The Shotgun Pellets Interior Ballistics Analysis by Discrete Element Method (DEM) of LS-DYNA®

Shigan Deng
Department of Power Vehicle & Systems Engineering
Chung Cheng Institute of Technology, National Defense University, Taiwan

Jason Wang
Livermore Software Technology Corporation

Ta-Chiang Wu
The Master Program of Weapon Systems Engineering
Chung Cheng Institute of Technology, National Defense University, Taiwan

Abstract

This research used the Discrete Element Method (DEM) of Finite Element Software (LS-DYNA) successfully simulated the interior ballistics performance of shotgun pellets and the deformation of wad and shot cup. This research used 12-gauge shotgun with #9 bird shot which has 433 pellets inside the shot, as an example. There are four components are modeled by finite element: barrel, wad with shot cup, case, and pellets of the shot. The input forces are the chamber pressure on the bottom of wad, which is calculated by Vallier-Heydenreich empirical formula, and the air resistance in the front faces of shot cup. The outputs are velocity/acceleration history of the wad with shot cup and pellets, the distribution of pellets after exits muzzle, and the deformation of the wad with shot cup. The calculated muzzle speed of pellets is 423m/s, compare to 412m/s of Sporting Arms and Ammunition Manufactures Institute (SAAMI) tested, there is only 2.67% error. The results of this research could lead the traditional test-oriented shotgun industry into contemporary Computer Aided Engineering (CAE) by introducing the DEM of FEM to the industry.

Keywords: Shotgun, Interior Ballistics, Pellets Distribution, Discrete Element Method, Finite Element Analysis

1. Introduction

In recent years, the Computer-Aided Engineering (CAE) techniques and software are developed rapidly. Because of its fidelity simulation results, they are recognized by many standard bodies as one of the test and verification tools. Also because of its fast and cost-effective advantages, many industries like aerospace, automobile, machine center …etc., are officially adopted CAE to analyze the static and dynamic behaviors of their products before manufacture. Among those industries, there is one special industry, the traditional armament industry exists over 500 years which produce artilleries, riffles, and guns, still using traditional design (no CAE) process. No because they won’t, but don’t know how.

The armaments large as artilleries or small like pistols and rifles, has very complex interior ballistics behaviors. Actually, their ballistic behaviors are so complicated that are multi-physics coupled phenomenon, which involves dynamics, kinetics, plastics, heats, and explosive, and whole process was done within few mini-sec. So, most of the large armament company using empirical formula which done by collection of many test data. But these empirical formulas usually are armament oriented, which cannot be generalized, and all parameters are confidential. Among these industrials, the shotgun business is the one that focus on commercial market instead of military, and it is worth to promote their business from traditional test orientated process to CAE.

Up till now, there is no research on CAE applied to Shotgun development. Instead, most of the shotgun research are focus on the pellets distribution pattern for various distance by observed enormous tests and experiments, then use the statistical methodology concluded and predicted the distribution pattern [1][2][3][4][5][6] [7]. There is also some commercial computer software in the market to predict pellets distribution pattern. Such as shotgun-insight [4] and Target Telemetrics [8].

In above mentioned references, David J. Compton [7] has designed and developed measurement facility to acquire accurate pellets shot cloud experimental data, then using those experimental data statistically to create a stochastic model to predict the disperse of the pellets. In the conclusion on his PhD thesis, he clearly expressed the pellets shot clouds depend on the launch condition like interior ballistics of the gun, cartridge and pellet properties and the interactive and individual performances of the pellets. To fully understand the behavior of shot clouds, all combinations of these effects need to be examined, especially detailed inspection near the muzzle.

In this research, we are focusing on the shotgun interior ballistics and dynamics, and choose 12-guage bird shot which has 437 pellets inside the shot as an example, to simulate pellets interior ballistics and dynamics on the barrel, and the distribution after pellets exit the muzzle

2. Shotgun shells and pellets

The shotgun firing mechanism is about the same as most of rifles. The feature of shotgun is on its projectiles. It is generally a smoothbore firearm (musket) which deliver pellets or slug (Fig.1). The slug type of shotgun required accuracy on firing, so its barrel has spiral rifling like rifles. Shotgun can be used for hunting, sporting, military, and law enforcement purposes. It has large caliber and low speed properties, the low speed causes its weakness in penetration and far distance lethality. Which also cause the momentum release to the close target, increase its lethality in closer target.

