Mechanics Research Communications 70 (2015) 94–101

Contents lists available at ScienceDirect

Mechanics Research Communications

journal homepage: www.elsevier.com/locate/mechrescom

Smoothed particle hydrodynamics formulation for penetrating impacts on ballistic gelatine

L. Taddei*, A. Awoukeng Goumtcha, S. Roth

University of Bourgogne Franche-Comté, IRTES Laboratory, 90 010 Belfort, France

ARTICLE INFO

Article history:
Received 2 June 2015
Received in revised form
19 September 2015
Accepted 21 September 2015
Available online 30 September 2015

Keywords:
Penetrating ballistic impact
SPH
Biomechanics
Soft tissues
Ballistic gelatine

ABSTRACT

A particle method is applied to the investigation of impact biomechanics in the case of penetrating ballistic. A three dimensional model is proposed using the Smoothed Particle Hydrodynamics (SPH) method combined with Finite Elements (FE) method. The problem consists in the violent impact of a steel sphere on soft tissues, simulated by 20% ballistic gelatine (BG) material which is considered as a very interesting human tissue surrogate. Comparisons with experimental data are established to validate the proposed model. The results, in terms of penetrating curves, show very promising results. The use of particle methods appears to be an interesting way to model high speed loading, especially penetrating ballistic impact whose classical FE modelling can bring some important limitations in terms of mesh and element distortions.

1. Introduction

The investigation of penetrating ballistic impact can find some interest in three main frameworks: The military research to design weapons, projectiles and structural protections; Medical research, where information about the damages on soft tissues are needed in order to choose appropriate surgery; and forensics to get helpful information in the case of gunshot investigation. For these three fields, physical quantities are useful to estimate the characteristic and severity of a wound gunshot. Nevertheless, because of ethical principles, experimental tests on human body are not easy to conduct, thus alternatives are necessary. Moreover, in addition to the ethical principles, the observation of ballistic trauma like tissue disruptions (crush and stretch) is complicated to carry out on cadavers. Thus, to overcome these problems, human surrogates able to reproduce the density and the mechanical behaviour of soft tissues are required. Many works go in this way where gels and soaps are used [3,4,11,33], especially with the work of Fackler and Malinowski [15] who introduced the ballistic gelatine (BG). Though, it is advanced in Bresson et al. [10] that experimental tests are not sufficient to investigate how the gunshot occurred and to estimate the tissue damages. Then, to complete the recovering data, numerical simulations are needed.

Two common gelatine compositions, which are the 10 and 20 percent, both dedicated to ballistic cases, are largely studied and provide interesting mechanical behaviour close to real biological tissues. Comparison between gelatine and porcine or chicken meat had been established and concluded that the gelatine simulates close enough soft tissues [3,4,29,34]. In this way, approximation of the human tissue behaviour can be estimated. Hence, many studies have been performed in order to explore rigorously the material parameters and mathematical models necessary for numerical simulations. Studies have shown that the BG is strain rate dependent, as the human tissues are, and is a better simulant than other materials [3,4]. A hyper-visco-elastic behaviour is also observed by the use of specific high compressive tests. According to this, hyper-elastic model have been proposed and give correct estimations for compressive solicitations [12–14]. Moreover, hydrodynamic aspect of the gelatine has been investigated leading to consider this material as a fluid for specific loading [3,29,31]. This last kind of investigation allows modelling the gelatine in shock configuration, and especially in penetrating impact cases.

Since several years, numerical methods have become very interesting in term of efficiency. The number of applications and the background about these methods have greatly increased and provide strong tools, such as the Finite Elements (FE) method or the Computational Fluid Dynamics (CFD). Nevertheless, these classical methods suffer from difficulties like moving boundaries for Finite Differences or CFD methods and large deformations in structural simulations. In this last case, additional specific techniques

* Corresponding author. Tel.: +33 03 84 58 20 20; fax: +33 03 84 58 32 86.
E-mail address: lorenzo.taddei@utbm.fr (L. Taddei).

http://dx.doi.org/10.1016/j.mechrescom.2015.09.010

could allow dealing with large strains but introduce others issues. Hence, alternatives can be interesting like the meshfree methods and especially the Smoothed Particle Hydrodynamics (SPH), which is a purely Lagrangian method with no grid needed. Firstly introduced in the astrophysical field by Lucy [27], Gingold and Monaghan [17], it has become very popular in fluid mechanics for its capability to deal with extreme deformations while a Lagrangian description is considered. This last method is available with the commercial explicit code Radioss which is a leading structural analysis solver for highly non-linear problems under dynamic loadings. Every computation will be conducted with this solver.

Libersky, Petschek and Randles are all pioneers in the use of SPH method in the context of High Velocity Impact (HVI) involving solid materials and have proposed basic foundations in the case of high strains [22–24,30]. For instance, in Libersky and Petschek [22] the very base of the modelling with the SPH method of materials with strength is presented. In addition, at the same period an interesting work was proposed by Johnson et al. [21] to treat similar problems but with the combination of Finite Elements with SPH particles. The idea was to introduce a particle in the place of a Lagrangian element (i.e. refereed to Finite Element) when this one was too distorted. Nevertheless, this method is not largely used and a combination between two parts with the two elements kind defined at the initial state is preferred and will be used for this model.

