Design of Lightweight Composite Barrel for Water Jet Disruptor Unit in Bomb Disposal Robot

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***Abstract*—This study deals with a lightweight composite disruptor barrel used in a bomb disposal robot for a disposal operations of improvised explosive devices (IEDs). Powered by a blank .50 BMG cartridge to produce a high-speed water jet to disengage the circuit of IED, the lightweight disruptor barrel consists of an aluminum liner for water and temperature resistance and a carbon fiber reinforced polymer composite (CFRP) as a shell for main load carrying. The composite shell is fabricated by a filament winding technique to ensure a good quality of CFRP. Due to difference in water jet and regular gun firing, the internal pressure of disruptor barrel needs to be estimated by using strain gauges and high-speed data acquisition device. Then, the design phase using finite element method (FEM) simulations with smooth particle hydrodynamics (SPH) technique and material damage criteria are performed in order to optimize the thickness of composite shell and liner geometries. Finally, a lightweight composite disruptor barrel is fabricated and tested as a validation.**

***Index Terms*—disruptor barrel, Carbon Fiber Reinforced Polymer Composite (CFRP), Finite Element Method (FEM), Smooth Particle Hydrodynamics (SPH), filament winding**

I. Introduction

Recently, the bomb disposal robot developed by the faculty of engineering, King Mongkut's University of Technology North Bangkok (KMUTNB) namely DYNA-T have successfully replaced humans in improvised explosive devices (IEDs) disposal operations at the EOD unit of Thailand. This robot uses a blank .50 BMG cartridge to produce a high-speed water jet from stored water in the disruptor barrel to disengage the circuit of IED. For the current model, the disruptor barrel is made of steel which bases on a military machine gun which is considered to be overdesigned and has a lot of weight penalty so that a robot requires a lot of power to move the disruptor unit and it is also difficult to transport by operators. For this reason, this research aims to design a lightweight composite barrel by using a multi-material structure. It consists of a metallic liner for water and temperature resistance and a CFRP composite as a shell for main load carrying. This material has a very high strength to weight ratio especially when using a filament winding technique to fabricate the composite shell. In order to design the lightweight barrel properly, the internal pressure in the disruptor barrel during water jet firing is a key parameter to define the strength of the barrel. Since the firing of water jet is different from the regular air firing of .50 BMG cartridge and the information found in the literature [1] is limited only to air firing, the disruptor firing tests on the current steel barrel have been carried out to characterize this pressure. The measurement method for these tests is a stain gauge with high-speed data acquisition. The measured strains are then converted to internal pressure using material properties. Even though the use of strain gauge is not the most accurate method to determine the internal barrel pressure, this method still has the important advantage over the others. Using strain gauge method does not require a barrel modification other than some surface preparation for gauge installation. For the direct measurement such as copper crusher and piezoelectric methods, a barrel needs to be drilled in order to install the equipment. The previous works [2,3] mentioned about the thermal strain from the continues air firing tests when using strain gauge method. It was also taken into account in their strain analysis. However, in the case of disruptor water jet firing, the water has a superior heat dissipation than the air. It is also a single shot test so that the thermal effect should be weak and can be negligible in the strain analysis. With the barrel pressure identified from water jet firing, the design phase using the finite element method (FEM) simulation is then performed. The objective is to optimize the thickness of composite shell as well as metallic liner geometries. The smooth particle hydrodynamics (SPH) technique is used in the dynamic simulations in order to properly model the water jet firing event of the disruptor. The SPH is a particle method that mostly applies to high velocity and large deformation analysis [4-6]. Although, it can be applied to a quasi-static problem as well. In the work of Tatsuo et al. [7] and Sun et al. [8], the SPH particle models were compared to the classic FEM model for the unconfined uni-axial compression test. They found that the accurate results can be achieved and depends on the number of particles, smoothing length and accuracy of boundaries. Concerning to the material behaviors and damage criteria, the rate dependency of materials also needs to be taken into account. From water jet firing test, the strain rate was