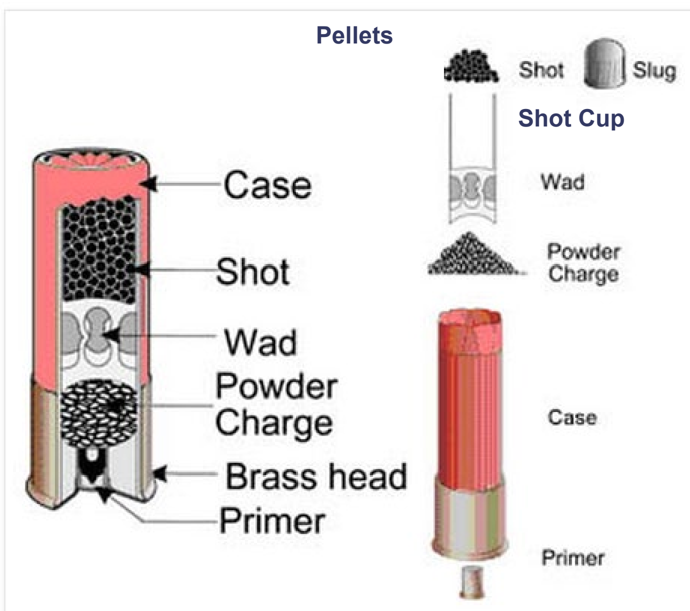

Fig. 1 Typical shotgun shell [9]

When firing the pellets type of shotgun, the shot pellets from a shotgun spread upon leaving the barrel (Fig. 2), and to form a lethal area. The spreading of the shot allows the user to point the shotgun close to the target, rather than having to aim precisely as in the case of a single projectile.

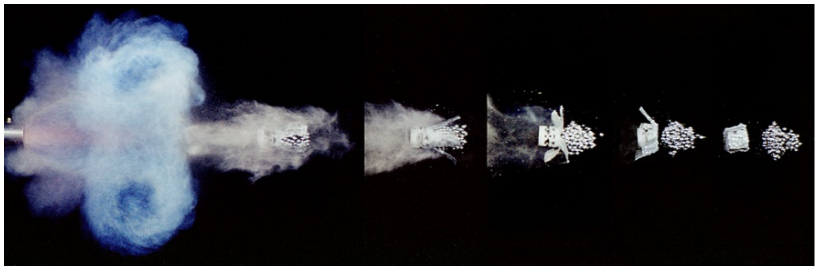

Fig. 2 Pellets exit from shotgun muzzle [6]

Shot is termed either birdshot or buckshot depending on the shot size (Fig. 3). Informally, birdshot pellets have a diameter smaller than 5 mm (0.20 in) and buckshot are larger than that. Pellet size is indicated by a number; for bird shot this ranges from the smallest 12 (1.2 mm, 0.05 in) to 2 (3.8 mm, 0.15 in) and then BB (4.6 mm, 0.18 in). For buckshot, the numbers usually start at 4 (6.1 mm, 0.24 in) and go down to 1, 0, 00 ("double aught"), 000, and finally 0000 (9.7 mm, .38 in).

Fig. 3 Different shotgun shots [10]

As the shot leaves the barrel upon firing, the three-dimensional shot string is close together. But as the shot moves farther away, the individual pellets increasingly spread out and disperse (Fig. 4). Because of this, the effective range of a shotgun, when firing a multitude of shot, is limited to approximately 20 to 50m. The pattern of pellets within a 30-inch circle should be of a proper, even density to ensure a clean kill. The pattern should contain a sufficient percentage of the load, which should be at least 55% to 60%.

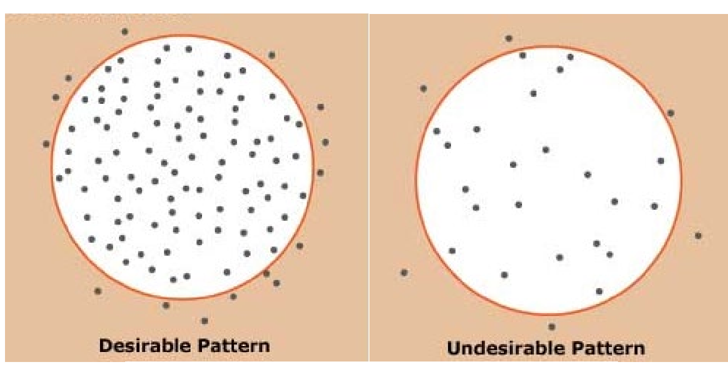

Fig. 4 Pellets distribution patterns [11]

To control this effect, shooters may use a constriction within the barrel of a shotgun called a choke (Fig. 5). The choke, whether selectable or fixed within a barrel, effectively reduces the diameter of the end of the barrel, forcing the shot even closer together as it leaves the barrel, thereby increasing the effective range. The tighter the choke, the narrower the end of the barrel. Consequentially, the effective range of a shotgun is increased with a tighter choke, as the shot column is held tighter over longer ranges.

