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Development of high velocity gas gun with a new trigger system-numerical analysis

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Abstract. In development of high performance armor vests, we need to carry out well controlled experiments using bullet speed of more than 900 m/sec. After reviewing trigger systems used for high velocity gas guns, this research intends to develop a new trigger system, which can realize precise and reproducible impact tests at impact velocity of more than 900 m/sec. A new trigger system developed here is called a projectile trap. A projectile trap is placed between a reservoir and a barrel. A projectile trap has two functions of a sealing disk and triggering. Polyamidimide is selected for the trap material and dimensions of the projectile trap are determined by numerical analysis for several levels of launching pressure to change the projectile velocity. Numerical analysis results show that projectile trap designed here can operate reasonably and stresses caused during launching operation are less than material strength. It means a projectile trap can be reused for the next shooting.

1. Introduction

According to National Institute of Justice, USA, more than 3000 police officers have saved their lives by body armor in a period of 43 years since 1970s [1]. US National Institute of Justice (NIJ) set standard of body armor. In the standard, performance of body armor and test methods to evaluate the performance are elaborated. According to the NIJ standard 0101.06 issued in 2009 [2], body armor is classified into type IIA, II, IIIA, III, and IV. Minimum performance of type IV, which is most tough in five types, is set forth as “Type IV flexible armor shall be tested in both the “as new” state and the conditioned state with .30 caliber AP bullets (U.S. Military designation M2 AP) with a specified mass of 10.8 g and a velocity of 878 m/s ± 9.1 m/s.”

On the other hand, improvement in fire arms or development of new fire arms is always promoted. As result, powers of fire arms are increased further and further. As mentioned above, in order to save human lives from bullet shooting, armor vests have been constantly developed. Unfortunately, performance of armor vest does not defeat newly developed fire weapon. Therefore, US Defense Advanced Research Agency started a project of armor vest development widely calling for proposal from related inventors in 2009 [3], it is called “Armor Challenge Phase 2”. This project aims to develop an armor vest satisfying the following conditions:

(1) Projectile size: 7.62mm in Bullet diameter, and 51mm in Case length, weight: 9.7g, or 11.3g
(2) Projectile speed: 915-930 m/sec
(3) Weight of vest: less than 30 kg/m^2

(4) Cost: competitive with current body armors

For impact studies, gas guns are used to accelerate a projectile through a barrel and to generate the required impact onto a target under controlled conditions. Many light gas guns have been developed and installed for impact studies in laboratories over the world. Gas gun facilities can be applied to simulate different situations, varying with the characteristics of the gun itself. To obtain highly accurate data, precise and reproducible impact tests must be carried out.

A key device for precise and reproducible impact tests is a trigger system of a light gas gun. Gas guns developed until now utilize one of the following three trigger systems;

- Mechanical system [4]
- Solenoid valve [5]
- Rapture disk [6]

A mechanical trigger system in principle uses a mechanical sliding system to open valves between a gas reservoir and a barrel. A mechanical trigger system is often utilized by air rifles and air hand guns.

In studies of impact phenomena, a gas gun installed in a laboratory also utilizes a mechanical trigger system [4]. Mechanical trigger system is typically used in low-speed gas guns. During the operation of a mechanical trigger system takes some milliseconds to fully open the valve. Therefore, a certain time lag for a projectile to be accelerated fully by the compressed gas is always necessary. This time lag is sometime fatal disadvantage to get high muzzle velocity.

A solenoid valve trigger mechanism is similar to a mechanical trigger system. The difference is a driving force to open a valve. In a mechanical trigger system, the driving force to open a valve is given by a mechanical mechanism while in a solenoid valve trigger system, a driving force is generated by an electro-magnetic mechanism. Flow volume of a solenoid valve is constantly improved, and one example of flow volume in the latest developed solenoid valve is around 1.67 x 10^{-2} m^3/sec (normal) for back pressure of 10 MPa. If we use this solenoid valve for a trigger system of a high speed gas gun of which a barrel diameter is 6.0 mm, fluid flow in the barrel through the solenoid valve is around 590.9 m/sec when the gas pressure is 10 MPa. It is obvious that we cannot obtain high muzzle speed of more than 900 m/sec.

