Composite Structures 184 (2018) 484–496

Contents lists available at ScienceDirect

Composite Structures

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

Ballistic performance study on the composite structures of multi-layered targets subjected to high velocity impact by copper EFP

Jianfeng Liu[a], Yuan Long[a], Chong Ji[a,b,*], Qiang Liu[a], Mingshou Zhong[a], Song Ge[a]

[a] College of Field Engineering, PLA Army Engineering University, Nanjing, Jiangsu 210007, China
[b] State key Laboratory of Explosion Science and Technology, Beijing Institute of technology, Beijing 100081, China

ARTICLE INFO

Keywords:
Ballistic performance
Composite structures
Layer order
Air gap
Explosively formed projectile

ABSTRACT

Investigation ballistic performance of metallic target against projectile impact is of practical interests in the design of protective composite structures like armors. Subjected to high velocity impact of explosively formed projectile (EFP) which is a kind of easy-deformable and soft projectile, the ballistic performance of monolithic and composite structures including three-layered in-contact and spaced mild steel targets has been studied. Terminal effects of multi-layered targets are summarized to assess the pros and cons of composite structures from a macro perspective. Correspondingly, microstructure evolution of the crater and morphology features of fracture surfaces are analyzed to reveal failure mechanisms of sub-structures. The results show that the monolithic target presents less effective than in-contact or spacing multi-layered targets as the dominant response of multi-layered targets are local plastic deformation and bulging which involved bending and stretching behavior. The multi-layered targets with the thinner sub-structures in front and thicker sub-structures at back are superior to resist the penetration of the copper EFP. Moreover, the air gap increases the ballistic resistance of three-layered targets especially as the width of air gap is larger than one quarter length of projectile. The results will not only help to reveal different penetration mechanisms by which structures respond to dynamic extremes but also help to improve the ballistic resistance of armors.

1. Introduction

As a chemical energy projectile which is one of the most common weapon used to defeat the armor [1–3], EFP (Explosively formed projectile) will experience essentially plastic strains up to 300%, at strain rates of the order of $10^4\ s^{-1}$ [4,5] during the formation and penetration process. Actually, the main body of EFP will be fragmented or eroded during the penetration process of semi-infinite or infinite targets (with thickness orders of magnitude greater than the projectile dimensions) at high velocity impact, only leaving some fractional mass in the crater wall and bottom [6,7]. The formation and penetration process of EFP is schematically shown in Fig. 1.

The target, as the key component in the projectile-target system, attracts more and more attentions for many researchers to improve the ballistic resistance performance [8,9]. Setting multi-layered composite structures [10,11] to enhance the ballistic resistance of targets is also the most common method in recent years but the protection effectiveness of multi-layered structures remains a subject of debate [12–26]. Note that in those studies various shape of projectiles and different target structures are considered. On the basis of an extensive experimental programs related to perforations of single and three-layered metallic targets against hemispherical-nosed cylindrical projectiles impact, Alavi Nia and Hoseini [12] indicate that the monolithic target has greater ballistic limit velocities than multi-layered targets. An opposite conclusion is obtained by Radin [13] et al. and Holmen et al. [14]. They perform normal impact tests of blunt and conical-nosed projectiles on the multi-layered plates and the ballistic performance of monolithic plate are always higher than those of the multi-layered targets for both types of projectiles. As relation to the layer order, Almohandes et al. [15] find that the ballistic resistance of layered targets increases as the thickness of the back plate increases according to experimental investigations related to composite structures of varies configurations impacted by standard 7.62 mm bullet projectiles. In Deng's [16] experimental study on the multi-layered plates against hemispherical-nosed projectiles impact, the multi-layered targets of a thicker front plate and a thinner back plate are superior to the multi-layered targets with a thinner front plate and a thicker back plate. Ben-Dor et al. [17] present an analytical model for the ballistic resistance of multi-layered ductile targets. They find that ballistic resistance is independent of the air gap width between the layers and on the sequence

* Corresponding author at: College of Field Engineering, PLA Army Engineering University, Nanjing, Jiangsu 210007, China.
E-mail address: blastingcaptain@163.com (C. Ji).

http://dx.doi.org/10.1016/j.compstruct.2017.09.072
Received 7 July 2017; Received in revised form 19 September 2017; Accepted 26 September 2017
Available online 28 September 2017
0263-8223/

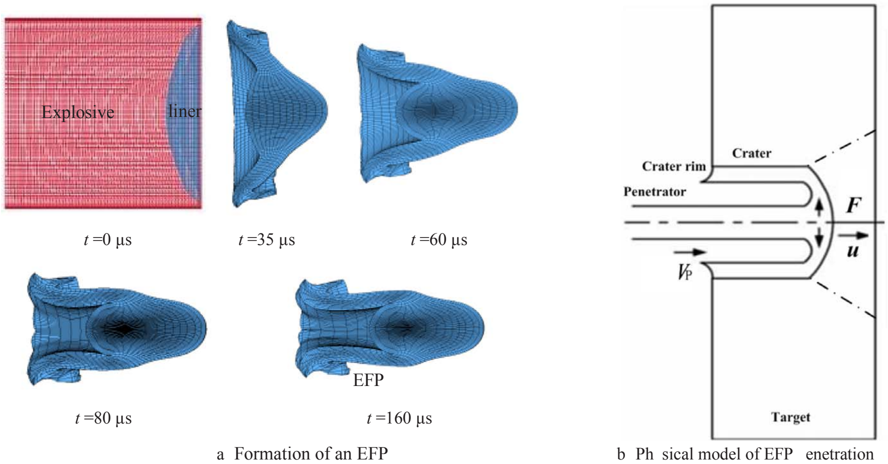

Fig. 1. The formation and penetration process of EFP [7].

