi(m,\theta,r)\langle \mathbf{K}\mathfrak{s}_{rZ}[\varepsilon], (\varepsilon - \mathfrak{s}_{rZ}[\varepsilon])_t\rangle\,\mathrm{d}r$$

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Conclusion

- Rainflow method for fatigue evaluation in elastoplastic materials (uniaxial cyclic loading) allow to consider dissipated energy as a measure for fatigue
- The solution cannot be expected to exist globally: singularities (thermal shocks) occur in finite time
- Phase transition in the model accounts also for decreasing fatigue rate
- The time of failure can be shifted and considering a sufficiently large time interval of observation (usual engineering viewpoint) a global solution of the corresponding PDEs system can be found
- The resulting full system of energy and momentum balance equations is consistent with the first and the second principles of thermodynamics; mathematical analysis of the model is work in progress

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