A rapture disk trigger system is usually used for a highspeed gas gun. Then, a rapture disk is placed between a gas reservoir and a barrel. When pressure of a reservoir gas is gradually increased and the rapture disk is broken by the pressure, the rapture disk opens up very quickly, and large compressed gas volume flows in the barrel to accelerate a projectile. As compared with a solenoid valve, a rapture disk can pour a larger volume of gas into the barrel. As a result, a gas gun using a rapture disk can produce high muzzle velocity. Thus, a rapture disk is successfully used for high velocity gas gun, but it is based on fracture of thin plate of a metallic material. Fracture process of materials is substantially a random process or a probabilistic process. This means that rapture disk fracture involves randomnesses in several senses. The first one is fracture pattern. The second is breaking pressure. The third is gas flow resulted from the former factors. The reproducibility of impact test is therefore, of poor quality.

As mentioned above, usual trigger systems have substantial time lag for a propellant gas to reach a projectile after the trigger system is activated. This may cause disturbance in flow and loss in acceleration of projectile

Consequently, this research aims to develop a new trigger system for a high velocity gas gun, which can realize precise and reproducible impact tests at impact velocity of higher than 900 m/sec, and eventually, to develop an armor vest preventing a bullet of more than 900 m/sec from penetration. A new trigger system developed here is called a projectile trap. This new trigger system is based on a novel concept and simultaneously possesses two functions of sealing between a reservoir and a barrel and launching without time lag.

2. Developent of New Trigger System

2.1. Basic Concept of Gas Gun System

This research aims to develop a new trigger system for a single stage gas gun using helium gas as a propellant medium. A single stage gas gun has the following specifications:

(1) Spherical projectile: 6.0 mm in diameter, 0.36 g in mass, and made of silicon nitride Si_3N_4
(2) Maximum projectile speed: more than 900 m/sec
(3) Barrel: 6.05 mm in inner diameter, and 650.0 mm or more in length
(4) Pressure media: Nitrogen gas for low velocity, and Helium gas for high velocity

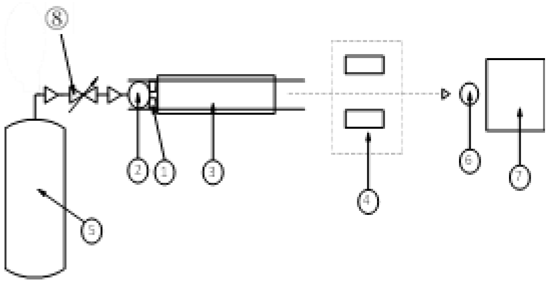

Figure 1. Scematic view of a high velocity gas gun with a new trigger system

In the usual trigger systems, a sealing or trigger position is a little far from a projectile. To eliminate this disadvantage, a new trigger system has simultaneously two functions of sealing and propelling. In Figure 1, basic concept of a high velocity gas gun with a new trigger system is schematically illustrated.

Items ①and ② are a projectile trap and a projectile. A new trigger system consists of these two components. Item ③ is a barrel, item④ is a projectile-velocity measurement device, item ⑤ is a helium gas reservoir, item ⑥ is a flying projectile and item ⑦ is a projectile catcher and item ⑧is a solenoid valve. A projectile and a projectile trap, a new trigger system seals a boundary between a room behind of a projectile and a barrel.

A compressed helium gas from the reservoir flows into a room behind a projectile. However, the new trigger system prevents gas leak into the barrel. When a compressed helium gas flows in further, the pressure of the room behind the projectile is elevated and the projectile trap is pressed and bent. The projectile can pass through the projectile trap at a certain pressure.

The projectile trap is changed in an inner hole diameter and thickness so that the pressure for the projectile to pass through the projectile trap can be adjusted for a required level. The required pressure level is determined by a projectile muzzle velocity.

The projectile triggered by this system is accelerated in the barrel and launched from an end of the barrel at a certain velocity. To measure the projectile velocity, a measurement device is constructed by use of a photodiode and two laser beams.

2.2. Materials of Projectile and Projectile Trap

In development of a new trigger system for a high velocity gas gun, material selection for projectiles and projectile trap is one of importance factors. The Torlon is a polymer of polyamidimide and high wear resistance without lubrication. Its fracture elongation is more than 10 %. This material is quite suitable for the projectile trap. Torlon can be treated as a non-linear material with a hyperelastic property. In Torlon products, Torlon 4203L is selected because of high strength and large fracture strain. For the projectile material, silicon nitride Si3N4 is selected. The mechanical properties of two materials are shown in table 1.