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approximately $0.8x10^3$ to $1.5x10^3$ s^{-1} which is classified as an intermediate strain rate [9]. For a high-strength structural steel S690, its yield strength improves around 20% for 1 s^{-1} strain rate and 60% for $2.5x10^3$ s^{-1} strain rate [10]. In case of an aluminum grade 6061-T6, its yield strength is fairly constant for 10^{-3} to 10^4 strain rates at low temperature and for 10^{-3} to $5x10^3$ strain rates at 300 ℃ [11]. Focusing on a CFRP composite, this material consists of two constituents: carbon fibers and epoxy resin. As a brittle material, an ultimate strength of carbon fiber is independent to strain rate while an epoxy polymer shows an improvement in its behavior with strain rate. As a result, an ultimate strength of CFRP composite is unchanged with strain rate in case of unidirectional ply and improve with strain rate for angle plies [12,13]. After complete a final design, a composite disruptor barrel prototype is fabricated using filament winding technique for validation tests. Fig. 1 shows the composite disruptor barrel from this work successfully installed on DYNA-T.

Figure 1. Composite disruptor barrel installed on DYNA-T

II. Barrel Pressure Identification

A strain gauge method was used to estimate the internal pressure inside the disruptor barrel generated by a blank .50 BMG cartridge during water jet firing. The 350Ω general-purpose resistance strain gauges with EDX-200A-1 data logger and CDV-40B strain card from Kyowa were used. This system is capable to measure at very high sample frequency of 100kHz simultaneously up to three channels which is fast enough to capture the event from this high-speed water jet firing test. With the assumption of non-axial strain, three strain gauges were installed at 90° and 45° angle with respect to the longitudinal axis at the root and in the middle of the disruptor barrel as shown in Fig. 2. Since the test was very aggressive and difficult to setup, the strain gauge wires were risk to be ripped off due to the barrel surge. With two gauges in the middle of the barrel, they are kind of back-up each other, the barrel pressure is still be estimated by only one gauge. Moreover, the results from 90° and 45° gauges can be used to confirm a non-axial strain assumption. According to Mohr's circle theory of strain, if there is no axial strain, the strain readout at the same region from 45° gauge should be a half of the strain from 90° gauge. The experimental results from two gauges in the middle are shown in Fig. 3. The maximum strain from 90° gauge are approximately double comparing to the result from 45° gauge (1972 vs 1102 $\mu m/m$). Unfortunately, the two gauges in the middle of the barrel were damaged after the first test, their results are used only for the validation of non-axial strain assumption.

