Aerospace Science and Technology 39 (2014) 153–168

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Separation characteristics study of ridge-cut explosive bolts

Juho Lee [a], Jae-Hung Han [a,*], YeungJo Lee [b], Hyoungjin Lee [c]

[a] *Department of Aerospace Engineering, KAIST, 335 Gwahangno, Yuseong, Daejeon, 305-701, Republic of Korea*
[b] *Advanced Propulsion Technology Center, The 4th R&D Institute, Agency for Defense Development, 488 Bugyuseong daero, Yuseong, Daejeon, 305-152, Republic of Korea*
[c] *PGM R&D Lab., LIG NEX1 Co. Ltd., 702 Sampyeong, Bundang, Seongnam, Gyeonggi, 463-400, Republic of Korea*

ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 27 August 2014
Accepted 30 August 2014
Available online 16 September 2014

Keywords:
Explosive bolts
Pyrotechnics
Separation characteristics
Euler–Lagrange interactions
Hydrocodes
AUTODYN

ABSTRACT

Explosive bolts are one type of reliable and efficient pyrotechnic release devices used for many applications. Although numerous explosive bolts have been designed and utilized, most design processes rely on experience based on repetitive experiments. In order to provide a better understanding of the separation behavior of explosive bolts, separation behavior analysis environments for the ridge-cut explosive bolts are established. Ridge-cut explosive bolts, which are separated by ridge-cut mechanism or spallation, are analyzed using AUTODYN. From the behavior analysis of explosive bolts whose design was based on the author's prior experience, the numerical analysis method is verified, including appropriate failure criteria. Utilizing the proposed methodology, the separation characteristics of ridge-cut explosive bolts according to confinement conditions, and especially the gap distance between the bolt body and the fixture, are studied. A degradation in separation reliability due to tight gap distance is observed in separation experiments. This separation phenomenon is specifically clarified by the separation behavior analysis. Based on the numerical study of separation characteristics, some design improvements considering manufacturing tolerance are proposed here.

1. Introduction

Explosive bolts are one of the reliable and efficient pyrotechnic release devices used in applications such as launcher operation, stage separation, rocket sled release, thrust termination and the release of external tanks [4,7]. In general, an explosive bolt consists of a bolt with a cavity filled with an explosive charge or a removable cartridge. Due to their simplicity, explosive bolts have high reliability and are robust against environmental disturbances compared with other types of release devices. Various designs of explosive bolts exist and can be categorized into either high-explosive or pressure types. To break the bolts, high-explosive type explosive bolts utilize a shock wave generated by detonation, while pressure type explosive bolts utilize high pressure generated by an explosion in the cavity. It is well known that the high-explosive type bolt has a higher reliability, and ridge-cut explosive bolts belong to that type. Ridge-cut explosive bolts have other advantages: they produce minimal fragments, little swelling and a clean break [15]. They also minimize so-called banana peel effects which severely degrade separation reliability.

Although numerous explosive bolts have been designed and utilized over the last 50 years, only a few works have been published on them; only some textbooks [7,10,26] and technical reports [4] are available. For the ridge-cut explosive bolts, a simple design theory is well established [15,19,20]. However, the theory does not provide full understanding of the complex separation phenomena and characteristics. Therefore, most explosive bolt design processes rely on experience or knowledge gained from expensive explosion experiments. For example, the appropriate amount of explosives has been determined from repetitive explosion tests. The use of a minimum weight of explosives is strongly preferred as long as reliable separation is guaranteed. If an excessive weight of explosives is used, a large number of fragments or shrapnel will be created, which degrades reliability. Furthermore, pyrotechnic shock generated by excessive explosives can cause malfunctions in adjacent electric components [13].

Recent advances in multi-disciplinary numerical analysis enable us to design separation bolts with less experiments; extensive numerical analysis can be conducted to evaluate the separation success rate without repetitive experiments, and to improve reliability of separation by design modification. However, it is very difficult to find literature that addresses numerical analysis methodologies or results related to the separation behavior of explosive bolts; some relevant previous works are reported in the following.

---

[*] Corresponding author. Tel.: +82 42 350 3723; fax: +82 42 350 3710.
E-mail address: jaehunghan@kaist.ac.kr (J.-H. Han).

http://dx.doi.org/10.1016/j.ast.2014.08.016

Katayama et al. [17,16,18] performed a numerical study on a conical shaped charge including jet formation and penetration, and a numerical simulation of the local damage and dynamic response of structures composed of reinforced concrete and geological materials subjected to loading by high explosives. Balden and Nurick [2] performed numerical analysis on the post-failure motion of steel plates subjected to blast loading and compared their results with previously conducted experiments [23,28]. Bonorchis and Nurick [5,6] conducted several localized blast loading experiments and developed a localized blast loading model for plates by comparing experiments and numerical simulations focused on boundary conditions and welded stiffener. Yuen and Nurick [29] performed numerical simulations of the crushing of square tubes having blast-induced imperfections, to study their characteristics and compare them with experiments [30]. Ambrosini and Luccioni [1] numerically studied craters formed by blast loads on the soil surface. The numerical model and the analysis procedure were validated by the diameters of the experimental craters. Coghe et al. [8] performed penetration experiments and numerical analysis of ballistics for diverse geometries to investigate the origins of the bodywork effect (K-effect). The bodywork effect refers to the manner in which a high-hardness steel armor plate inside the bodywork of a vehicle degrades the overall ballistic resistance. Banadaki and Mohanty [3] found the parameters of the Johnson–Holmquist model for Barre granite by comparing experimental and numerical blast-induced fracture patterns. Most previous studies verified their numerical analysis methods by comparing the final shapes of the deformation, fracture and cracks after the blast.

