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Accurate 1D structural models for the analysis of non-homogeneous biomechanical structures

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The simulation of biomechanical systems requires nowadays a multifield approach involving computational fluid mechanics of haematic flows, structural modeling of biological tissues and high-fidelity fluid-structure techniques [1]. In order to gain more insight into the complex biomedical processes during therapeutical interventions and for the optimization of treatment methods and disease preventions, constitutive modeling of biological tissues and related computer simulations are active subjects of current research [2]. As well as in other physical applications such as aerospace and civil engineering, non-homogeneous structures are widely used in biomechanical field. For example, healthy arteries consist of three layers with different mechanical properties: the intima, the media and the adventitia. In last decades, a large use of three-dimensional models for the structural analysis of biological tissues has been necessary with the main disadvantage of huge computational cost simulations.
This paper investigates the capabilities of the CUF one-dimensional (1D) model in describing the structural static and dynamic behavior of arbitrary non-homogeneous structures. A first assessment of this refined model for biomechanical applications is also carried out in order to reduce the huge computational cost required by solid modeling without forgoing structural accuracy. The finite element method (FEM) is employed and the direct time integration scheme for the dynamic response is the implicit Newmark's method.
Higher-order 1D models with generalized displacement variables based on CUF have recently been proposed by Carrera and co-authors for the structural analysis of isotropic and composite structures [3]. CUF is a hierarchical formulation which considers the order of the model as a free-parameter of the analysis. Refined 1D models revealed to be a powerful and easy-to-use tool for the analysis of static and divergence aeroelastic problems [4]. An extension of CUF 1D finite elements to the free vibration analysis of conventional and joined wings was done in [5]. The accuracy capabilities of using variable kinematic CUF modeling in compact and thin-walled beam-like structures with time-dependent loadings was investigated in the work by Carrera and Varello [6].
In this paper, two applications of CUF 1D models to the static and dynamic response of structures with arbitrary cross-sections are presented. The first case concerns the propagation of a wave in a three-layer cylinder with a thin circular cross-section. The second case is the structural analysis of a clinic artery case retreived from the biomechanical literature [2, 7]. This example is a preliminary application of the CUF 1D model to the study of a biomechanical case.
The first analysis aims at proving the capabilities of the higher-order CUF 1D model in the dynamic response analysis of non-homogeneous structures. The three layers of the cylinder are made of different isotropic materials. The thickness $h = 2$ mm is equal for each layer and is small enough to consider overall the cylinder as a thin-walled structure, since the external and internal diameter are respectively equal to $d_e = 100$ mm and $d_i = 94$ mm. The length L of the cylinder is equal to 500 mm. The wave is here described as a step profile of pressure p applied to the internal edge of the cylinder along the longitudinal axis. In particular, such a pressure is applied only on the upper edge of the cylinder in order not to have an axisymmetric solution. The simply supported cylinder is modeled with a 1D finite element mesh of 10 B4 elements.

The dynamic response of the structure is computed over the interval [0,0.005] s via the Newmark's method. At the starting time, the wave is close to the constrained section and so it slightly affects the cylinder which basically bends as though the load were a uniform pressure on the upper half of the cylinder. As the wave moves in the cylinder, the deformed configuration of the cross-sections changes along the longitudinal axis assuming a typical triangle-like shape. Local effects due to the wave loading and inertial effects are computed by an eight-order model ($N = 8$) and depicted in Fig. 1 for the time istant $t = 0.0039333$ s. The results clearly show the accuracy of the present refined model in detecting the three-dimensional deformation despite its one-dimensional approach, according to previous dynamic computations through CUF 1D models [6]. The present method shows features not present in standard one-dimensional theories such as the thickness changing of the thin-walled laminated surface and the in-plane and out-of-plane cross-section deformations.

Once the capabilities of higher-order CUF 1D models have been assessed for the non-homogeneous cylinder case, a human external iliac artery with a pronounced atherosclerotic plaque is considered as application of an arbitrary cross-section structure. The components of the artery are identified by hrMRI (high resolution magnetic resonance imaging) and histological analysis [7]. This approach considers eight different tissue types: non-diseased intima, fibrous cap, i.e. the fibrotic part at the luminal border, fibrotic intima at the medial border, calcification, lipid pool, non-diseased media, diseased fibrotic media and adventitia. As done in [2], for the present numerical investigations the non-diseased intima is neglected. Furthermore, the fibrotic intima at the medial border and the diseased fibrotic media are treated as one component, the fibrotic media. The section width and heigh are approximately the same and equal to 20 mm.