Finally, this paper investigates 20% BG response under penetrating ballistic impact, analysing the mechanical behaviour of this human surrogate impacted by spherical steel projectiles. A previous work has been conducted in [5] by the use of a full Finite Elements model. Here is proposed another formulation with the SPH method for its ability to treat efficiently high strains. The formulation used is presented in Section 2. However, this method based on the Monte-Carlos method is time consuming as much as the number of particles is important. Hence, a work is established in Section 3 to propose a reduced model combining SPH and FE elements adapted to HVI with important penetration depths. From this model, in Section 4 two investigations are conducted: the influence of the artificial viscosity is observed to point out that this numerical aspect stabilises the dynamic response but modifies the penetration behaviour; to determine a good contact condition adapted to HVI, simulations on the discretisation length are conducted. Finally, as it had been established in [5], the ten ballistic configurations from the experimental support [32] are simulated to validate the model. The results in term of penetration depth curves and projectile velocity evolution are presented in Section 4. The comparison between experimental and numerical results and the efficiency of the reduced model proposed are discussed in Section 5 and conclusions are given in Section 6.

2. Smoothed Particle Hydrodynamics Method

In this section are presented the basic principles and equations used by the explicit solver to treat SPH elements. Vectors and matrix are written in bold type.

2.1. Integral representation

Let f be a smooth function defined in the domain $\Omega \subset \mathbb{R}^3$ where $\boldsymbol{r}$ describes the position vector. Using the convolution of f with the Dirac delta function δ, it can be written the next equality:

$$\forall \boldsymbol{r} \in \Omega, \quad f(\boldsymbol{r}) = \left(f * \delta\right)(\boldsymbol{r}) \tag{1}$$

Then, as the SPH method can be understood in the framework of interpolation theory, a function noted ζ can be introduced in order to interpolate the Dirac delta function. This approximation is called the integral representation denoted by the $\langle\rangle$ brackets and given by the Eq. (2):

$$\langle f(\boldsymbol{r})\rangle \doteq \int_{\Omega} f(\boldsymbol{\tau})\,\zeta(\|\boldsymbol{r}-\boldsymbol{\tau}\|)\,\mathrm{d}\boldsymbol{\tau} \tag{2}$$

where the ζ function, from $\mathbb{R}^3$ to $\mathbb{R}_+$, is often called the window function. $\|\boldsymbol{r}-\boldsymbol{\tau}\|$ denotes the L^2 norm of the difference between these two vectors on Ω and the particular point $\zeta(0)$ is called the kernel. The ζ function has to satisfied the next conditions:

(i) Has to be normalized,

$$\forall \boldsymbol{r} \in \Omega, \quad \int_{\Omega} \zeta(\|\boldsymbol{r}-\boldsymbol{\tau}\|)\,\mathrm{d}\boldsymbol{\tau} = 1$$

(ii) Has to have a compact support,

$$\mathrm{supp}(\zeta) = \left\{d \in \Omega | \, \zeta(d) \neq 0\right\}$$

(iii) Has to be symmetric,

$$\forall d \in L^2\left(\Omega\right), \zeta(d) = \zeta(-d)$$

(iv) Has to decrease with the distance from the kernel,

$$\forall (d_1, d_2) \in L^2\left(\Omega\right) | \, d_2 > d_1, \zeta(d_1) > \zeta(d_2)$$

According to the previous properties of the ζ function it comes by simple developments and hypothesis from Eq. (2) the first derivative approximation:

$$\langle f'(\boldsymbol{r})\rangle = -\int_{\Omega} f(\boldsymbol{\tau})\,\frac{\partial}{\partial \boldsymbol{\tau}}\zeta(\|\boldsymbol{r}-\boldsymbol{\tau}\|)\,\mathrm{d}\boldsymbol{\tau} \tag{3}$$

2.2. Weighted function

The ζ function can take several forms but the most obvious and simplest choice is to take a Gaussian function where the shape can be manipulated by a parameter h called the smoothing length. Nevertheless, the Gaussian suffers from problems like the absence of compact support. Thus, other forms are proposed where the most popular is the polynomial kernel function, which is constructed with piecewise B-Splines. In classical SPH literature the ζ function is called the Kernel function and is noted W.

$$W(\|\boldsymbol{r}-\boldsymbol{\tau}\|, h) \doteq \zeta(\|\boldsymbol{r}-\boldsymbol{\tau}\|) \tag{4}$$

with the following condition:

$$\lim_{h \to 0} W(\|\boldsymbol{r}-\boldsymbol{\tau}\|, h) = \delta(\|\boldsymbol{r}-\boldsymbol{\tau}\|) \tag{5}$$

The form taken in this work is the most frequently used expression for the Kernel function which is the piecewise cubic polynomial form. This one is given by:

$$W(q, h) = \frac{\sigma}{h^{\nu}} \begin{cases} 1 - \dfrac{3}{2}q^2 + \dfrac{3}{4}q^3 & \text{if } 0 \le q \le 1 \\ \dfrac{1}{4}(2-q)^3 & \text{if } 1 \le q \le 2 \\ 0 & \text{elsewhere} \end{cases} \tag{6}$$

where σ is a normalization coefficient and ν the dimensional order. In this analysis, h is taken as one time the discretisation and as it is a 3D model, σ is equal to $1/\pi$ and ν to 3. The relative distance