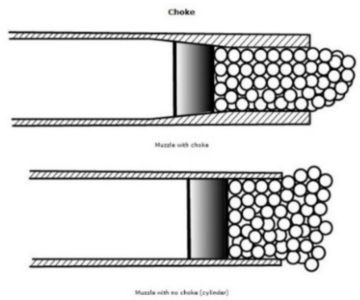

Fig. 5 Shotgun chokes [12]

Because shotguns are so popular in the western countries, there are many research related to shotgun. In 2010, Dr. A.C. Jones published a book named “Sporting Shotgun Performance” [5]. In this book, the shotgun principle, test results are detailed described. The only theorem used to analyze pellets exterior ballistics is Computational Fluid Dynamics (CFD), and the wall shear stress on the pellets due to pellet speed. There are also many research articles about distribution disperse patterns with choke design

3. The Model Preparation

CAD Models:

To simulate shotgun pellets interior ballistics and dynamics, the thing needs to do is to create CAD models for barrel, shot case, pellets, and wad with shot cup, then assembly them together as Fig. 6. The12-gauge bird shot shell with 24 gm of #9 pellets (Fig. 7) was used to simulate the interior ballistics and dynamics. There are total 437 pellets inside shot cup.

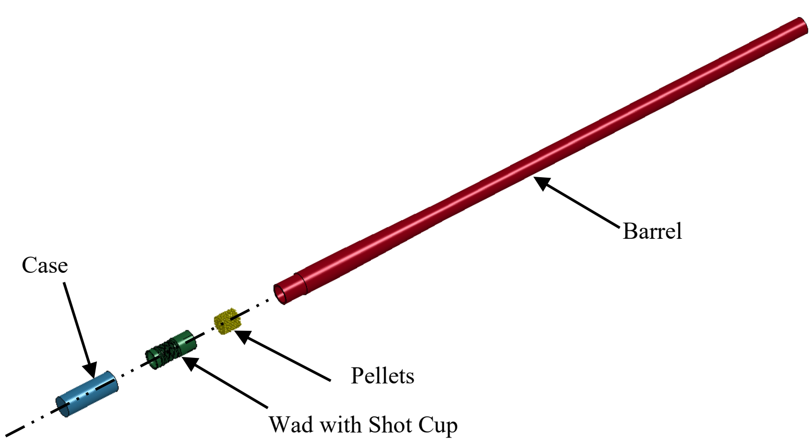

Fig. 6 Shotgun CAD models assembly

Fig. 7 12-gauge bird shot shell with 24 gm of #9 pellets

FEM Models:

The CAD models are then translated to FEM models. The barrel, case, and wad with shot cup, are modeled by solid elements, and the pellets are modeled by Discrete Element Spheres (DES). The FEM model of barrel has 199,692 elements with 282,312 nodes. While case and wad were modeled by 28,254 elements with 34,727 nodes, and 11,220 elements with 17,713 nodes respectively (Fig. 8, 9, 10). The LS-PrePost® can automatically transform solid elements to DES elements, but it can only get 370 to 380 DES elements, which has about 13% difference from 437 pellets. To get more accuracy number of DES elements, the author wrote a code used global searching algorithm, which found 433 DES elements (Fig. 11), only 4 nodes difference to the real pellets.

