

# Specimen size effect of explosive sensitivity under low velocity impact

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**Abstract.** Low velocity impact may ignite the solid high explosives and cause undesired explosion incidents. The safety of high explosives under low velocity impact is one of the most important issues in handling, manufacture, storage, and transportation procedures. Various evaluation tests have been developed for low velocity impact scenarios, including, but not limited to the drop hammer test, the Susan test, the Spigot test, and the Steven test, with a charge mass varying from tens of milligrams to several kilograms. The effects of specimen size on explosive sensitivity were found in some impact tests such as drop hammer test and Steven tests, including the threshold velocity/height and reaction violence. To analyse the specimen size effects on explosive sensitivity under low velocity impacts, we collected the impact sensitivity data of several PBX explosives in the drop hammer test, the Steven test, the Susan test and the Spigot test. The effective volume of explosive charge and the critical specific mechanical energy were introduced to investigate the size-effect on the explosive reaction thresholds. The effective volumes of explosive charge in Steven test and Spigot test were obtained by numerical simulation, due to the deformation localization of the impact loading. The critical specific mechanical energy is closely related to the effective volume of explosive charge. The results show that, with the increase of effective volume, the critical mechanical energy needed for explosive ignition decreases and tends to reach a constant value. The mechanisms of size effects on explosive sensitivity are also discussed.

## 1. Introduction

The concern about the safety of high explosives is increasing with safety issues playing a dominant role in explosive science and technology. It has already been demonstrated that low velocity impact can ignite many solid high explosives and then evolve into dangerous events. The sensitivity of high explosives under low velocity impact is one of the most important problems during handling, manufacture, storage, and transportation. Several evaluation tests have been developed for specific accident scenarios, including, but not limited to the modified drop weight impact test [1-2], Susan test [3-4], Steven test [5-11] and Spigot test [12]. The effects of specimen size on explosive sensitivity were found in some impact tests, such as drop hammer impact test and Steven tests [13], in which specimen size was found to largely influence the threshold velocity/height and reaction violence of explosives.

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In this paper, to further analyse the size effects on explosive sensitivity under low velocity impacts, the impact sensitivity data were collected for several PBX explosives: PBX-1, PBX 9501, PBX 9404, LX-04, and LX-14. Several low velocity impact experiments were considered, including the modified drop weight impact test, the Steven test, the Susan test and the Spigot test. The effective volume of explosive charge and the threshold specific mechanical energy were introduced to investigate the size-effect on the PBX explosive ignition thresholds under low velocity impact.

## 2. Impact tests of explosive sensitivity

The modified drop weight test setup [2] consists of a drop hammer, an embedded explosive pill, a Teflon confinement ring, an impact anvil, and a steel target plate. The drop hammer is hung from a certain height, and then is released to impact the steel target plate on the ground vertically, as shown in figure 1(a). The Teflon ring was used to keep the explosive material from flowing into the gap at the joints. The reaction threshold drop height was used to evaluate the sensitivity of explosive.

The Steven test, introduced by Chidester and co-workers, has been firstly performed at Lawrence Livermore National Laboratory as well as a modified version at Los Alamos National Laboratory. Figure 1(b) shows the basic Steven test geometry [13] and the schematic diagram of different projectiles. The test involves a target with high explosive charge which is impacted at increasingly higher velocities with a steel projectile until a reaction occurs. The target consists of a high explosive charge confined by a PTFE ring (or a radial gap between explosive and holder), a thick steel cover plate on the impact face and a steel holder. The reaction threshold velocity was used to evaluate the sensitivity of explosive in Steven test.

The setup of Susan test [4] is shown in figure 1(c). The projectile used in Susan test carries an explosive charge about  $\phi 50 \text{ mm} \times 100 \text{ mm}$  and its total weight is about 5.44 kg. The projectile is designed to simulate the situation of collapse, in a manner of squeeze and nip on explosive between metal surfaces in the process. The projectile is accelerated by an air-gun or propellant-gun to hit a massive steel target with a certain velocity. The flying velocity of the projectile is measured by a timekeeping system to evaluate the sensitivity of the explosive charge.

