A simple formulation applied to finite strain viscoelastic solids and compressive flows

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Abstract. When writing movement equations in stresses for continuous media, it makes no difference if the media is solid or fluid. The fundamental difference in the solution of these two problems relies on the respective constitutive laws. For solids shear stresses are related to shear strains and the Navier-Cauchy equation takes place, while for fluids, shear stresses are related to the time rate of shear strains, resulting in the Navier-Stokes equation. For solid and fluid isothermal problems, the pressure is related to the volumetric change. Based on hyperelastic relations, we present an original total Lagrangian numerical approach capable of modeling simple large strain viscoelastic solids (Kelvin-like) and free-surface compressive viscous isothermal fluid flows. The proposed model is implemented in an in house positional prismatic finite element formulation and is explored in numerical examples.

Keywords: Large strain hyperelasticity, Kelvin-like viscoelasticity, Compressive isothermal fluid flow, Total Lagrangian formulation.

1 Introduction

The finite element method (FEM) has been very successfully employed to solve solids and structural problems since pioneer works [1,2,3,4,5]. Problems involving large strains, large displacements and hyperelastic nonlinear constitutive relations, also solved by FEM, bring important contributions to the understanding of highly deformable solids as one can see in references [6,7,8,9,10] including plasticity and viscoplasticity.

Regarding solids, in this study we propose a simple Kelvin-like viscoelastic numerical modeling that does not uses the usual Kröner-Lee decomposition [10]. Due to the facility of using arbitrarily unstructured meshes and, particularly, due to the simplicity on boundary conditions enforcement over complex boundaries, the FEM has been conquering more space in fluid mechanics see [11,12] among others.

For free surface flow problems it is not possible to apply a pure Eulerian description, in this context, so called Arbitrary Lagrangian Eulerian (ALE) stabilized formulations have been developed [13,14]. As an alternative to ALE, the Particle Finite Element Method (PFEM) [15] is present, providing a good solution for free surface flows with topological changes in the fluid domain. However, this method demands constant remeshing and special attention in defining physical properties.

Here we take advantage of the large strain solid mechanics developments and its tensor algebra (in a more fundamental stage) to propose a total Lagrangian formulation to be applied in both Kelvin-like viscoelastic solids and isothermal-compressible-viscous free-surface flows with finite distortions and free of topological changes (no surface break and no fluid-fluid surface contact). To achieve this goal, we apply the Flory's [16] multiplicative decomposition to split the constitutive law into elastic volumetric, elastic deviatory, viscous volumetric and viscous deviatory parts. Representative examples are used to validate the proposed model.

2 Movement equation – weak form

The Eulerian movement equation is written as:

$$\nabla \cdot \sigma^t + \vec{b} = \rho \ddot{\vec{y}}, \qquad \sigma = \sigma^t \tag{1}$$

in which σ_{ij} is the Cauchy stress acting at plane *i* in direction *j*, ρ is the mass density, $\ddot{y}_i$ is the material point acceleration in *i* direction and b_i is the volume force acting in direction *i*. The second part of equation (1) corresponds to three rotation equilibrium equations that are satisfied by the symmetry o the Cauchy stress tensor [17]. The first part of Equation (1) contains the 3 translation strong equilibrium equations that will be numerically solved in this study.

There are several ways of writing the weak form of equation (1), see [18,19] when the positional FEM is the subject. Here the Virtual Work Principle is employed multiplying equation (1) by an arbitrary variation of position δy_i as follows:

$$\delta w = \left(\nabla \cdot \sigma^t + \vec{b} - \rho \ddot{\vec{y}}\right) \cdot \delta \vec{y} = 0 \tag{2}$$

Integrating equation (2) over the analyzed domain V and applying the divergence theorem, results:

$$\delta W = \int_V \left(\nabla \cdot \sigma^t + \vec{b} - \rho \ddot{\vec{y}}\right) \cdot \delta \vec{y} \; dV = 0 \tag{3}$$

$$\delta W = \int_V \rho \ddot{\vec{y}} \cdot \delta \vec{y} \; dV - \int_V \vec{b} \cdot \delta \vec{y} \, dV - \int_A \sigma^t \cdot \delta \vec{y} \cdot \vec{n} \; dS + \int_V \sigma^t : \nabla(\delta \vec{y}) \, dV = 0 \tag{4}$$