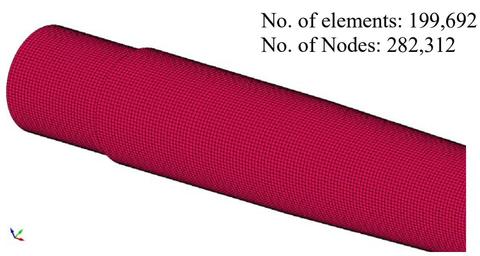

Fig. 8 Part of FEM model of Barrel

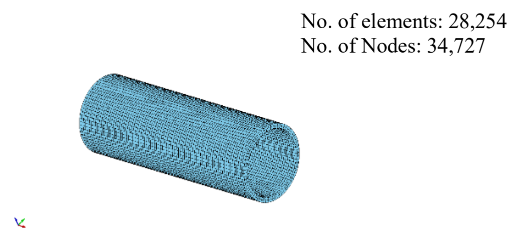

Fig. 9 FEM model of Case

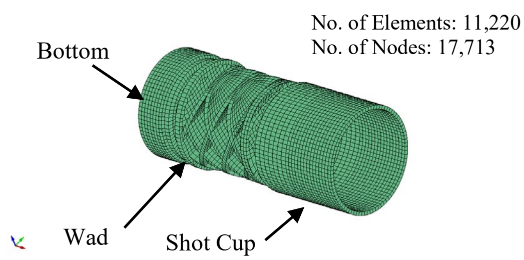

Fig. 10 FEM model of Wad with Shot Cup

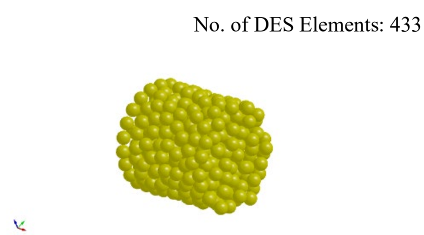

Fig. 11 FEM model of Pellets

Material Models:

The material models for barrel, case, wad, and pellets are AISI4140, Nylon66, and Lead respectively. The material properties are listed as Table 1. The barrel and case are modeled as rigid body for simplification reason, because compare to Nylon66, AISI 4140 steel is much stronger material. The Nylon66 is a soft non-metal material, to model this material in such a short time simulation, it will need to considerate the strain rate effect. So, in this research, we used simplified Johnson Cook material model for Nylon66. The simplified Johnson-Cook material parameters are acquired from [13].

Part	Material	Material Model	Material Properties
Barrel	AISI 4140	Rigid body	ρ= 7.85 g/cm3, E= 200 Gpa, υ=0.30
Case	AISI 4140	Rigid body	ρ= 7.85 g/cm3, E= 200 Gpa, υ=0.30
Wad with shot cup	Nylon 66	Isotropic_Elastic_Failure (Simplified Johnson-Cook Model)	ρ= 1.14 g/cm3, E= 3.68 Gpa, υ=0.402 A=105 Mpa, B= 325 Mpa, n= 0.72702, c= 257
Pallets	Lead	Rigid body	ρ= 13.0862 g/cm3, E= 14 Gpa, υ=0.42

Table 1 Material properties

Input forces:

There are two forces are applied to this simulation model, one is the chamber pressure applied to the bottom of wad, the other one is the air resistance pressure applied to the front surface of shot cup. The chamber pressure is calculated by Vallier-Heydenreich empirical formula [13] as shown in Fig. 12. The Vallier-Heydenreich empirical formula used projectile weight, barrel length, projectile muzzle velocity, powder charge weight … etc. to calculate chamber pressure. All these data can be found in SAAMI Z299.2 – 2015 [15]. The air resistance pressure was calculated by following equation.

$$P_a = \frac{F_a}{A} = \frac{1}{2} C_d \rho_a V_w$$

Where P_a: air resistance pressure
F_a: air resistance force
A: area to apply
C_d: drag coefficient
ρ_a: air density
V_w: wad velocity

The air resistance pressure P_a was calculated after the first simulation to get wad velocity V_w, then applied to the front faces of shot cup to simulate at second time.

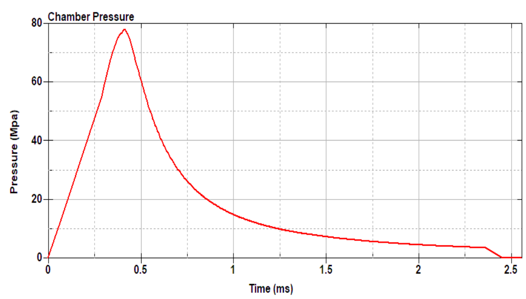

Fig. 12 Chamber Pressure

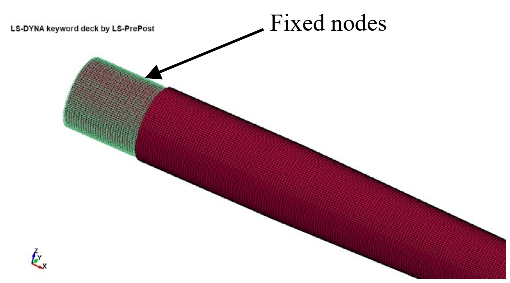

Fig. 13 Boundary condition

Boundary conditions:

The only boundary condition applied to this simulation is the fixed nodes on the clamp side of the barrel (Fig. 13).

Simulation Environments:

This simulation was done on the HP work station of Windows 10 OS (Intel® core™ i7980XE cpu@2.60Ghz with 16-core), 64GB RAM. The LS-DYNA version to run this simulation is Windows smp R11.0.0 rev. 129956. The total CPU run time is 22 hours 1 min. 27 sec.