The Spigot test was firstly conducted by Gibbs and Popolato at Los Alamos National Laboratory in 1980 [11]. The tests simulate the effects of a large charge in a weapon being impaled by some type of blunt-ended rod. The test structure, as shown in figure 1(d), involves an explosive charge, which is machined as a larger cylinder. The explosive charge is glued into the counterbore of an inert plastic bonded material, which has the same shock impedance characteristics as the explosive. The open end of the explosive charge is covered with a steel plate, which has a hole at its center. A steel pin, with a flat head and a long pole is fitted through this hole, so that the shaft protrudes from the bottom of the explosive. The tested structure is dropped from a certain height or accelerated to a certain velocity by a piston accelerator. The steel pin impacts onto the steel target on the ground. The threshold drop height or the threshold drop velocity is used to evaluate the sensitivity of explosive.

## 3. Specimen size analysis

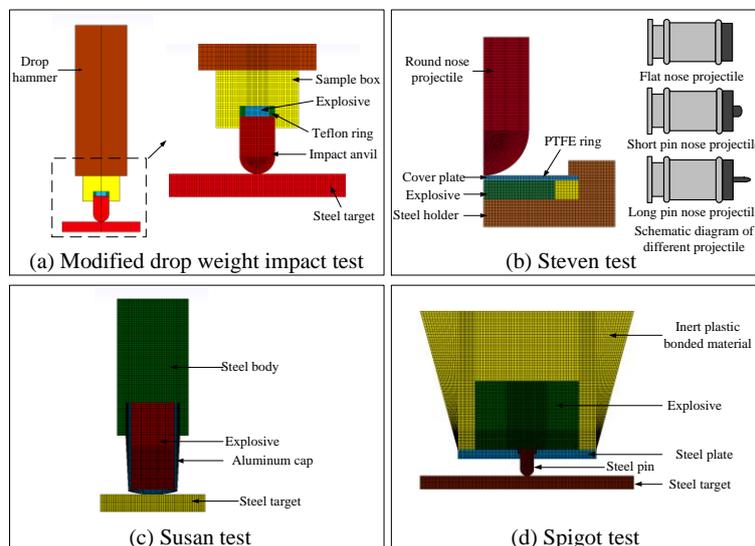
The diameter of explosive charge in the modified drop weight impact test, Steven test, Susan test and Spigot test is in ranges of 10~20, 70~140, 50 and 50~150 mm, respectively. For the modified drop weight test, the impact loading is acted on the whole volume of explosive charge, and the impact energy can be calculated from the drop hammer's potential energy. For Susan test, the explosive is confined in an aluminium cup and accelerated with a certain velocity to impact the steel target. The whole explosive charge is squeezed and nipped between the aluminium cup and the steel body of the projectile. The impact energy can also be derived from the projectile's kinetic energy. However for Steven test and Spigot test, the impact loading is mainly acted on a localized volume of the explosive charge, due to the diameter difference between the projectiles and the steel pin. In these low velocity impact tests, in general, mechanical energy converts into heat in explosives due to deformation when the kinetic energy of projectile acts on the explosive charge, causing temperature rise or even chemical reaction of explosives. Therefore, we introduced the critical specific mechanical energy and the

effective volume of explosive charge to investigate the specimen size effect on the explosive reaction thresholds under low velocity impact.

The effective volume of explosives is the actual volume which experiences the insults during impact loading. In this paper, we use the plastic zone for different explosive charges in different impact tests to calculate the effective volumes. The plastic zone was determined by numerical simulation. The critical specific mechanical energy was defined as the acted mechanical energy per unit effective volume under lowest impact velocity or lowest drop height causing explosion. The mechanical energy is derived from kinetic energy of projectile or the potential energy of drop weight in different tests.