In the work of Balzani et al. [2] only a two-dimensional simulation of the cross-section is carried out in order to keep the computational effort relatively low. This simplified approach totally neglects the important effects due to the third out-of-plane dimension. These effects are fundamental especially for a biomechanical case where the haematic flow field and the non-standard structural behavior of biological tissues need a complete three-dimensional description. Obviously, the introduction of the third direction would typically need the use of solid (3D) elements instead of 2D plate or shell FEs. This means a much higher computational effort. In order to take into account the out-of-plane direction and analyze a complete solid structure, CUF 1D models are thus here proposed since they require a low computational cost though their remarkable 3D performance. The artery cross-section is extruded along the out-of-plane direction for 40 mm and a clamped boundary condition is taken into account for both the free edges (at $y = 0$ and $y = L$). The structure is here modeled with a 1D FE mesh of 10 B4 elements.

The static analysis is performed with a uniform pressure load of 180 mmHg (= 24 kPa) applied on the surface bounding the lumen, i.e. the inside space of the artery. A solid model has been built in NASTRAN and modeled with a mesh of 244320 HEXA8 solid elements (260172 nodes) with a total number of DOFs equal to 761244. Higher-order CUF models with a variable expansion order N are employed and compared to solid FEM. Classical beam models are completely not able to study this case due to their kinematic hypotheses on the cross-section deformation. In this case, even low-order theories are not enough to catch an acceptable solution compared to the 3D simulation. The more the expansion order N is, the more the results obtained through the 1D formulation are accurate, approaching the solid FE solution. An excellent agreement with NASTRAN solid results is achieved with $N = 22$. A high value of N is required since the deformation over the cross-section is located in the region close to the artery lumen, whereas far from the lumen the deformation is approximately zero. Figure 2 shows the deformation of the midspan cross-section, where the maximum displacement is located. It is important to note the remarkably lower computational effort required by CUF 1D model. In fact, the $N = 22$ model describes the three-dimensional structural behavior of the artery with a number of degrees of freedom equal to 25668, about 30 times lower than the DOFs required by the solid FE model.

In conclusion, the implementation of CUF 1D models in a time integration Newmark's scheme has revealed the shell-solid capabilities of such approach in accurately describing the structural dynamics of non-homogeneous components with a sizeable reduction in computational cost. Moreover, the CUF 1D model seems to a be a promising numerical tool for the analysis of biomechanical problems.

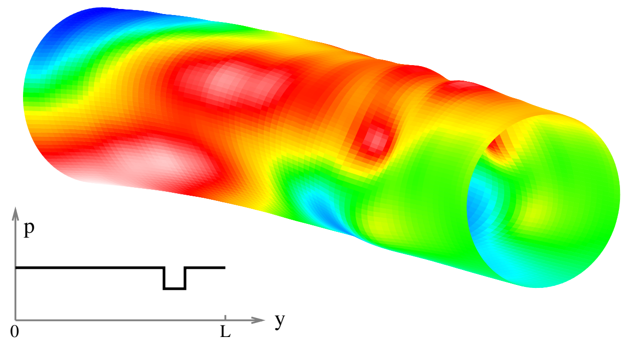

Figure 1: Effect of the wave propagation in the cylinder. $t = 0.0039333$ s.

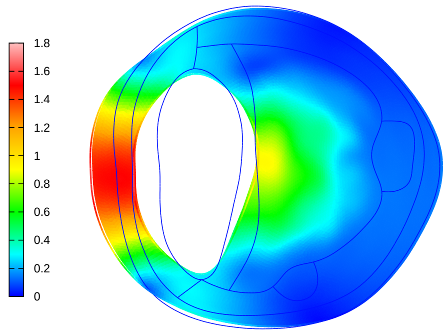

Figure 2: Displacements over the midspan cross-section of the atherosclerotic plaque. $N = 22$.

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