4. Simulation Results

After setup the model, this research successfully simulated the 24 gr 12-guage shot with #9 pellets firing process and get the interior ballistics and dynamics performance of pellets and wad with shot cup. The first simulation has not applied air resistance pressure. It is used to get the velocity of wad with shot cup. Then the calculated air resistance pressure is applied to the front faces of the shot cup to simulate the whole process at second simulation. There is no air resistance pressure applied to the pellets during all simulations. The simulation started in t= 0 and ended in t= 7.0ms. From Fig. 14, we can see wad exits from muzzle at around t= 2.4ms, and the wad is largely deformed by chamber pressure. It is also shown the button of wad pushing the pellets outside the barrel, and the shot cup gradually opening and slowing down. Compare to the experiment video [15] at Fig. 15, we can see the simulated pellets distribution shape is amazingly match the experiment which appears to be a diamond shape at the beginning. The most important simulation data for the ballistics and dynamics performance of pellets, velocity and acceleration, are shown in Fig. 16 and Fig.17, respectively. From Fig. 16, we can see the DES velocity history, and DES node 282742 reach its highest velocity of 423 m/s at time of exits the muzzle (t= 2.4ms), and DES node 282744 reaches its highest acceleration of 1,200 m/s^2 in t= 0.202ms. We can also see the wad with shot cup reaches its highest velocity at 423 m/s in t= 2.4ms, then dropped due to air resistance force. Compare the 423m/s muzzle velocity of DES to 412m/s (1350ft/s) of SAAMI tested [14], there is only 2.67% of error, which means this research can simulate the pellets interior ballistics and dynamics performance precisely. Besides of the pellets interior ballistics dynamics performance, this simulation can also compute the stress and strain of wad with shot cup at all time, especially during the compression process inside the barrel (Fig. 18), which can assist the design the shape of wad with shot cup.