### 3.1. Determination of the effective volume of explosive charge by numerical simulation

The numerical simulation of mechanical response for different explosives in modified drop weight impact test, Susan test, Steven test and Spigot test are conducted using LS-DYNA, to determine the plastic zone during impact. Figure 1 presents the typical LS-DYNA mesh of four tests.



**Figure 1.** Typical LS-DYNA mesh of four different low velocity impact tests.

For the modified drop weight test with different specimen size designs and Susan test, the effective volume is independent of geometry of the designs and is equal to the explosive charge volume, due to the overall impact loading on the whole volume. The numerical results of the plastic zone verified it, and the effective volumes of explosives in these two tests are shown in table 1.

**Table 1.** The effective volumes of explosives in the modified drop weight impact test and Susan test.

Tests	Specimen size/ mm	Effective volumes / cm <sup>3</sup>
Modified drop weight test	Φ20×20	6.28
	Φ40×40	50.24
	Φ60×60	169.56
Susan test	Φ50×100	196.25

For Steven test and Spigot test, the effective volumes are closely related to the experimental geometry and the mechanical property of explosives, due to the localization of the impact loading. The numerical simulations of these two tests are conducted for different explosives with different experimental geometries, respectively. The Steven test geometries for different explosives in the simulation are based on different experimental designs conducted by Chidester et al. [8], Vandersall et al. [9], Idar et al. [10], Dai et al. [15] and our group [13]. Table 2 shows the numerical results of the

effective volumes in Steven test. The Spigot test geometries are based on the experimental designs used by LLNL for PBX 9404 [16] and our group for PBX-1 [14]. The results of the effective volumes in Spigot test are 219.54 cm<sup>3</sup> and 192.45 cm<sup>3</sup> for PBX 9404 and PBX-1, respectively.

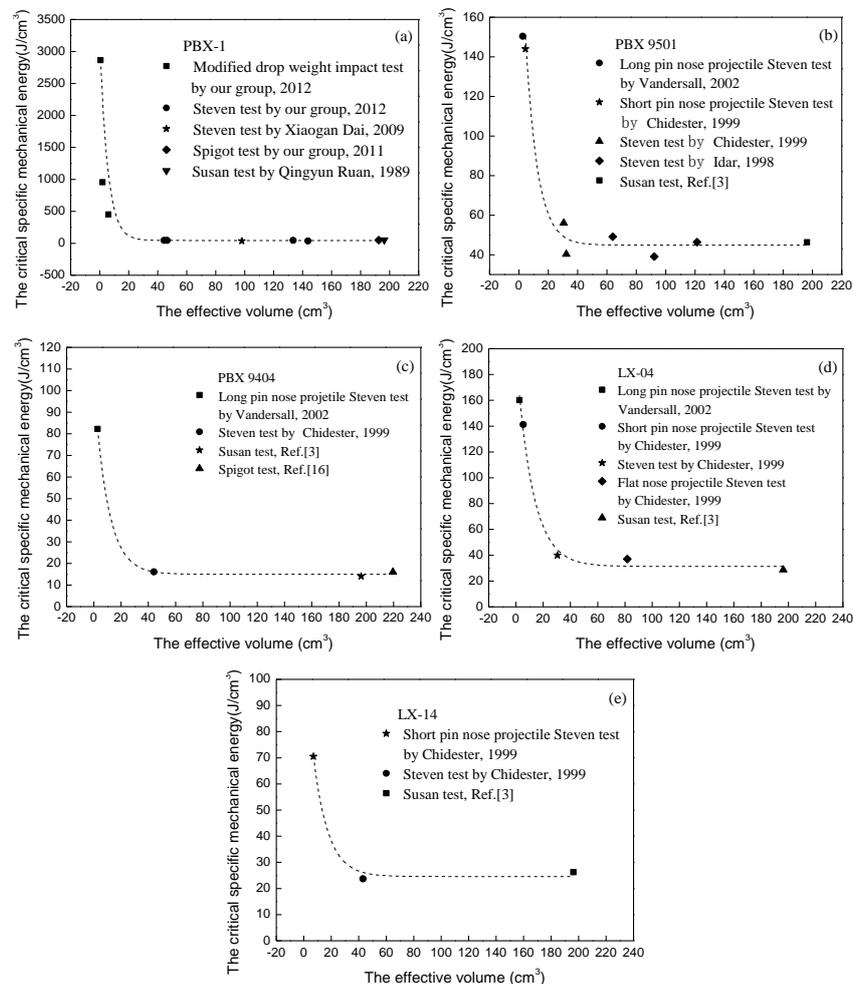
**Table 2.** The numerical results of the effective volumes for different explosives based on different geometries of Steven test.