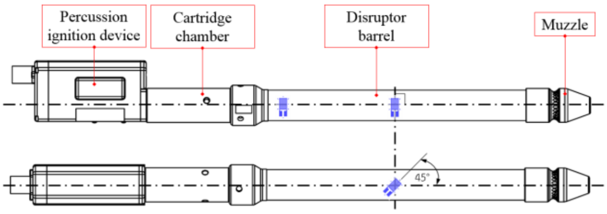


Figure 2. Strain gauges installation on the disruptor barrel

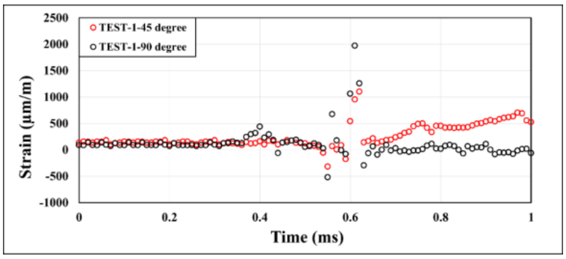


Figure 3. Strain results from 90° and 45° gauges in the middle of the barrel

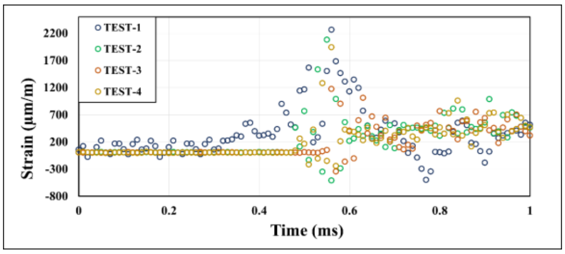


Figure 4. Strain results from 90° gauge at the root of the barrel

The results from 90° gauge at the root of the barrel are shown in the Fig. 4. The measured strains are the hoop strain denoted by ε_θ. The internal barrel pressure, P_i is then calculated by the average of maximum hoop strain from all tests (1856 $\mu m/m$) using the Eq. (1-2) where $\varepsilon_\theta, \varepsilon_z$ represent hoop and axial strain, E and ν are Young's modulus and Poisson's ratio of steel (210 GPa and 0.3), σ_θ is a hoop stress at external surface and finally r_i and r_o are inner and outer radius of the barrel. The Eq. (1) relates stress to strain with material properties and using plane stress assumption since the barrel is open end [2]. With $\varepsilon_z = 0$, the internal barrel pressure, P_i is finally determined at 559 MPa which is greater than the pressure from air firing at 469 MPa [1]. This was unexpected since after each test there was always a gun power left on the target meaning that the combustion was not completed as in air firing. The reason for this contradiction will be discussed later.

$$\sigma_\theta = E\frac{(\varepsilon_\theta + \nu\varepsilon_z)}{(1-\nu^2)} \quad (1)$$

$$P_i = \frac{\sigma_\theta (r_o{}^2 - r_i{}^2)}{(2 r_i{}^2)} \quad (2)$$

III. FEM Simulation: Mesh Size and Pressure Profile

In this section, the FEM dynamic simulation with the smooth particle hydrodynamics (SPH) technique has been carried out to optimize the design of the lightweight composite barrel. In order to implement this simulation technique properly, the mesh size and the input pressure profile needs to be investigated with the experimental results from the steel barrel. The static simulation on a cylindrical steel barrel was performed in order to find the proper mesh size that matches the internal applied pressure at 589 MPa to the hoop strain measured from the 90° strain gauge at 1856 $\mu m / m$. With some iterations, the proper mesh size was identified at 2 mm. Concerning to the pressure profile, the dynamic simulation with SPH technique was then performed on the steel barrel in order to directly compare the hoop strain to the experimental results. The model for simulation is shown in Fig. 5. The muzzle (black) and end cap (yellow) are treated as a rigid body while the steel barrel (grey) and water (azure blue) are deformable solid and fluid respectively. The water mesh will be transformed into particles with SPH technique allowing them to undergo large deformation than the conventional element. The mechanical properties of steel and water are summarized in Table I. The barrel is fixed at its end and the pressure from .50 BMG is applied on the end cap to push the water through the front muzzle.

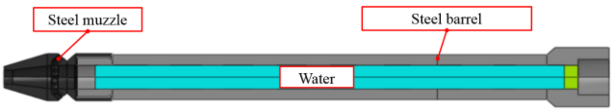


Figure 5. Model of steel disruptor barrel

TABLE I. Mechanical Properties of Steel and Water

	Steel	Water [8]
Density (kg/mm^3), ρ	7.7 x 10^{-6}	1 x 10^{-6}
Young's modulus (GPa), E	210	
Poisson's ratio, v	0.3	
Viscosity (Ns/mm2)		1 x 10^{-8}
C_o (mm/s)		1.5 x 10^6

