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Ballistic resistance of the carbon nanotube fibres reinforced composites – Numerical study

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ABSTRACT

The numerical investigations were carried out to determine the ballistic resistance of the carbon nanotube (CNT) fibres reinforced composites. In this paper, the fundamental studies of the reinforcement characteristics are presented. It includes the single fibre mechanical and geometric properties as well as fibres distribution and volume (mass) concentration. The continuum matrix material includes a certain amount of fibres made of CNTs. An impact of the projectile with the sharp nose on the metal matrix composite plate was analysed. The computer simulations were performed with the finite element method implemented in LS-DYNA code. The plane formulation allows analysing extremely dense meshes. The obtained results presented the significant role of the carbon nanotube fibres.

1. Introduction

The paper describes researching on the modern, composite material, which can be used in the amours of tanks, combat vehicles, and aeroplanes. The carbon nanotube (CNT) fibres were applied as a reinforcement of the aluminium alloy matrix. An advanced armour systems must satisfy high ballistic resistance levels according to STANAG 4569 norm remaining lightweight and thin as well. Add–on panels are expected. It means that such panel can be treated as non-integral part of vehicle, which can be exchanged easily if it was destroyed or damaged. The appropriate balance between the total mass of panels and protection level must be accomplished to conserve the vehicle mobility. The investigations are aimed at application of the modern materials including composites and structures e.g. multilayer systems. It is possible that typical materials as RHA steel, ceramics, Kevlar could be replaced with CNT fibres reinforced composites.

In the numerical model of a carbon nanotube fibres penetration problem reinforced composites were considered. Generally, the ballistic resistance was studied with respect to fraction of CNT fibres in the material composition and their mechanical properties. The matrix material was assumed as 7017 aluminium alloy. The main task rests on comparing of the numerical results of the penetration process for some selected cases. The quantitative assessment was based on the calculated value of the kinetic energy versus time – Ek(t) of the not destroyed part of the projectile. Two-dimensional numerical models for selected cases were developed. An explicit time integration algorithm was used for the solution of the problem equations.

The initial stage of the problem is presented in the Fig. 1. Two-dimensional models of the projectile and target were developed with strain rate and temperature dependent material constitutive relations. A perpendicular impact of the 12.7 × 108 mm B32 armour-piercing projectile on a 80 mm thick block of the CNT fibres reinforced 7017 aluminium alloy was modelled. The target block without any reinforcement was accepted as a reference case. The study considered plain strain, as well as axisymmetrical formulations.

The projectile model was reduced to the steel core. This part of the projectile plays a crucial role in the penetration process. Geometry of the projectile's core: length equals 47.3 mm and diameter equals 10.8 mm. The target is a square 200 mm wide and its thickness is 80 mm.

2. Carbon nanotubes characteristics

The structure of carbon nanotubes is similar to fullerenes, but they have a cylindrical, not spherical shape [1,2], usually capped with fullerene-like hemispheres. Their name well describes their shape and size – the order of magnitude of nanotubes diameters is about several nanometres, while their length may be millions of times larger, Fig. 2. The unique mechanical and electrical properties of Single-Wall (SWCNT) and Multi-Wall (MWCNT) nanotubes are a rich source for physical research and may lead to new applications in material engineering. Their resistance to

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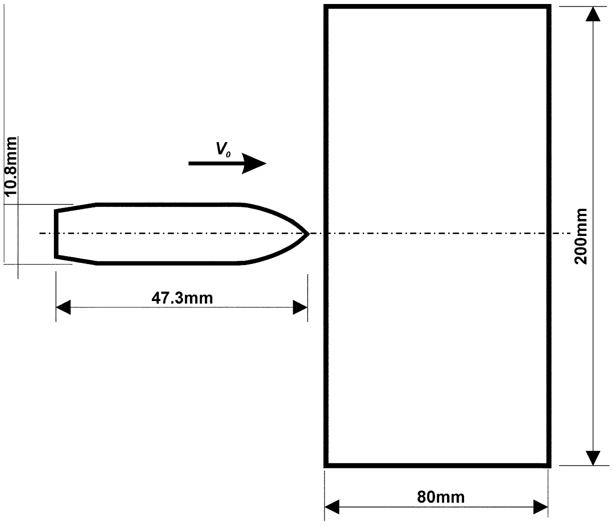

Fig. 1. Dimensions of the 12.7 × 108 mm B32 projectile's hard steel core.