of the plates in the target when impacted by conical projectiles. The obtained results are in good agreement with experimental data from Almohandes et al. [14] and Deng et al. [15] also find the air gap size has slight influence on the ballistic resistance. However, Alavi et al. [12], Radin et al. [13] and Marom et al. [18] consider the ballistic resistance of in-contact multi-layered targets is greater than those of spaced multi-layered targets. Considering different experimental conditions, researchers often derive conclusions from a certain kind shape of projectile against the particular structural targets [19–21]. Making comparisons or referencing the results from different investigations are also difficult due to the existence of various variables.

Subjected to high velocity impact by EFP, the dynamic response and penetration mechanism of the target are obviously different from the traditional kinetic energy projectile [8,10,22–24]. In recent years, many researchers have studied the ballistic performance of monolithic targets subjected to high velocity impact of EFP. Li et al. [27] summarize the mechanism of EFP impacting 30CrMnMoRE steel target through ANSYS/LS-DYNA software and experimental methods and provide practical suggestions to improve ballistic performance of armors. In another EFP impact experiment performed by Wu et al. [1], a #45 steel (the carbon content is about 0.45%) [28]target of finite thickness is subjected to plug failure mode according to morphological analysis of fracture surfaces and the recycled fallen pieces. Ji et al. [29] even study the behaviors of multi-layered Q235 steel targets with air gaps subjected to normal and oblique impact of EFP simulants. The residual velocities of EFP simulants decrease significantly with the increase of obliquity angle, and to some extent, a larger impact obliquity angle may result in the ricochet of EFP simulants. However, reports on high velocity impact crater in targets especially the composite structures penetrated by EFP are limited and inconsistent. The dynamic response process of target is still far from understand completely and there are still many basic issues that should to be investigated further. Besides, investigation of the dynamic response of different multi-layered targets subjected to high velocity impact by EFP will not only help to reveal different penetration mechanisms by which structures respond to dynamic extremes, including high stresses and high strain rates, but also help to improve the ballistic resistance of armors.

The rest of the paper is organized as follows. Section 2 describes the numerical modeling methodology and failure mechanism of monolithic target subjected to high velocity impact by copper EFP. Section 3 and Section 4 detail the influence of layer order and air gap on the ballistic performance of multi-layered targets penetrated by EFP, respectively. The last section draws the main conclusions of this work.

2. Numerical modeling and failure mechanism of steel target penetrated by copper EFP

2.1. Experimental setup

In order to study the influence of layer order and air gap width on the ballistic performance of multi-layered targets subjected to high velocity impact by EFP, a kind of EFP warhead is designed with copper liner, as shown in Fig.2.

The complete EFP warhead consists of a metallic liner, high-energy explosive (HE), case, a slotted ring or sleeve and a detonator. The height of charge is 60 mm and the diameter of charge is 70 mm. The

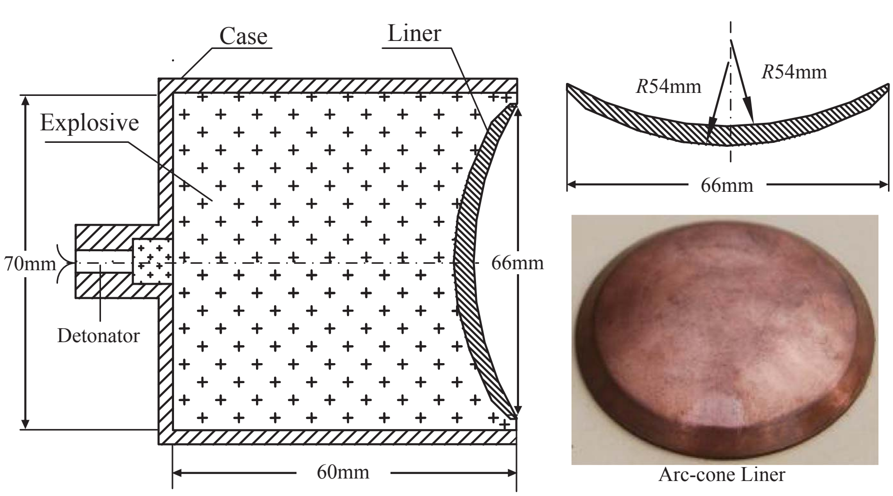

Fig. 2. Structure of the EFP warhead and the liner.