Explosive	Projectile	Specimen size / mm	Geometry	Effective volumes / cm <sup>3</sup>
PBX-1	Round nose	Φ98×13	Reference [16]	44.48
	Round nose	Φ140×13	Reference [16]	46.52
	Round nose	Φ98×39	Reference [16]	133.43
	Round nose	Φ140×39	Reference [16]	143.73
	Flat nose	Φ98×13	Reference [15]	98.06
PBX 9501	Long pin nose	Φ110×12.85	Reference [9]	2.58
	Short pin nose	Φ110×12.85	Reference [8]	4.45
	Round nose	Φ110×12.85	Reference [8]	30.53
	Round nose	Φ110×12.85	Reference [8]	32.22
	Round nose	Φ127×12.7	Reference [10]	63.84
	Round nose	Φ127×25.4	Reference [10]	92.24
	Round nose	Φ140×25.4	Reference [10]	121.37
PBX 9404	Long pin nose	Φ110×12.85	Reference [9]	2.75
	Round nose	Φ110×12.85	Reference [8]	44.03
LX-04	Long pin nose	Φ110×12.85	Reference [9]	2.55
	Short pin nose	Φ110×12.85	Reference [8]	5.34
	Round nose	Φ110×12.85	Reference [8]	30.42
	Flat nose	Φ110×12.85	Reference [8]	81.75
LX-14	Short pin nose	Φ110×12.85	Reference [8]	7.03
	Round nose	Φ110×12.85	Reference [8]	43.03

### 3.2. Analysis of specimen size effects

Figure 2 gives relationships between the effective volume and the critical specific mechanical energy for PBX-1, PBX 9501, PBX 9404, LX-04, and LX-14 under low velocity impact. It is shown that, with the increase of the effective volume, the critical specific mechanical energy significantly decreases, and then tends to be a constant value when the effective volume is large enough. For these five PBX explosives, the constant values of the critical specific mechanical energies are 44.04 J/cm<sup>3</sup>, 44.86 J/cm<sup>3</sup>, 15.01 J/cm<sup>3</sup>, 31.34 J/cm<sup>3</sup> and 24.59 J/cm<sup>3</sup> respectively. These constant values may indicate the sensitivity level of explosives under low velocity impact.

The specimen size effect is associated with the thermal prosperities of the explosive. Part of the plastic work transforms to heat causing temperature rise and even ignition of the localized volume of explosive. During this process, the heat conduction can not be ignored. Comparing with a larger volume of explosive, the heat dissipation is faster than a smaller one. So it needs more stimulus energy, in other words, a bigger specific mechanical energy is needed for ignition.



**Figure 2.** The relationship between the effective volume and the critical specific mechanical energy.

#### 4. Summary

In this paper, the effective volume of explosive charge and the critical specific mechanical energy were introduced to investigate the specimen size effect on the explosive reaction thresholds under low velocity impact. Four different tests (including the modified drop weight impact test, Steven test, Susan test and Spigot test) and five different PBX explosives (including PBX-1, PBX 9501, PBX 9404, LX-04, and LX-14) were considered. Numerical simulations were conducted by LS-DYNA to determine the plastic zone of explosive charge during impact, which was used to calculate the effective volumes of explosive charge in impact tests. The results show that, with the increase of the effective volume, the critical specific mechanical energy significantly decreases, and then tends to be a constant value which indicates the sensitivity level of explosives under impact.

#### Acknowledgement

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