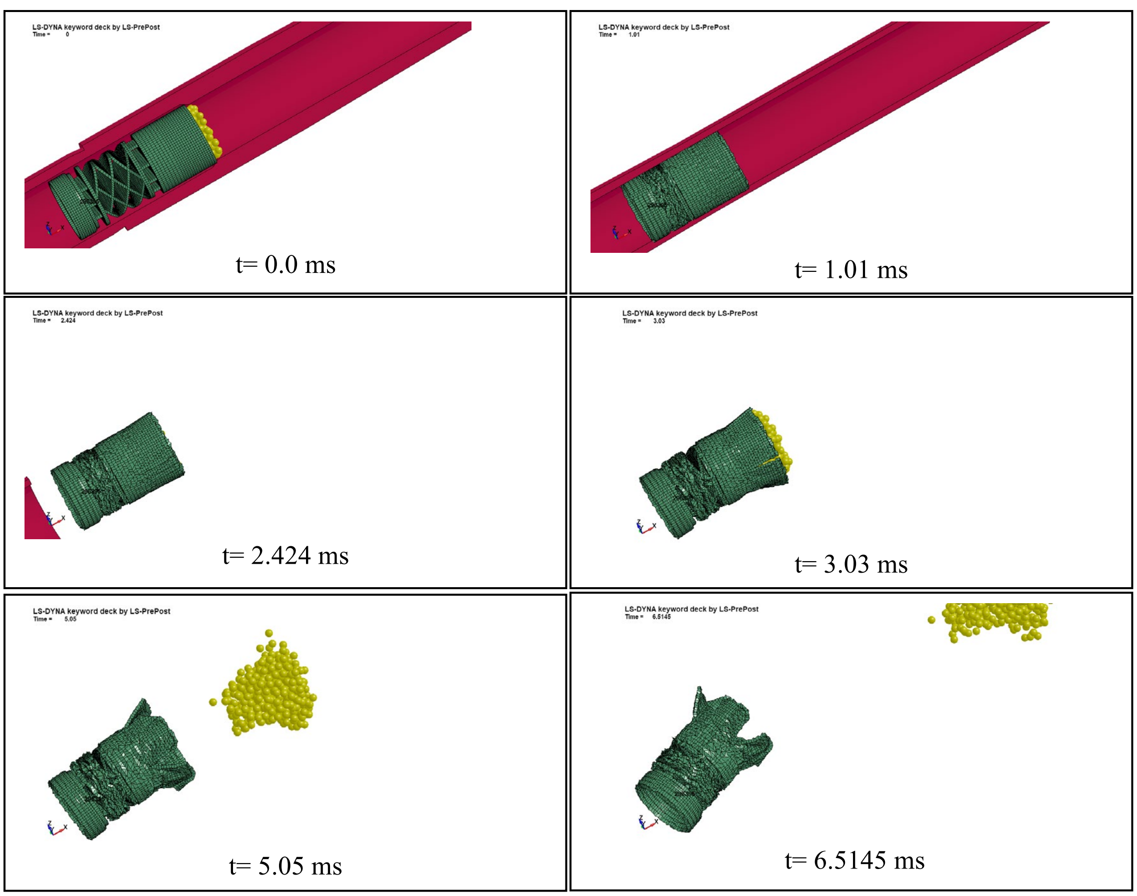

Fig. 14 The Simulation of interior dynamics of pellets

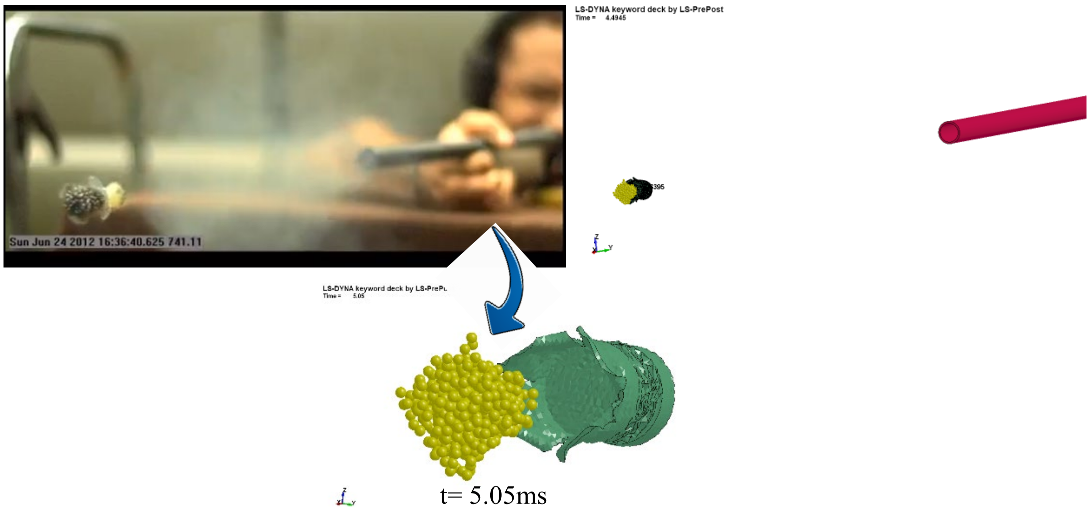

Fig. 15 Compare to experiment

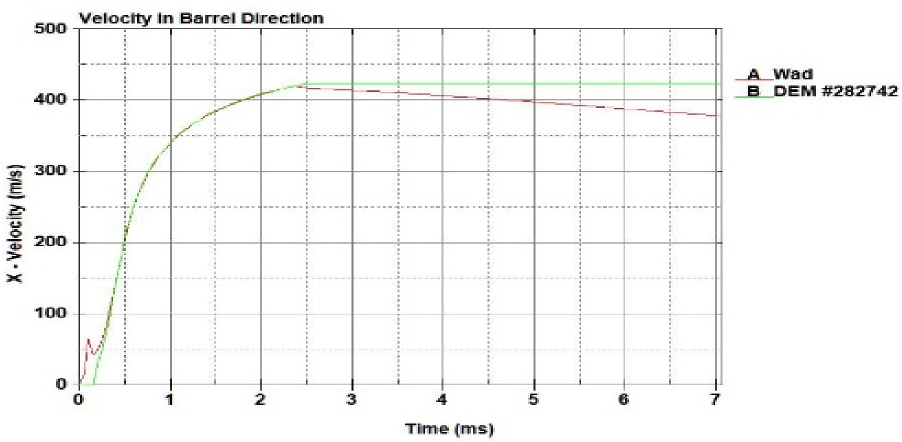

Fig. 16 DES velocity

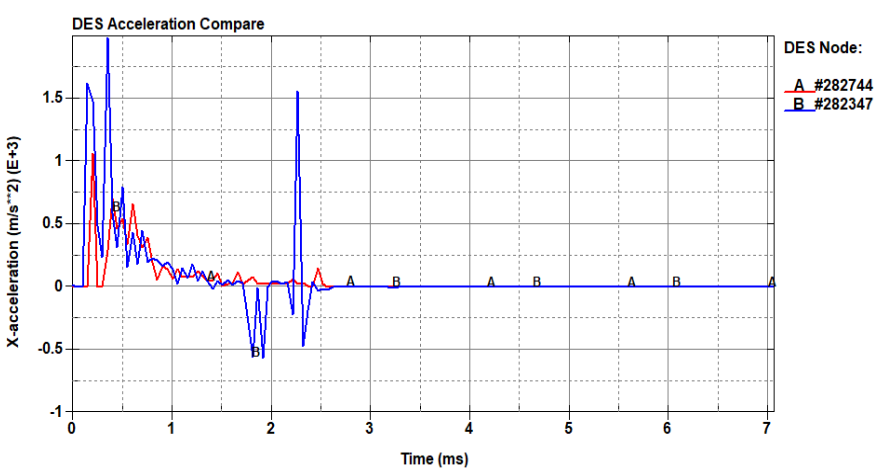

Fig. 17 DES acceleration

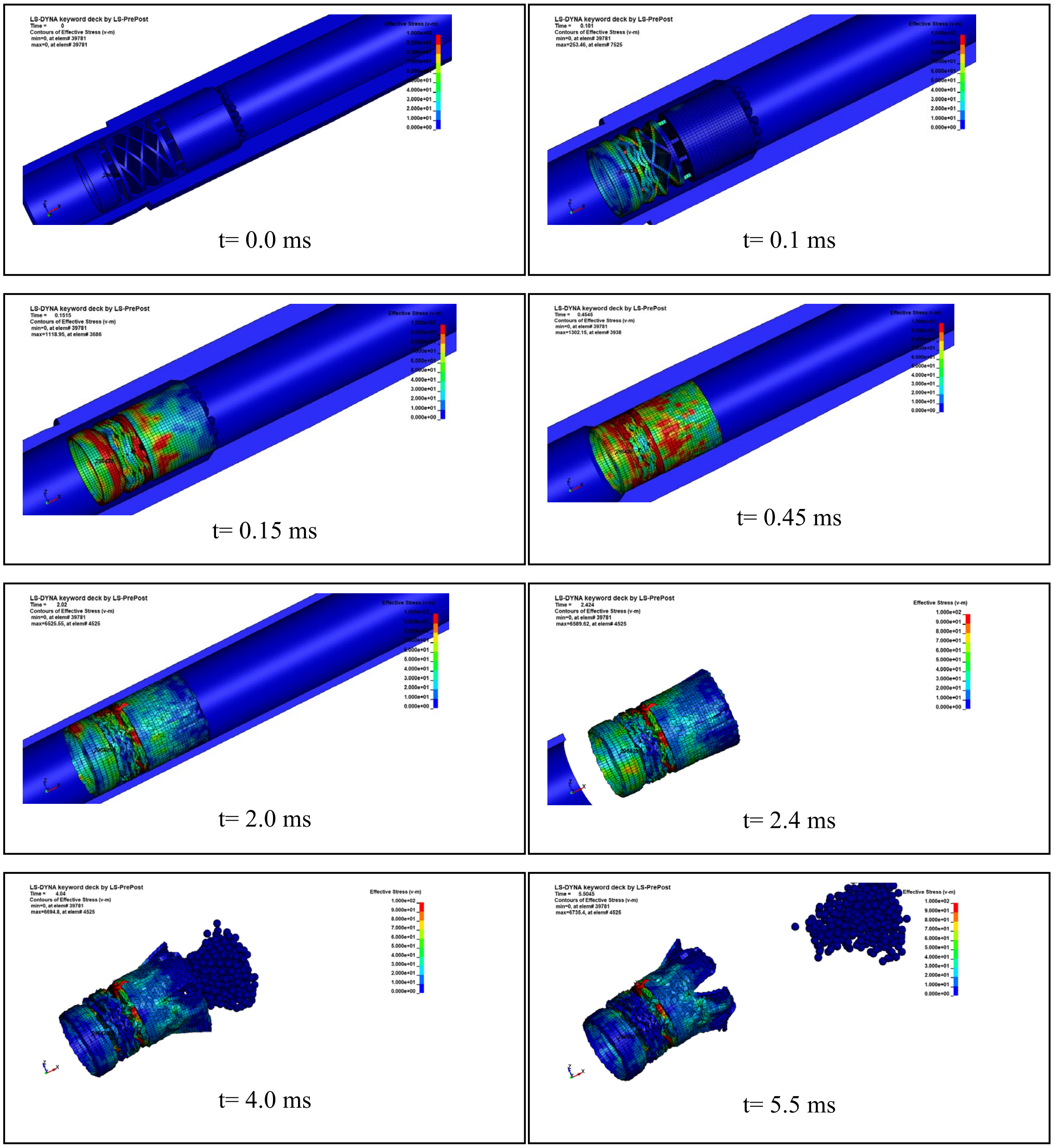

Fig. 18 the Von Mises Stress history of wad with shot cup

5. Conclusions and Suggestions

This research focused on pellets interior ballistics and dynamics performance analysis of the shotgun inside the barrel using DEM of LS-DYNA. In this research, the shotgun pellets interior ballistics and dynamics performance has been successfully simulated. Not only the pellets interior ballistics parameters like pellets velocity and acceleration can be calculated, the pallets distribution pattern after muzzle and the stress and strain on wad are also be acquired. This information can be used to assist the design of shotgun to get better performance. Apply this CAE technique could also be a revolutionary change for the shotgun development industry.