Table 1. Material properties of Projectile and Projectile Trap [7][8]

Material Properties	units	Projectile	Projectile Trap
Young's Modulus	GPa	290	-
Density (ρ)	Kg/m^3	3200	1420
Poison Ratio (υ)	-	0.28	0.45
Tensile Strength	MPa	525	192
Compressive Strength	MPa	5500	220
Tensile Strain at fracture	%	-	15
Compressive Strain at fracture	%	-	80

2.3. Alignment of a projectile trap and a projectile

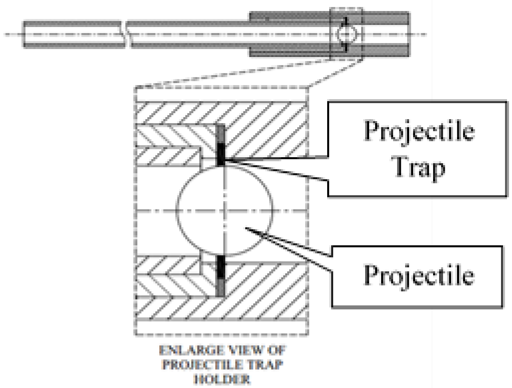

Figure 2. Schematic illustration of projectile trap

A projectile and a projectile trap must firmly contact with each other for sealing function. To assure the firm contact, a projectile trap is machined for a center hole that fits to a spherical projectile surface. In figure 2, schematic view of cross section of a projectile trap is illustrated. A diameter of the hole at the trap upper surface is the same as a spherical projectile diameter. In this research, a trap hole is automatically decided when thickness of a projectile trap is identified. The geometries and dimensions of projectile trap is determined by simulation using ANSYS Multiphysics v13.0. The projectile trap trigger mechanism is simulated by creating a model of projectile and projectile trap with contact. Then the launching pressure is applied to the model. In addition, we must know stresses generated in a projectile trap during a launching process in order to design a practical dimensions of a projectile trap and make sure that a new launching system is feasible, realistic, practical, and reliable.

3. Numerical Analysis of Projectile Trap

3.1. Model Geometry

In simulation, a situation of a spherical projectile contacting with a projectile trap is considered as shown in figure 3. The problem is axisymmetric and the model is a solid of revolution in respect of z axis. In the figure, a half of cross section is shown. A half circle of the radius R, 3.0 mm represents a projectile and a rectangle represents a projectile trap. L1 denotes trap length and is fixed at 0.5 mm, L2 denotes fixed support area, and t denotes thickness of the trap. The projectile trap geometries will be changed only in thickness to obtain appropriate launching pressure.

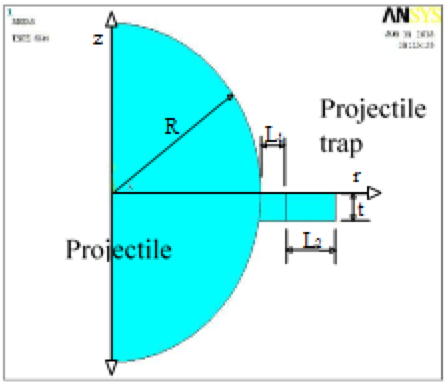

Figure 3. Projectile trap trigger system model

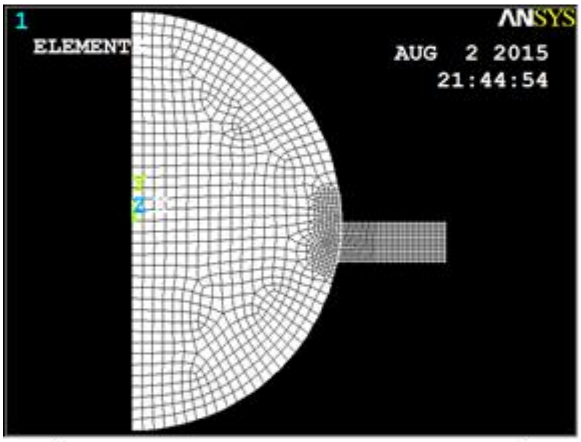

Figure 4. Mesh model of projectile and projectile trap

In figure 4, mesh model is shown. Total mesh number is 1354 and total node number is 4105. At the contact boundary, contact elements are generated.