in which n_j is the *j-th* component of the unit vector of surface area A. By the Cauchy formula $p_i = \sigma_{ji} n_j$ (where p_i is the surface force) and, considering the symmetry of the Cauchy stress one writes:

$$\delta W = \int_V \rho \ddot{\vec{y}} \cdot \delta \vec{y} \; dV - \int_V \vec{b} \cdot \delta \vec{y} \, dV - \int_A \vec{p} \cdot \delta \vec{y} \; dS + \int_V \sigma : \delta \varepsilon \; dV = 0 \tag{5}$$

with $\delta \varepsilon_{ij} = (\delta y_{i,j} + \delta y_{j,i}) / 2$ being the real strain variation (Eulerian reference), that is usually known in its rate version $\dot{\varepsilon}_{ij} = (\dot{y}_{i,j} + \dot{y}_{j,i}) / 2$ [17]. One may note that in equation (5) the following terms are present:

$$\delta W = \delta K + \delta P + \delta \Psi \tag{6}$$

where K is the kinetic energy, P is the potential of applied external forces (considered conservative) and Ψ is the Helmholtz free energy for isothermal states that includes, in this study, the strain energy density and the viscous dissipation. Moreover, equation (5) is the weak form of the movement equation (or dynamic equilibrium) of a continuum media in the Eulerian description.

I order to write the Lagrangian version of equation (5) one uses the continuity theorem and the equivalence of the internal virtual work, i.e.:

$$\int_V \rho \ddot{\vec{y}} . \delta \vec{y} \; dV = \int_{V_0} \rho_0 \ddot{\vec{y}} \cdot \delta \vec{y} \, dV_0 \,, \quad \sigma : \delta \varepsilon = S : \delta E \tag{7}$$

in which E is the Green-Lagrange strain, S is the second Piola-Kirchhoff stress and ρ_0 is the mass density regarding the initial volume V_0. Introducing equations (7) into equation (5) results:

$$\delta W = \int_{V_0} \rho_0 \ddot{\vec{y}} \cdot \delta \vec{y} \, dV_0 - \int_{V_0} \vec{b}^0 \cdot \delta \vec{y} \, dV_0 - \int_{A_0} \vec{p} \cdot \delta \vec{y} \; dS_0 + \int_{V_0} S : \delta E \, dV_0 = 0 \tag{8}$$

The way the continuum will behave depends upon the constitutive model applied to find the seconds Piola-Kirchhoff stress.

It is necessary to recall some large strain relation as [17]:

$$C = A^t \cdot A \,, \quad E = \frac{1}{2}\left(C - I\right) \quad \text{and} \quad \sigma = \frac{1}{J} A \cdot S \cdot A^t \tag{9}$$

where A is the gradient of the change of configuration function (deformation gradient), J its determinant, C is the right Cauchy-Green stretch tensor and I is the second identity tensor..

3 Flory decomposition and hyperelasticity

The right Cauchy-Green stretch tensor (equation (9)) is decomposed into its isochoric and volumetric parts as proposed by Flory [16]. One starts defining

$$A = \hat{A} \cdot \overline{A} \,, \quad \hat{A} = J^{1/3} I \quad \Rightarrow \quad Det\left(\hat{A}\right) = J \quad \overline{A} = J^{-1/3} A \quad \Rightarrow \quad Det\left(\overline{A}\right) = 1 \tag{10}$$

Applying equation (10) in equation (9) results the isochoric part of the stretch as:

$$\overline{C} = J^{-2/3} A^t \cdot A \tag{11}$$

where $Det(\bar{C}) \equiv 1$. The volumetric part is defined imposing expression (10) in (9), i.e.:

$$\hat{C} = \hat{A}^t \cdot \hat{A} = J^{2/3} I \tag{12}$$

in which $Det(\hat{C}) = J^2 = Det(C)$.