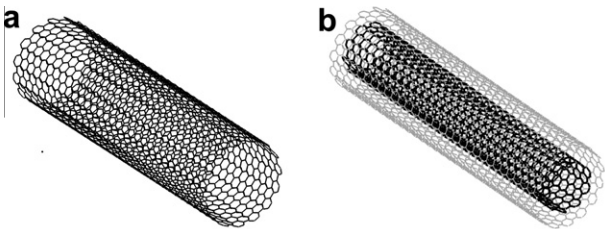

Fig. 2. View of the CNTs. Single-Wall CNT (a) and Multi-Wall CNT (b).

stretching measured with Young modulus reaches tera pascals *[Tera Pascals]*. It makes nanotubes the strongest known fibre requiring 600 J/g energy to be broken. To compare, bulletproof Kevlar requires 27–33 J/g while a spider's web thread requires 150 J/g. Table 1 shows typical values of the main CNT parameters [1,3–6].

All these properties make CNTs promising candidates as reinforcement fillers for developing nanocomposites. These superior and unique properties make CNTs very attractive for many structural applications such as an aerospace structure (lightweight, low density), body and vehicle armours (extremely high tensile strength, high modulus, low density).

Young modulus of nanotubes is the highest of all known Young modulus in material engineering. The problem with nanotubes is that their size allows using their properties only in nanotechnology. The solution is creating fibres consisting of billions of nanotubes that would maintain mechanical properties of single nanotubes [3,5,7–9]. The obtained nanotube fibre is very elastic, but its Young modulus is much lower than that of a single tube – equalling 9–15 GPa. Nevertheless, it is still impressive. Table 2 contains the primary parameters of CNT fibres. Their strength is measured in N/tex, where tex is a specific type of unit, used in the textile industry. It is the linear mass density in g/km.

Table 1
Carbon nanotubes properties [1,3–6].

Designation	Symbol	Value range	Unit
Tensile strength	TS	30–200 [3,1,4]	GPa
Elastic modulus	*E*	1000–1800 [1,3,4]	GPa
Cross-section area	CSA	0.79–1256	nm^2
Length	*L*	1–1000 [4,5]	Mm
Diameter	*D*	1–40 [4,1]	Nm
Bulk density	BD	1.74–2.1 [6]	g/cm^3
Strain at failure	SF	10–30 [4]	%

Table 2
Carbon nanotube fibre properties [3,5,7–9].

Designation	Symbol	Value range	Unit
Specific tensile strength	STS	1–10 [7,8,5]	N/tex
Linear mass density	LMD	0.03–0.135 [8]	tex
Cross-section area	CSA	12.56–314	μm^2
Length	*L*	0.3–200 [3,9]	mm
Diameter	*D*	4–20 [3,9]	μm
Bulk density	BD	0.4–1.1 [7–9]	g/cm^3
Strain at failure	SF	1.8–8 [3,5]	%

3. Main idea

This work presents fundamental studies of the reinforcement characteristics. It includes the single fibre mechanical and geometric properties as well as fibres distribution and volume (mass) concentration. The reinforcement concept is illustrated in the Fig. 3. The continuum matrix material includes a certain amount of fibres made of CNTs. The fibres can be spread randomly or in assumed pattern across the matrix volume. Both ends of each fibre should realize displacement constraints thorough the connection with the matrix material. This effect is known as a functionalization and is observed in case of elastomer matrix composites. The main idea is based on relatively short CNT fibres randomly spread across the matrix material volume. The literature data [1,2,4] prove that carbon nanotube fibres can significantly improve the essential strength parameters of aluminium [1] or nickel [4] alloys. For example, in case of 2024Al matrix composite reinforced with 1 wt.% CNT a 16% yield growth and 23% tensile strength were observed [1]. To obtain better results, optimization methods can be used which match adequate parameters, e.g. concentration, geometry, strength (see Figs. 4 and 6).

Two-dimensional plane formulation was applied to develop projectile and target models but with the strain rate and temperature dependent material constitutive relations. Reinforcement was considered as 1D cable elements built in the matrix material. The classical mechanics is still applicable in this model scale as showed in [6] where the molecular dynamics were applied in order to analyse the CNT formation. The plane 2D formulation enables the analysis of extremely dense meshes.

4. Numerical model

For the purpose of the 7017 aluminium alloy reinforced nanotube fibres study, several models of targets were built, Table 3. They include the strength and fraction of the CNT fibres parametric study.

A numerical model consists of two parts: aluminium target reinforced CNT fibres and projectile's steel core. Two reference cases were selected to help with the analysis result. The first one, called CNT0-plain, is a 2D plane model and the target's material is an aluminium alloy without CNT fibres. The second one, called CNT0-axsym, is a model with axial symmetry, because it is closer to the projectile's behaviour in a real problem. The target in this case is also a pure aluminium alloy. Generally, the target is a block, the thickness of which equals 80 mm and the length of the edge equals 200 mm. All analysed cases were built with the application of a four-node quad element topology. The typical node to node distance was equal to about 0.25 mm in all numerical models of targets and projectiles. The total number of nodes per single case