**Exercise 4.1**

*Displacement formulation of linear elastodynamics: strong and weak forms, Galerkin FE model*

**General IBVP of linear elastodynamics**

Find $u_i = u_i(\boldsymbol{x}, t) = ?$, $\varepsilon_{ij} = \varepsilon_{ij}(\boldsymbol{x}, t) = ?$, $\sigma_{ij} = \sigma_{ij}(\boldsymbol{x}, t) = ?$ satisfying in $\Omega$:

$$\sigma_{ij|j} + f_i = \varrho\, \ddot{u}_i\,, \qquad \varepsilon_{ij} = \frac{1}{2}\big(u_{i|j} + u_{j|i}\big)\,, \qquad \sigma_{ij} = \begin{cases} C_{ijkl}\, \varepsilon_{kl} & \text{(anisotropy)}\,, \\ 2\mu\, \varepsilon_{ij} + \lambda\, \varepsilon_{kk}\, \delta_{ij} & \text{(isotropy)}\,, \end{cases}$$

with the initial conditions (at $t = t_0$):

$$u_i(\boldsymbol{x}, t_0) = u_i^0(\boldsymbol{x}) \quad \text{and} \quad \dot{u}_i(\boldsymbol{x}, t_0) = v_i^0(\boldsymbol{x}) \quad \text{in } \Omega\,,$$

and subject to the boundary conditions on $\Gamma = \Gamma_u \cup \Gamma_t$ $(\Gamma_u \cap \Gamma_t = \emptyset)$:

$$u_i(\boldsymbol{x}, t) = \hat{u}_i(\boldsymbol{x}, t) \ \text{ on } \Gamma_u\,, \qquad \sigma_{ij}(\boldsymbol{x}, t)\, n_j = \hat{t}_i(\boldsymbol{x}, t) \ \text{ on } \Gamma_t\,.$$

1. Derive the displacement formulation of elasticity (Navier's equations)
2. Derive the weak variational form of the displacement formulation
3. Derive the Galerkin FE model (i.e., $\mathbf{M}\, \ddot{\mathbf{q}}(t) + \mathbf{K}\, \mathbf{q}(t) = \mathbf{Q}(t)$)

**Exercise 4.2**

*A simple thermo-elastic problem*

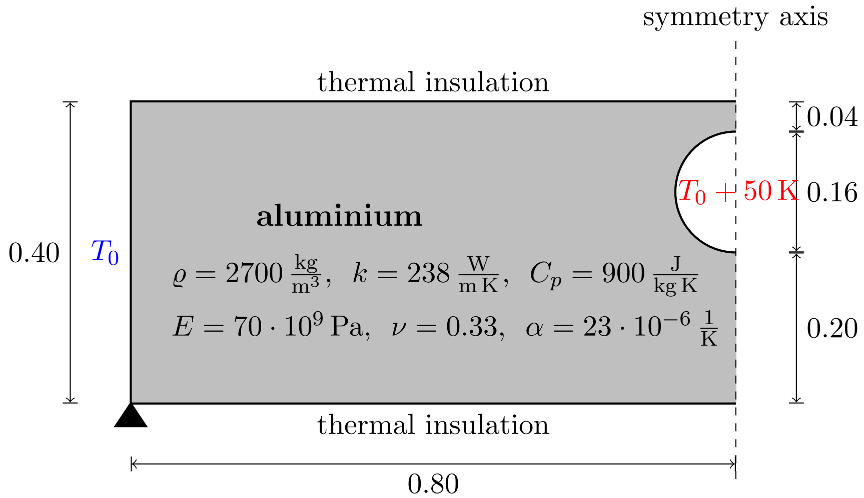



FIGURE 1: An uncoupled theromelastic problem: solve the conductive heat transfer problem and use the temperature variation obtained in the domain as a thermal load for a coupled mechanical problem.

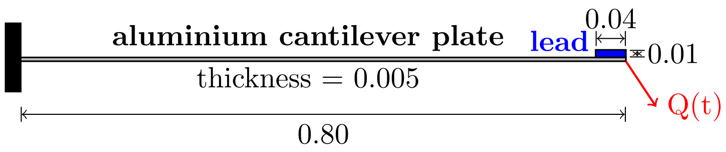
**Exercise 4.3**

*Using the Weak Form PDE Interface in COMSOL Multiphysics*

**Weak form for harmonic linear elasticity**

$$\omega^2 \int_\Omega \varrho\, u_i\, \delta u_i - \int_\Omega \sigma_{ij}\, \delta u_{i|j} + \int_\Omega f_i\, \delta u_i + \int_{\Gamma_t} \hat{t}_i\, \delta u_i = 0$$

$$\text{Here:} \quad \sigma_{ij} = \sigma_{ij}(\boldsymbol{u}) = \begin{cases} C_{ijkl}\, u_{k|l} & \text{– for anisotropic material} \\ \mu\, \big(u_{i|j} + u_{j|i}\big) + \lambda\, u_{k|k}\, \delta_{ij} & \text{– for isotropic material} \end{cases}$$




$$\varrho_{\text{Al}} = 2700\,\frac{\text{kg}}{\text{m}^3}\,, \qquad E_{\text{Al}} = 70\cdot 10^9\,\text{Pa}\,, \qquad \nu_{\text{Al}} = 0.33\,,$$

$$\varrho_{\text{Pb}} = 11340\,\frac{\text{kg}}{\text{m}^3}\,, \qquad E_{\text{Pb}} = 16\cdot 10^9\,\text{Pa}\,, \qquad \nu_{\text{Pb}} = 0.44\,.$$

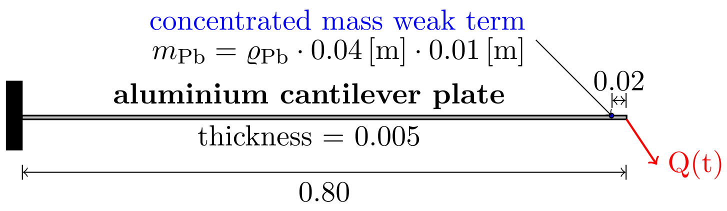



FIGURE 2: Simplified simulation of the influence of a heavy lead lump by adding a concentrated mass term to the weak form of a harmonic elastodynamic problem.

- Constants:

```
omega = 2*pi*f
mu = E/2/(1+nu)     lam = nu*E/(1+nu)/(1-2*nu)
```

- Domain expressions (for an isotropic material):

```
s11 = 2*mu*u1x + lam*(u1x+u2y)
s22 = 2*mu*u2y + lam*(u1x+u2y)
s12 = mu*(u1y+u2x)
```

- Domain integrand (in $\Omega$):

```
omega^2*rho*( u1*test(u1) + u2*test(u2) )
- s11*test(u1x) - s12*test(u1y+u2x) - s22*test(u2y)
f1*test(u1) + f2*test(u2)
```

- Neumann boundary integrand (on $\Gamma_t$):

```
t1*test(u1) + t2*test(u2)
```

- Concentrated mass weak term:

```
omega^2*mass*( u1*test(u1) + u2*test(u2) )
```