3.2. *Material Model*

Projectile material is silicon nitride Si3N4. Its mechanical properties are shown in table 1. This material is regarded as linear elastic under this research conditions. On the other hand, projectile trap material is polyamidimide, Torlon, in which large non-linear property can be seen in the stress and strain relation as shown in figure 8. In this numerical analysis, this material is represented as isotropic hyper-elastic one. Mooney-Rivlin five-parameter model is utilized to express material behaviours. In figure 5, Mooney-Rivlin five-parameter model is well compared with the experimental data.

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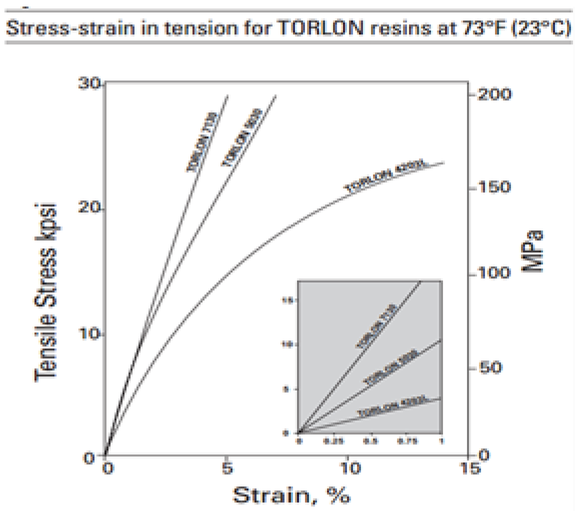

Figure 5. Stress strain graph of Torlon materials [8]

3.3 Numerical Analysis Results

3.2.1 Flat projectile trap

In the numerical analysis, pressure load is applied on the projectile surface above the projectile trap. The pressure is gradually increased until the projectile is launched from the trap. First, stress analysis is carried out for a flat projectile trap. One numerical analysis result is shown in Figure 6 for the trap thickness of 0.5 mm and the trap length L1 of 0.5 mm. For applied pressure of 13.0 MPa, von Mises equivalent stress contours are plotted in the figure.

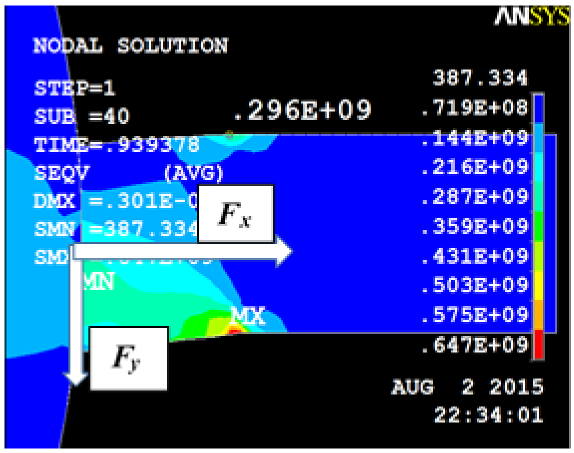

Figure 6. Contours of von Mises equivalent stress in a flat trap

The figure indicates the stress states just before launching of the projectile. The stress concentration takes place at the end of the support, right hand side of trap, where the contour color is blue. Main principal stress is compressive. However, von Mises equivalent stress is more than 647 MPa at the compression side and 296 MPa at the tension side, which is much larger than Torlon compressive and tensile strength, 172 MPa and 192 MPa, respectively.

This means that the flat projectile trap will be failed before launching of the projectile. Then, we consider applied forces to the projectile trap. One is a friction force generated by contact between the projectile and the projectile trap, denoted by Fy in the figure. Another force is compressive force generated by press of the projectile, denoted by Fx. Because Fy generates bending moment in the projectile trap, both the forces cause compression stresses at the edge of the support.

3.2.2 Slant projectile trap

To reduce the stress concentration, a new trap configuration is considered. In the flat trap, compressive stresses due to the friction force and the press force are superimposed at the supporting edge. If the trap is inclined as shown in Figure 7, bending moment due to the press force becomes clockwise direction while the friction force generates counterclockwise bending moment. Eventually, resultant moment at the supporting edge can be reduced significantly.

