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Validation of the material point method for the simulation of thin-walled tubes under lateral compression

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ABSTRACT

This paper evaluates the performance of the material point method for the simulation of thin-walled tubes under lateral compression. Validation is carried out against actual experimental results for three different scenarios, namely: quasi-static loading, impact on rigid target, and wave propagation. A systematic approach is taken to gain insight on the trade-off between accuracy and computational cost at different levels of refinement of the model. Accuracy is assessed by comparing simulation results against experimental data. Computational cost is measured by the simulation runtime, or more specifically, in terms of the ratio between simulation time and execution time. Results indicate that, from highest influence to lowest, the factors affecting accuracy are: grid resolution, particle count along the thickness of the tube, and particle count along the circumference of the tube. Overall, it is demonstrated that the MPM is a reliable and accurate method to model circular thin-walled tubes under various excitation conditions.

1. Introduction

Tubes are one of the common forms of thin-walled members used in protective structures [1]. This is the direct result of having characteristics such as low cost, high energy-absorption and ease of manufacturing. As a result, their energy-absorption properties have been the focus of many researchers. Gupta et al. [2] carried out quasi-static lateral compression experiments on tubes. They used aluminum and mild steel tubes with different diameters and thicknesses and reported their load-deformation curves. Xu et al. [3] carried out collision tests on circular aluminum rings with different diameters and thicknesses. A Hopkinson bar was used in these experiments allowing initial velocities to range between 16.5 and 125 m/s. Time history versus force curves as well as rebound velocities and contact durations were recorded from the experiments. Parameters affecting the collision of rings on a rigid target were numerically explored by Bao and Yu [4]. Xiang et al. [5] carried out experiments under the effect of combined lateral compression and shear. This involved one group of tubes that were freely placed between the loading platens and another group that were fixed to the platens. They also proposed an analytical model that takes into account traveling plastic hinges and the plastic energy associated with their travel.

The behavior of thin-walled tubes has also been investigated through numerical studies. Such analyses are particularly interesting when it comes to parametric studies on energy absorption properties [4,6]. Numerical simulation of tubular systems under load has been mainly carried out in the framework of the finite element method (FEM). The availability of commercial software and their overall robustness, built upon years of research, has made the FEM to be first in line for such simulations. However, with the advent of particle methods and their potentiality to simulate large deformations of complex geometries under dynamic loading [7], it is worthwhile to evaluate such methods in relation to energy-absorbing systems.

Meshless methods have shown to be well suited for solving problems involving large deformations and fracture [8–12]. Among meshless methods, the material point method (MPM) has increasingly been gaining attention from the scientific community. In one of the very early works, Sulsky and Schreyer [13] utilized the MPM to simulate the Taylor impact problem involving large deformations. Ma et al. [14] later revisited the problem using a dual-domain MPM. Zhang et al. [15] simulated the dynamic response of saturated soil under impact. They demonstrate that the use of the MPM avoids the problems associated with more conventional methods such as the FEM. Li et al. [16] demonstrated the effectiveness of the MPM in relation to predicting cracking and fragmentation of brittle material under impact. They mention that the finite element method is ‘fundamentally ill-equipped’

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to properly deal with such problems. Wang et al. [17] used the MPM to simulate the process of explosive welding, a process that involves multiple physical phenomena including high velocity collision, plastic deformations and high temperature. They demonstrated the capabilities of the MPM to simulate such complex physical events in contrast to the limitations of mesh-based methods such as the FEM. Other applications of the MPM include: sloshing impact simulation [18], simulation of shock waves [19,20] and 3-phase fluid-solid-geomembrane simulations [21]. At the same time as MPM's range of application is being explored, advances are also being made, both from the theoretical [22–24] and implementation [25,26] standpoints.

In relation to thin walled energy absorbers, Baroutaji et al. [1] have recently put forward a comprehensive review. According to them, research in this field has reached a point where the aim is to dissipate energy in a predictable and controlled fashion. This has lead to the development of composite geometries and the use of composite material. Examples involve nested tubes [6] or the use of filler materials such as aluminum foam [27]. Such composite systems tend to behave in a manner more complex than a simple circular ring and also exhibit more varied modes of failure [27]. Nevertheless, the typical circular tube is still an important component of these composite systems and the formation and spread of the plastic hinge remains a primary mechanism through which energy is dissipated.

With thin-walled tubes being one of the most common elements used in energy-absorption systems, it is necessary to have a numerical method that can effectively capture localization of plastic strains and inertia effects for different rates of loading. Given its inherent capabilities to tackle problems involving large deformations, contacts and dynamic loading, the material point method (MPM) has the qualities to become a major contender against more well-known techniques such as the finite element method.