Multiplying equations (11) and (12) one recovers the Cauchy-stretch tensor, completing the description.

$$C = \hat{C} \cdot \bar{C} = \bar{C} \cdot \hat{C} . \tag{13}$$

For hyperelastic materials, the Helmholtz free energy is written as a sum of scalar potentials depending upon the invariants of the isochoric and volumetric parts of the cauchy-Green stretch tensor, as:

$$\psi = \psi^{vol}(J) + \psi^{iso1}(\bar{I}_1) + \psi^{iso2}(\bar{I}_2) \quad \text{or simply} \quad \psi = \psi^J + \psi^1 + \psi^2 \tag{14}$$

in which $\bar{I}_1$ and $\bar{I}_2$ are the first and second invariants of the isochoric part $\bar{C}$ and J is the third invariant of the volumetric part $\hat{C}$. Using the concept of energy conjugate, $\delta\psi = S : \delta E = \partial\psi / \partial E : \delta E$ the second Piola-Kirchhoff stress can be written as:

$$S_{elas} = \frac{\partial \psi}{\partial E} = \frac{\partial \psi^J}{\partial E} + \frac{\partial \psi^1}{\partial E} + \frac{\partial \psi^2}{\partial E} \quad \text{or simply} \quad S_{elas} = S^J + S^1 + S^2 \tag{15}$$

it is important to mention that, for elastic applications, this is the stress placed in equation (8).

Without loss of generality, in this study we adopted the potentials proposed by [20,21]:

$$\psi^J = \frac{K}{8n^2}\left(J^{2n} + J^{-2n} - 2\right) \qquad \psi^1 = \frac{G}{4}\left(\bar{I}_1 - 3\right) \qquad \psi^2 = \frac{G}{4}\left(\bar{I}_2 - 3\right) \tag{16}$$

in which K is the bulk modulus, G is the shear modulus and $n > 0$ helps to control the volumetric stiffness for large strains. Using the chain rule over equation (15) one writes:

$$S^J = \frac{\partial \psi}{\partial J}\frac{\partial J}{\partial E} = \frac{\partial \psi}{\partial J}\mathfrak{E}^J \qquad S^1 == \frac{\partial \psi}{\partial \bar{I}_1}\frac{\partial \bar{I}_1}{\partial E} = \frac{\partial \psi}{\partial J}\mathfrak{E}^1 \quad \text{and} \quad S^2 = \frac{\partial \psi}{\partial \bar{I}_2}\frac{\partial \bar{I}_2}{\partial E} = \frac{\partial \psi}{\partial J}\mathfrak{E}^2 \tag{17}$$

For which the strain directions are given by:

$$\mathfrak{E}^J = \frac{\partial J}{\partial E} = JC^{-1}, \; \mathfrak{E}^1 = -\frac{2}{3}J^{-2/3}Tr(C)C^{-1} + 2J^{-2/3}I, \; \mathfrak{E}^2 = 2J^{-4/3}\left(-\frac{2}{3}C^{-1}I_2 + \left\{Tr(\mathrm{C})\mathrm{I} - \mathrm{C}^t\right\}\right) \tag{18}$$

Applying equation (9) it is easy to show that the Lagrangian stress components $\left(S^J, S^1, S^2\right)$ of equation (17) correspond exactly to the Cauchy stress components. $\left(\sigma^{vol}, \sigma^{iso1}, \sigma^{iso2}\right)$, which opens the possibility the following viscous stress.

4 The viscous stress

The primary idea to extend the hyperelastic model to incorporate viscosity in equation (1) would be assuming that the time rate of the split strain directions of equations (18) would suite a constitutive relation, i.e.:

$$S^*_{vis} = \frac{\bar{K}}{4}\dot{\mathfrak{E}}^{vol} + \frac{\bar{G}}{4}\dot{\mathfrak{E}}^{iso1} + \frac{\bar{G}}{4}\dot{\mathfrak{E}}^{iso2} \tag{19}$$

However, a simple time derivatives of volumetric and isochoric directions do not preserve direction. Thus, S^*_{vis} serves only as an inspiration to the following developments. Inspired in equation (19), in order to keep isotropy, a general viscous virtual work variation is given by:

$$\delta\psi = \frac{\bar{K}}{4}\frac{dJ^\alpha}{dt}\delta J + \frac{\bar{G}_{(i)}}{4}\frac{d\bar{I}_i^\gamma}{dt}\delta\bar{I}_i = \left(\frac{\bar{K}}{4}\alpha J^{\alpha-1}\dot{J}\frac{\partial J}{\partial E} + \frac{\bar{G}_1}{4}\gamma_1\bar{I}_1^{\gamma_1-1}\dot{\bar{I}}_1\frac{\partial \bar{I}_1}{\partial E} + \frac{\bar{G}_2}{4}\gamma_2\bar{I}_2^{\gamma_2-1}\dot{\bar{I}}_2\frac{\partial \bar{I}_2}{\partial E}\right) : \delta E \tag{20}$$