Suggestions

1. Although there is some shotgun software to predict pellets distribution/disperse patter by statistical methodology from tests and experiments data, there is no theoretical estimation of pallets distribution/disperse patter yet. The DES of LS-DYNA has the potential to calculate the pellets exterior ballistics performance like shoot range, trajectory, and distribution/disperse patter vs. distance, by activating the Eulerian (CFD) mode after pellets exits muzzle.
2. This research is the starting point of apply CAE technique to the shotgun pellets interior ballistics and dynamics performance analysis. In this research, there is only one example has been done, 12-guage with 24gr #9 bird shot. There are variety types of shotgun and shot exist in the market. It is worth to simulate some other kinds of shotgun pellets, and also the choke effects to further verify the CAE applications.

Acknowledgements

This research is done on LSTC at Livermore California under the assistance and support by Dr. John O. Hallquist, Dr. C. S. Tsay, and Dr. Jason Wang, the author is deeply appreciated these gentlemen, without them this research wouldn't be happened so fast.

References

1. David A. Boyer Larry D. Marshall Leslie M. Trzicak Walter F. Rowe, "Experimental evaluation of the distribution of the pellets in shotgun pellet patterns," Forensic Science International, Vol. 42, Issues 1–2, July 1989, Pages 51-59.
2. N. K. Nag, P. Sinha, "An investigation into pellet dispersion ballistics," Forensic Science International, Vol. 55, Issue 2, August 1992, Pages 105-130.
3. David J. Compton, "An Experimental and Theoretical Investigation of Shot Cloud Ballistics," phD. Thesis, University College London, November 1996.
4. A.C. Jones, "Sporting Shotgun Performance: Measurement, Analysis, Optimisation," Published by Hither Brome, ISBN 978-09566627-0-5, Oct. 1, 2010. (http://www.shotgun-insight.com/)
5. Adnan Çelikel1, Yasemin Balcı2, Bülent Üner3, Cengiz Bal, "The Effect of Barrel Length on Pellet Dispersion and Its Importance in Determination of Range of Fire," J for Med, Vol.26, No.2, 2012, Pages 115-123.
6. Jeffrey S. Lee, Gerald B Cleaver, "Exclusion of the Magnus Effect as a Mechanism for Shotgun Pellet Dispersion," SCIREA Journal of Physics, Vol. 2, Issue 3, June 2017, Pages 9-20.
7. David J. Compton, "An Experimental and Theoretical Investigation of Shot Cloud Ballistics," PhD Thesis, University of London, November 1996.
8. Target Telemetrics, "Shotgun Analyzer," (http://www.targettelemetrics.com/)
9. Firearms and Ballistics, Published by Melvyn Lynch, page 51. (https://slideplayer.com/slide/10581502/)
10. Gun News Daily, "Shotgun Shell Sizes: Comparison Chart and Commonly Used Terms," (https://gunnewsdaily.com/shotgun-shell-sizes-comparison-chart-terms/)
11. Hunter Ed Missouri Course, "When Is Your Shot Patterning Correct?," Unit 3, Topic 3, Page 6. (https://www.hunter-ed.com/missouri/studyGuide/When-Is-Your-Shot-Patterning-Correct/201025_700062374/)
12. Tobias Hassel, "Choke," Shotgun Science. (http://www.shotguns.se/html/choke.html)
13. Jianya Yi, Zhijun Wang, Jianping Yin and Zhimin Zhang, "Simulation Study on Expansive Jet Formation Characteristics of Polymer Liner," Materials, Vol. 12, Issue 5, 744, 2019.
14. Zürich Oerlikon, Oerlikon Pocket Book, pp. 81-85, 1958.
15. SAAMI, "Voluntary Industry Performance Standards for Pressure and Velocity of Shotshell Ammunition for the Use of Commercial Manufacturers," SAAMI Standard Z299.2 – 2015, 2019
16. Aimed Research, "High Speed Video Shotgun Shotshell Split Wad Expansion 25,000 frames per second," Nov. 2012. (https://www.youtube.com/watch?v=1if2QKHWmU4)