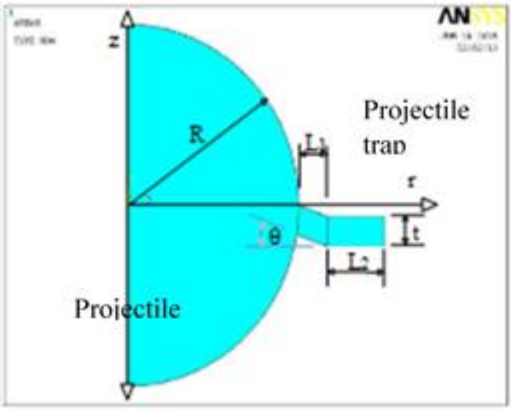

Figure 7. Slant projectile trap

In figure 8, von Mises equivalent stress is plotted as contours for applied pressure of around 13.0 MPa and in case of slant angle θ of 20 degrees. At the compression side, von Mises equivalent stress is more than 390 MPa, while at the tension side, von Mises equivalent stress is tremendously reduced to 68.8 MPa, which is much less than the tensile strength of Torlon.

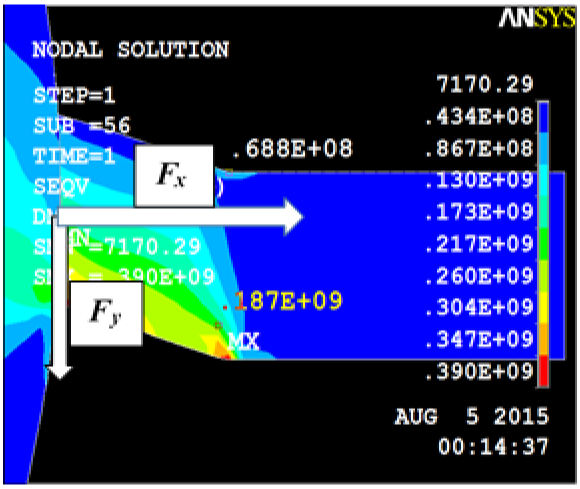

Figure 8. Von Mises equivalent stress distribution in the slant projectile trap

4. Final shape and dimension of projectile trap

Calculation is done for von Mises equivalent stress changing slant angles. Then, it is found that when the slant angle θ is 20 degrees, the offset effect is largest. When the slant angle θ is small, clockwise moment generated by the press force is small and then offset effect is small. On the other hand, when the slant angle is large, the clockwise moment becomes large and the large bending stress is caused at the supporting edge.

As shown in figure 8, von Mises equivalent stress due to the compressive stress reaches the maximum at the lower side supporting edge. The stress at the area exceeds compressive strength of Torlon. The von Mises equivalent stress is about two times of Torlon compressive strength. However, when we look at strain in the projectile trap, it should be noted that von Mises equivalent strain is not so large like the equivalent stress as shown in figure 9, and it is less than 9.0 % when the launching pressure is around 14.0 MPa.

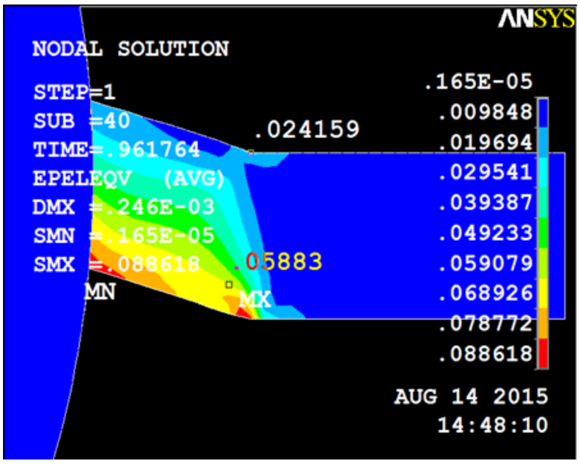

Figure 9. Von Mises equivalent strain distribution in the slant projectile trap

Compressive stress-strain curves of Torlon are not available in any brochures. Only one data of Torlon 4203 is published [9]. According to this data, Torlon 4203 has 150 MPa compressive yield strength and it can be compressed up to strain of more than 80 % without failure. Therefore, it can be speculated that because even if the von Mises equivalent stress is higher than compressive strength of the material, von Mises equivalent strain is rather small, catastrophic failure of projectile trap does not arise in this situation. Figure 10 indicates the maximum von Mises equivalent strain against the launching pressure for flat projectile trap and slant projectile trap at angle 20 degrees.

