



# Geilo Winter School 2012

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## Lecture 7: Dynamic hyperelasticity in FEniCS

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# Course outline

## *Sunday*

**L1** Introduction to FEM

## *Monday*

**L2** Fundamentals of continuum mechanics (I)

**L3** Fundamentals of continuum mechanics (II)

**L4** Introduction to FEniCS

## *Tuesday*

**L5** Solid mechanics

**L6** Static hyperelasticity in FEniCS

**L7** Dynamic hyperelasticity in FEniCS

## *Wednesday*

**L8** Fluid mechanics

**L9** Navier–Stokes in FEniCS

## Dynamic hyperelasticity

$$\begin{aligned}\rho \ddot{u} - \operatorname{div} P &= B && \text{in } \Omega \times (0, T] \\ u &= g && \text{on } \Gamma_D \times (0, T] \\ P \cdot n &= T && \text{on } \Gamma_N \times (0, T] \\ u(\cdot, 0) &= u_0 && \text{in } \Omega \\ \dot{u}(\cdot, 0) &= u_1 && \text{in } \Omega\end{aligned}$$

- $u$  is the displacement
- $\rho$  is the (reference) density
- $P = P(u)$  is the first Piola–Kirchhoff stress tensor
- $B$  is a given body force per unit volume
- $g$  is a given boundary displacement
- $T$  is a given boundary traction
- $u_0$  and  $u_1$  are given initial displacement and velocity

## Variational problem

Rewrite as a first-order system by introducing  $p = \dot{u}$ :

$$\rho \dot{p} - \operatorname{div} P = B$$

$$\dot{u} - p = 0$$

Multiply by test functions  $v$  and  $q$  and sum up:

$$\int_{t_{n-1}}^{t_n} \int_{\Omega} (\rho \dot{p} - \operatorname{div} P) \cdot v \, dx \, dt + \int_{t_{n-1}}^{t_n} \int_{\Omega} (\dot{u} - p) \cdot q \, dx \, dt = \int_{t_{n-1}}^{t_n} \int_{\Omega} B \cdot v \, dx$$

Integrate by parts and use  $v = 0$  on  $\Gamma_D$  and  $P \cdot n = T$  on  $\Gamma_N$ :

$$\begin{aligned} & \int_{t_{n-1}}^{t_n} \int_{\Omega} \rho \dot{p} \cdot v \, dx \, dt + \int_{t_{n-1}}^{t_n} \int_{\Omega} P : \operatorname{grad} v \, dx \, dt \\ & + \int_{t_{n-1}}^{t_n} \int_{\Omega} \dot{u} \cdot q \, dx \, dt - \int_{t_{n-1}}^{t_n} \int_{\Omega} p \cdot q \, dx \, dt \\ & = \int_{t_{n-1}}^{t_n} \int_{\Omega} B \cdot v \, dx \, dt + \int_{t_{n-1}}^{t_n} \int_{\Gamma_N} T \cdot v \, ds \, dt \end{aligned}$$

## Time discretization

Let the trial functions  $u, p$  be continuous and piecewise linear in time, and let the test functions  $v, q$  be piecewise constant:

$$\int_{t_{n-1}}^{t_n} \int_{\Omega} \rho \dot{p} \cdot v \, dx \, dt = \int_{\Omega} \rho (p(\cdot, t_n) - p(\cdot, t_{n-1})) \cdot v \, dx$$

$$\int_{t_{n-1}}^{t_n} \int_{\Omega} \dot{u} \cdot q \, dx \, dt = \int_{\Omega} (u(\cdot, t_n) - u(\cdot, t_{n-1})) \cdot q \, dx$$

$$\int_{t_{n-1}}^{t_n} \int_{\Omega} p \cdot q \, dx \, dt = k_n \int_{\Omega} p(\cdot, t_{n-1/2}) \cdot q \, dx$$

where  $k_n = t_n - t_{n-1}$  and  $p(\cdot, t_{n-1/2}) = p(\cdot, t_n - k_n/2)$

Approximate other integrals by midpoint quadrature:

$$\int_{t_{n-1}}^{t_n} \int_{\Omega} P : \text{grad } v \, dx \, dt \approx k_n \int_{\Omega} P(u(\cdot, t_{n-1/2})) : \text{grad } v \, dx$$

This is cG(1) or *Crank–Nicolson* method

## Discrete problem

Find  $(u^n, p^n) \in V_h$  such that

$$\begin{aligned} & \int_{\Omega} \rho(p^n - p^{n-1}) \cdot v \, dx + k_n \int_{\Omega} P(u^{n-1/2}) : \text{grad } v \, dx \\ & \quad + \int_{\Omega} (u^n - u^{n-1}) \cdot q \, dx - k_n \int_{\Omega} p^{n-1/2} \cdot q \, dx \\ & \quad = k_n \int_{\Omega} B^{n-1/2} \cdot v \, dx + k_n \int_{\Gamma_N} T^{n-1/2} \cdot v \, ds \end{aligned}$$

for all  $(v, q) \in \hat{V}_h$

## Stress–strain relations

- $F = I + \text{grad } u$  is the deformation gradient
- $C = F^\top F$  is the right Cauchy–Green tensor
- $E = \frac{1}{2}(C - I)$  is the Green–Lagrange strain tensor
- $W = W(E)$  is the strain energy density
- $S_{ij} = \frac{\partial W}{\partial E_{ij}}$  is the second Piola–Kirchhoff stress tensor
- $P = FS$  is the first Piola–Kirchhoff stress tensor

St. Venant–Kirchhoff strain energy function:

$$W(E) = \frac{\lambda}{2}(\text{tr}(E))^2 + \mu \text{tr}(E^2)$$

## Useful FEniCS tools (I)

Defining mixed function spaces:

```
V = VectorFunctionSpace(mesh, "CG", 1)
VV = V*V
```

Defining subfunctions:

```
up = Function(VV)
u, p = split(up)
```

Shortcut:

```
u, p = Functions(VV)
```

## Useful FEniCS tools (II)

### Time-stepping

```
t = dt
while t < T + DOLFIN_EPS:

    # Solve variational problem
    solve(...)

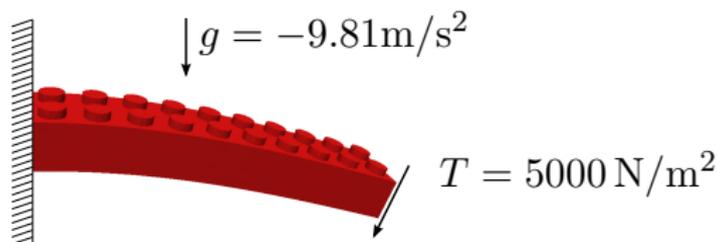
    # Move to next interval
    t += dt

    u0.assign(u1)

    # use up0.assign(up1) for a mixed system
```

## The FEniCS challenge!

Compute the deflection of a regular  $10 \times 2$  LEGO brick as function of time. Use the St. Venant–Kirchhoff model and assume that the LEGO brick is made of PVC plastic. The LEGO brick is subject to gravity of size  $g = -9.81 \text{ m/s}^2$  and a downward traction of size  $5000 \text{ N/m}^2$  at its end point. At time  $t = 0$ , the brick is at rest in its undeformed state.



To check your solution, compute the average value of the displacement in the  $z$ -direction at time  $T = 0.05$ . Use a time step of size  $k = 0.002$ .

*The student(s) who first produce the right answer will be rewarded with an exclusive FEniCS coffee mug!*