resulting the following expression for the second Piola-Kirchhoff viscous stress:

$$S_{vis} = \frac{\bar{K}}{4}\alpha J^{\alpha-1}\dot{J}\mathfrak{E}^{vol} + \frac{\bar{G}_1}{4}\gamma_1\bar{I}_1^{\gamma_1-1}\dot{\bar{I}}_1\mathfrak{E}^{iso1} + \frac{\bar{G}_2}{4}\gamma_2\bar{I}_2^{\gamma_2-1}\dot{\bar{I}}_2\mathfrak{E}^{iso2} \tag{21}$$

in which $\bar{K}$ is the fluid volumetric viscosity [22] and $\bar{G}_i$ are shear (isochoric directions 1 and 2) viscosities. In order to be coherent with the viscosity understanding we assume $\bar{G} = \bar{G}_1 = \bar{G}_2$. Adopting the viscous parameters $\alpha = 1$ and $\gamma_1 = \gamma_2 = 1/2$, Newtonian fluids and a simple Kelvin-Voigt visco-hyperelasticity are reproduced. Notice that, as the strain rate is written as function of dimensionless scalars (strain invariants) any value of α and γ_i can be adopted resulting in different viscous behavior. When these parameters are null, logarithm viscosity is assumed.

As we are interested in general numeric solution, one applies a finite difference scheme as:

$$S_{vis} = \frac{\bar{K}}{4}\alpha J^{\alpha-1}\frac{J_{s+1}-J_s}{\Delta t}\mathfrak{C}^{vol} + \frac{\bar{G}_1}{4}\gamma_1 \bar{I}_1^{\gamma_1-1}\frac{\bar{I}_{(1)s+1}-\bar{I}_{(1)s}}{\Delta t}\mathfrak{C}^{iso1} + \frac{\bar{G}_2}{4}\gamma_2 \bar{I}_2^{\gamma_2-1}\frac{\bar{I}_{(2)s+1}-\bar{I}_{(2)s}}{\Delta t}\mathfrak{C}^{iso2} \tag{22}$$

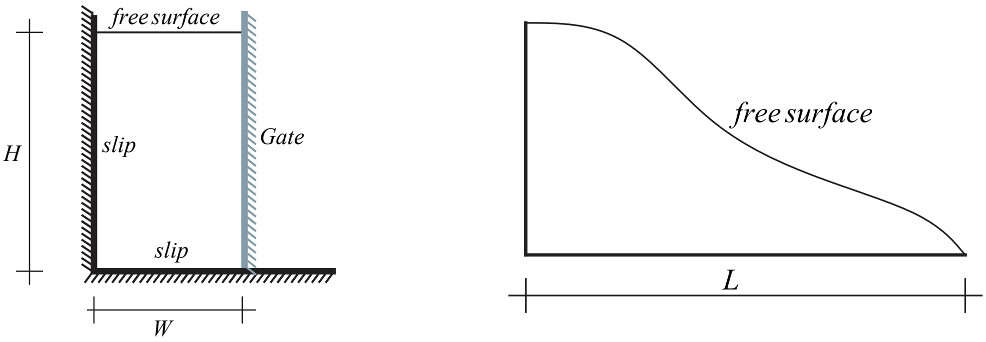
in which $s+1$ represents the current time. From this point one applies the usual position based FEM procedure to assemble the solution process. In short, the proposed model is assembled in equation (8) by:

$$S = S_{elas} + S_{vis} \tag{23}$$

5 Examples

5.1 Dam rupture - fluid

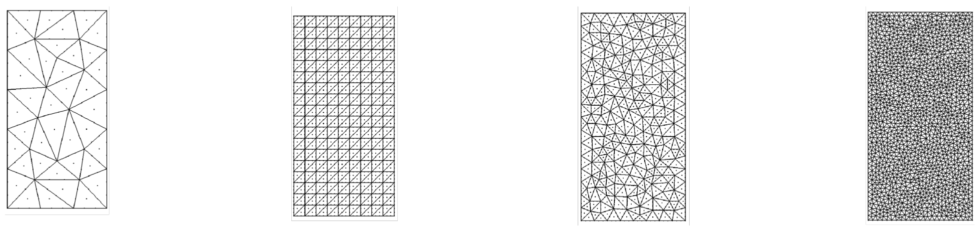
The present example is based on the experimental work of reference [23], reproduced numerically by [24,25] using an ALE fluid formulation. The analyzed problem is a dam initially with width W and height H, filled with fluid initially at rest. The dam suffers a subtle disrupt at the right wall (Gate), see Fig. 1. This problem is considered a first benchmark to test free surface flows solvers. The geometric and physical non-dimensional properties are [25]: $W = 0.35$, $H = 0.70$, $g = 1$, $\rho = 1$, $\bar{G} = \mu = 10^{-3}$. As reference [25] treats the fluid as incompressible we adopted a high value for the bulk modulus ($K = 2.15 \cdot 10^9$) to check the formulation overall behavior.