The aforementioned studies involving the numerical analysis of blast loading on structures were conducted using AUTODYN, which is an explicit analysis code for modeling the nonlinear dynamics of solids, fluids, and their interaction. Though AUTODYN and similar codes are commonly called hydrocodes, these codes can handle complex material models for impact, penetration and blast problems. Several solvers are available in AUTODYN: 1) finite element solvers for computational structural dynamics, 2) finite volume solvers for transient computational fluid dynamics (CFD), 3) mesh-free particle (smooth particle hydrodynamics, SPH) solvers for high velocities, large deformation, fragmentation and 4) their couplings for multi-physics problems. To analyze explosive bolts numerically, consideration of fluid–structure interactions with complex material models involving the bolt body and high explosives are crucial. Thus, the separation behavior of explosive bolts due to blast loading on structures can be numerically analyzed in AUTODYN, which can handle them both. Furthermore, material modeling of the bolt body for high strain rate including failure criteria requires the utmost circumspection.

In this study, separation behavior analysis environments for ridge-cut explosive bolts were established. The numerical analysis of a ridge-cut explosive bolt that was designed based on the author's prior experience clearly depicts the ridge-cut mechanism, including shock propagation and reflection, and the superposition of the release waves. Utilizing the developed numerical analysis framework, the separation characteristics of ridge-cut explosive bolts with a confinement condition were studied and some design improvements to prevent the degradation of separation reliability caused by manufacturing tolerance are proposed here.

2. Ridge-cut mechanism

There are several explosive bolt types, each with their own separation mechanisms. Among them, the separation phenomenon of ridge-cut explosive bolts cannot be explained in terms of classical fracture mechanics, but instead are explainable by the ridge-cut mechanism (Fig. 1). The ridge-cut mechanism explains the fracture or separation behavior that occurs when high explosives are detonated on one side of a metal structure which has a ridge on the other side. Due to the detonation, shock waves are generated and are emitted into the metal structure. As the shock waves encounter a free surface of metal, they reflect back as release waves. Superposition or collision of release waves at a location where the release waves meet causes solid particles to move in opposite directions. These particles' movements produce high tensile stress and eventually cause failure.

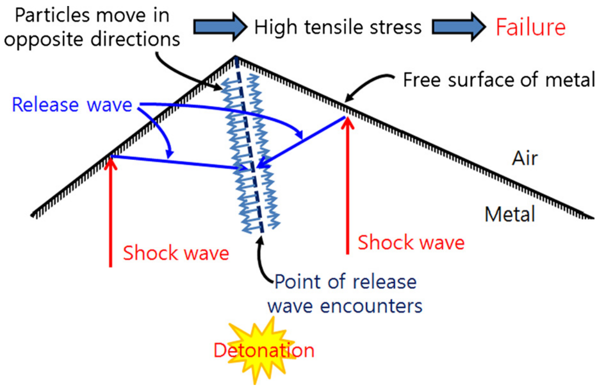

Fig. 1. Schematic of ridge-cut mechanism.

The ridge-cut mechanism is also widely known as spallation in the field of dynamic behavior of materials. Spallation is a dynamic material failure that occurs due to tensile stresses generated by the interaction of two release waves [22]. Hopkinson [11,12] studied spallation for the first time and found that the brittleness of steel increased under dynamic conditions. Rinehart [24,25] reported that there was a material-dependent critical value of normal tensile stress (σ_c) for spallation.

3. Ridge-cut explosive bolts

In this study, ridge-cut explosive bolts, which were designed based on the author's previous experience [19,20] shown in Fig. 2(a), were utilized as the reference ridge-cut explosive bolts. The bolt body and the fixtures of the ridge-cut explosive bolts are made of 17-4PH stainless steel. A removable initiator is utilized to initiate the priming material (LA) and to detonate the high explosives (PETN, RDX). From separation experiments using separation experiment equipment (Fig. 3), the reliability of separation of the ridge-cut explosive bolts was fully verified. The separation plane which was observed from experiments after separation (Fig. 2(b)) is depicted in Fig. 4. The observed separation plane was coincident to the one predicted using a ridge-cut mechanism.

4. Separation behavior analysis methodology

The separation behavior produced by the ridge-cut mechanism of the explosive bolts was analyzed using AUTODYN, which can handle complex material models and Euler–Lagrange interactions. To facilitate geometry modeling of the complex shape ridge-cut explosive bolts, ANSYS Workbench Explicit Dynamics was utilized prior to AUTODYN. Analysis of the ridge-cut explosive bolts was performed in 2-D axisymmetric to reduce computational costs. A brief review of the analysis procedure and material modeling are explained in the following sections.

4.1. Analysis procedure

In this study, ANSYS Workbench Explicit Dynamics were utilized for geometric modeling and meshing. Structural boundary condition, connections and body interaction were also defined. Meshing of the bolt structure was performed and the size of