This paper aims to evaluate the MPM in relation to the simulation of circular tubes acting as energy-absorption systems. This is accomplished by using an in-house computer code developed by the authors. The convected particle domain interpolation (CPDI, [28,29]) approach is used here as it allows an accurate representation of the circular geometry. For validation purposes, this paper makes use of the experimental results reported by Xiang et al. [5] on quasi-static lateral crushing of thin-walled tubes, the results of Xu et al. [3] on the impact of short tubes with a rigid target and the results of Shim et al. [30] on wave propagation in tubes. Validation is carried out in the form of a systematic refinement of the model, whereby the effect of grid resolution and material point count are investigated in relation to accuracy and runtime. Results indicate that grid spacing should be smaller than the thickness of the tube, whereas the number of material points across the thickness should not be less than 16. Overall, it is demonstrated that the MPM is a reliable and accurate method for the simulation of circular tubes subjected to various excitation conditions. With the main disadvantage of the MPM being its computational demand, the trade-off between the accuracy and runtime of the simulations is also examined. The findings of this research lay out the foundation to utilize the MPM for the simulation of more complex systems. These can include nested-tubes [31–34], auxetic cells [35] and auxetic panels [36,37].

The contents of this paper are organized such that: Section 1 presents a literature review on the current state of the field and Section 2 outlines the formulation of the MPM. Section 3 is dedicated to addressing common issues in relation to simulating thin-walled tubes and sets up the MPM model that will be used in the next three sections. Sections 4–6 delve into the numerical simulations and evaluate the performance of the model under different loading conditions. Section 4 validates the MPM for quasi-static conditions. This section also examines the convergence characteristics of the MPM in relation to lateral compression of thin-walled tubes. Building on these findings, Section 5 examines the case of a thin-walled tube impacting a rigid wall and Section 6 validates the MPM in relation to the speed of wave propagation within a thin-walled tube. Section 7 is the final and concluding section where the findings of this work are summarized.

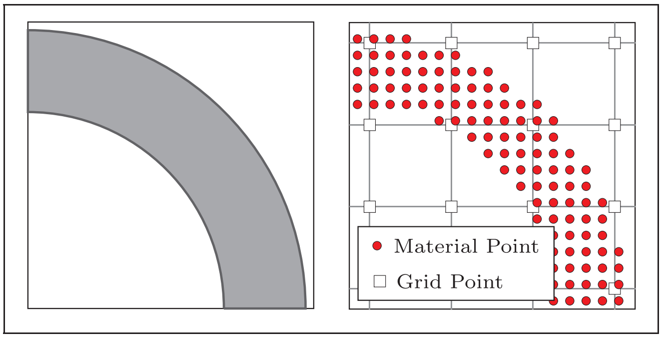

Fig. 1. MPM discretization of the physical bodies into distinct material points (also known as ‘particles’).

2. Numerical model

A general description of the material point method (MPM) and the constitutive material model is given in this section. The formulation of the MPM involves a number of material points (also referred to as particles), as well as a background grid consisting of an array of grid points. In what follows, subscripts ‘p’ and ‘i’ are respectively used for particles and grid points to make the necessary distinction between them.

2.1. Material point method

In the MPM, physical bodies are discretized into material points as shown in Fig. 1. Each material point holds the data required to represent the material properties and the kinematic state of a finite region of the body. These *Lagrangian* material points are laid out onto an *Eulerian* background grid, as illustrated in Fig. 1. The background grid itself is Cartesian with equal cell spacings in all directions. Having set up the framework, i.e. the material points and the background grid, the following steps are performed to update the state of the particles over each time-step. In the MPM literature, the following description is referred to as the ‘update stress last’ scheme. This process is schematically illustrated in Fig. 2.

Step 1: Projecting particle data to grid points

$$m_i = \sum_p \phi_{ip} m_p \tag{1}$$

$$\mathbb{v}_i = \frac{1}{m_i} \sum_p \phi_{ip} m_p \mathbb{v}_p \tag{2}$$

$$\mathbb{f}_i^{\text{int}} = -\sum_p \nabla\phi_{ip} \cdot \sigma_p dV \tag{3}$$

where m_p, $\mathbb{v}_p$ and σ_p denote the mass, velocity and Cauchy stress of particle ‘p’, respectively. As for grid points, m_i, $\mathbb{v}_i$ and $\mathbb{f}_i^{\text{int}}$ respectively denote mass, velocity and internal force at the grid point ‘i’. Moreover, ϕ_{ip} and $\nabla\phi_{ip}$ represent the value of the shape function and its gradient for grid point i at the location of particle p. It is important to note that since each material point carries a fixed amount of mass during the simulation, mass conservation is automatically satisfied in the system.

The use of Eqs. (1)–(3) means that material points (or particles) don't directly interact with each other. Their information is accumulated over the background grid where, in the next step, the equations of motion are integrated over time. As a result, this approach has the advantage of not requiring the costly step of a neighbor search, which is required in other meshfree methods such as the smoothed particle hydrodynamics (SPH) approach [38].