(a) Initial position (b) Flow

Fig. 1 – Analyzed problem

Fig. 2 shows the various adopted meshes, with number of nodes and element order. The elements are 3D prismatic with unitary thickness and linear approximation in this direction. Both, vertical and horizontal walls are slip walls and the adopted non-dimensional time step is $2.5 \cdot 10^{-4}$. The analysis is carried for 6700 time steps with the maximum of 3 iterations at each time.



(a) 38 - Cubic (b) 324 - Cubic (c) 392 – Cubic (d) 3004 - Linear

Fig. 2 - Definition of used meshes - number of elements and basis aproximation

In a first analysis stage, with the intact reservoir, the water is allowed to conform to meet the initial hydrostatic stress distribution. In the second stage, the right side wall (gate) is instantly removed and the fluid is free to flow. We compare the obtained results to the experimental values of [23]. The dimensionless time used by the references to make graphics is obtained by $t^* = t\sqrt{2g/W}$.

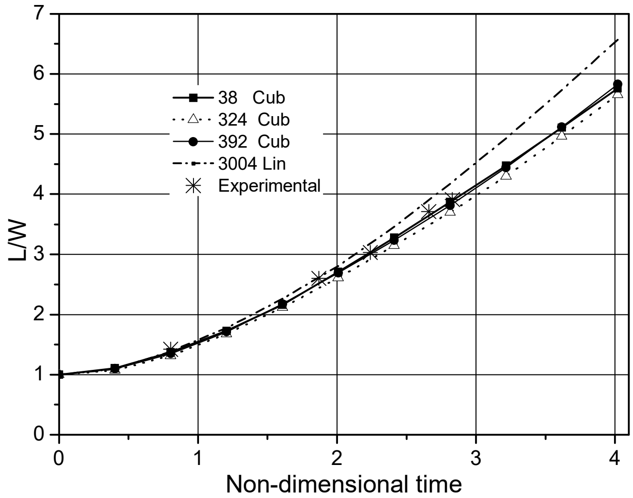


Fig. 3 – Relative enlargement of the fluid base along time.

Only the linear approximation, fig.3, presents results not so close to the experimental values.

5.2 Viscoelastic sandwich circular plate - solid

A simple supported circular plate with radius $R = 1m$ and thickness $t = 3cm$ is subjected to a transverse uniform loading. Only $1/4$ of the structure is modeled using 300 prismatic finite elements with cubic approximation parallel to the plate surface and linear along thickness, totalizing 3 unitary layers, see Fig. 4. The simple support condition is applied at nodes of the bottom face. The load $b_3 = 5000kN/m^3$ is applied as a volume force on the superior layer of the plate. When viscosity is considered we used $\gamma_1 = \gamma_2 = 1/2$, i.e., Kelvin-Voigt-like viscoelastic model. Three situations are considered:

(i) Only to verify the discretization, the three layers are considered elastic (steel) with properties: $E = 200GPa$ and $\nu = 0.25$ that corresponds to $K = 133GPa$ and $G = 80GPa$. For this case the achieved central transverse displacement is $w = 0.7043cm$, 2.9% greater than the Kirchhoff kinematics analytical solution that is $w_k = 0.684cm$. This result is expected as the adopted solid element is more flexible than the Kirchhoff kinematics.