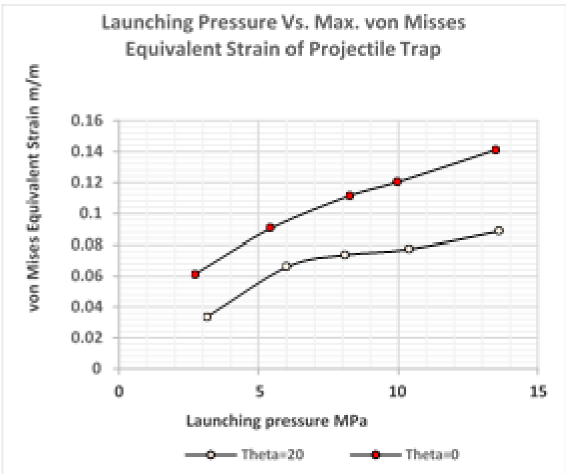

Figure 10. Max. von Mises equivalent strain of projectile trap against launching pressure

In figure 11, the maximum von Mises equivalent stress in tension side of the projectile trap is plotted against the launching pressure. According to simple calculation, the launching pressure of 13.0 MPa can accelerate a projectile more than 900 m/sec in 650 mm long barrel. In the figure, the results for slant angle of zero and 20 degrees are compared. It can be seen that the slant projectile trap is subjected too much smaller stress as compared with the flat trap.

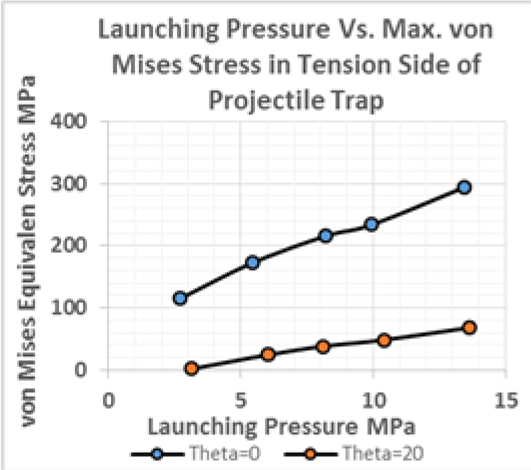

Figure 11. Max. von Mises equivalent stress at the upper supporting edge of projectile trap against launching

Finally, numerical analysis results can suggest that the shape and dimension of projectile trap shown in table 2 and figure 10 can be adopted for experiments.

Table 2. Projectile trap thickness and launching pressure associate with it

Trap Thickness t mm	Launching Pressure P MPa
0.5	13.5
0.46	10.4
0.42	8.0
0.38	6.0
0.34	3.2

Then the figure 12 displays the geometry and dimension of projectile trap for machined

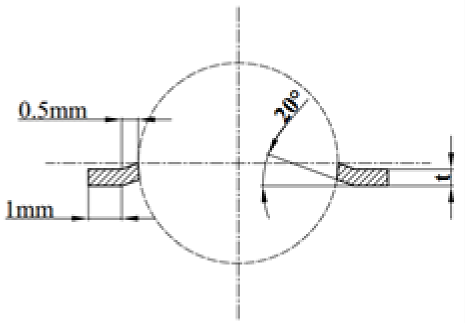

Figure 12. Geometry and dimension of projectile trap for machined

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5. Conclusion

Aiming to develop a new trigger system for light gas gun, this research carried out numerical analysis for a trigger system developed by a new concept. The following conclusions are obtained:

（1） Projectile trap is a new idea for trigger system of light gas gun. This has two functions of sealing and launching.

（2） When the projectile is launched, the gas immediately accelerates a projectile. There is not time lag like a rupture disk trigger system.

（3） Numerical analysis results show that if slant projectile traps are adopted, stress in the trap is significantly reduced.

We need to carry out experiment to assure the conclusions obtained above.

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