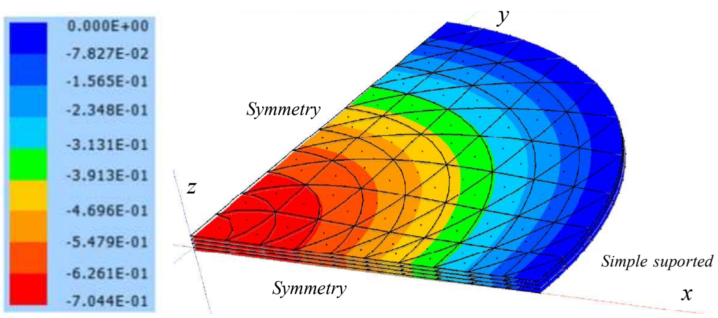


Figure 4 - Discretization, boundary conditions and transverse displacement $(w_{\max} = 0.7043cm)$

(ii) Keeping the loading of case (i), the material of the central layer is substituted by Polypropylene with the elastic properties [26] $E = 1.088GPa$ and $\nu = 0.49$ that correspond to $K = 18.13\,GPa$ and $G = 0.365\,GPa$. The adopted shear viscosity property is $\overline{G} = 6.756\,GPa \cdot s$. The central displacement for the elastic and viscoelastic cases are shown in figure 5, being the maximum elastic displacement

$w_{\max} = 0.7432cm$, 5.52% grater then the steel case (i). We used 100 time steps of $\Delta t = 0.01s$ for the viscoelastic analysis.

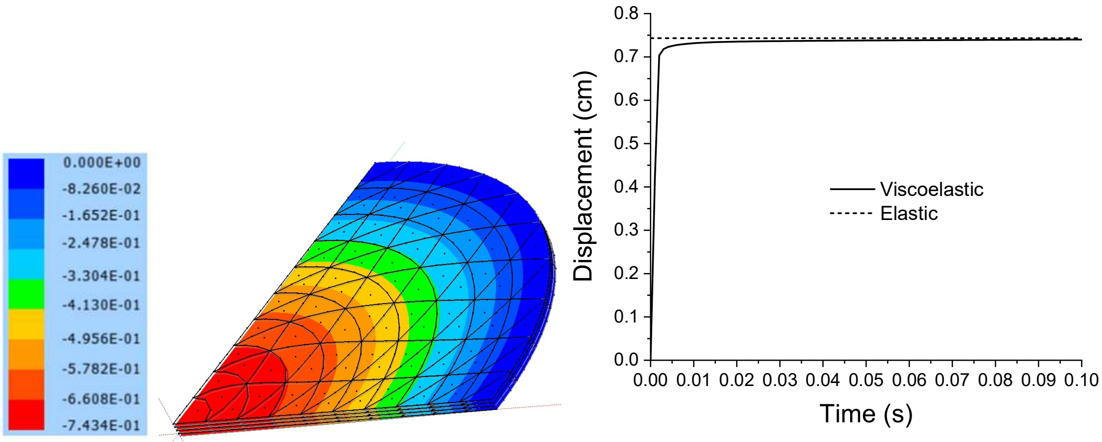


Figure 5 - (a) Elastic vertical displacement of sandwich plate, (b) Viscoelastic displacement at the plate center.

(iii) Considering the steel density $\rho_{steel} = 7000kg/m^3$ and the Polypropylene $\rho_{pol} = 910kg/m^3$, we perform a dynamic analysis considering the same load (suddenly applied). The central displacement along time is compared with the elastic result of case (ii) at figure 6. We used 500 time steps of $\Delta t = 0.01s$.

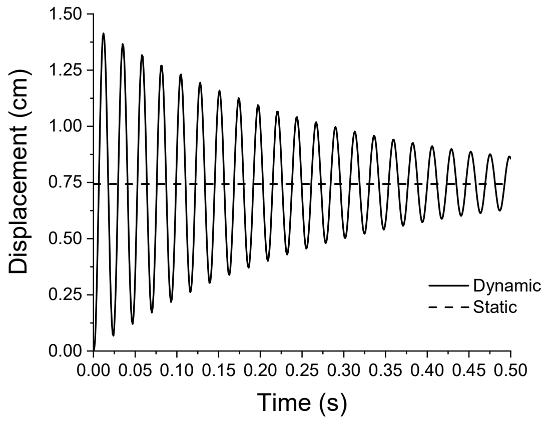


Figure 6 - Vertical displacement along time in a dynamic analysis

As one can see by this example, the formulation is capable to model general structures even using this simple viscoelastic model, i.e., the Kelvin-Voigt-like model

6 Conclusions

This work shows an alternative unified constitutive model for simple Kelvin-Voigt solids and isothermal free-surface compressive viscous flows. The formulation is presented using hyperelastic considerations and successfully implemented in a total lagrangian position based finite elements. Examples demonstrate that the formulation presents very good results for the proposed applications.

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