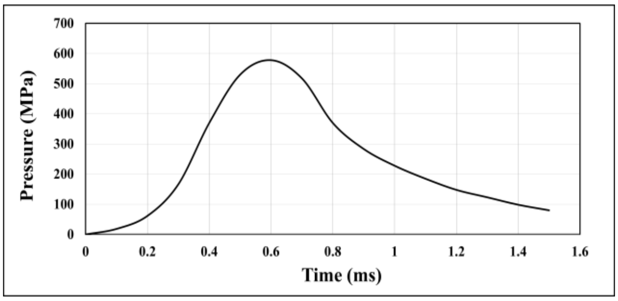


Figure 6. Pressure profile

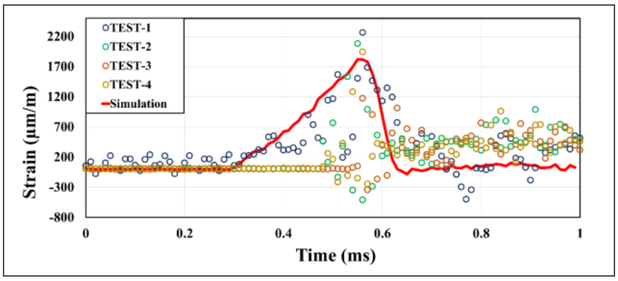


Figure 7. Hoop strain from simulation comparing to experimental results (steel barrel)

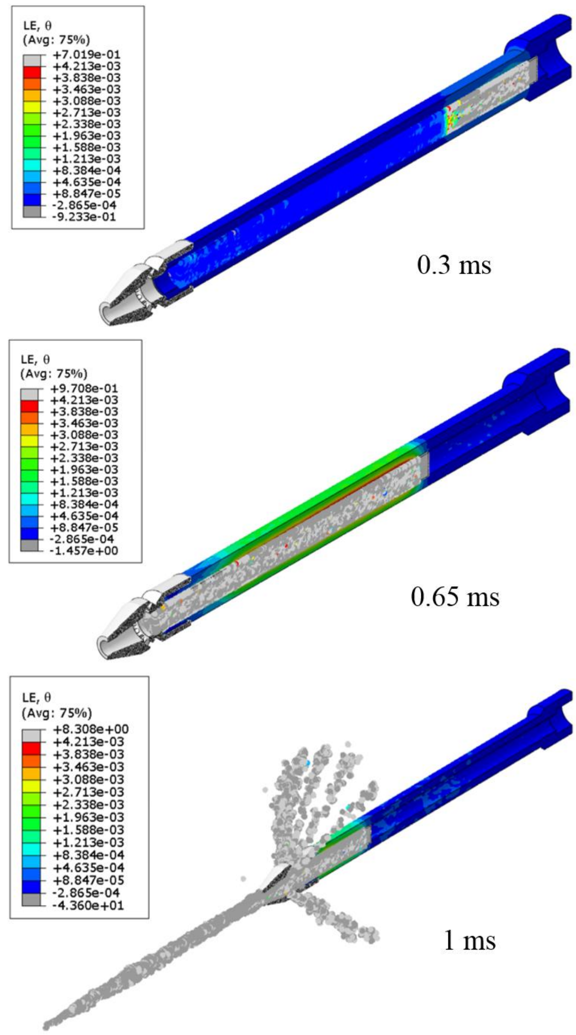


Figure 8. Simulation results at 0.3, 0.65 and 1 ms after water jet firing (steel barrel)

From the previous section, only peak pressure was estimated and the pressure profile should not be the same as the strain profile due to material dumping. Thus, the pressure profile in this study is estimated from the literature [1] by scaling the literature profile with the ratio of peak pressure. The Fig. 6 shown the proper pressure profile used in the simulations. Its peak is slightly shifted from 559 MPa to 578 MPa since it provided more accurate hoop strain when compare to the experimental results as shown in Fig. 7. With SPH technique, the visualization of result is clearly more realistic than the conventional finite element simulation (Fig. 8).

IV. FEM SIMULATION: COMPOSITE BARREL

Since the composite barrel needs to be equipped with steel muzzle and cartridge chamber as a part of disruptor unit (Fig. 2) by means of thread connection which is a weak point of composite material, the multi-material design has been chosen to provide a durability at the connection points. This design consists of the aluminum liner (Al6061-T6) as a liner to provide the thread connection and the CFRP composite shell as a primary load carrier (Fig. 9). This design is also well suitable for a filament winding process. The aluminum liner will serve as a mandrel allowing carbon fibers to wrap around and create a composite shell. The inflated zones on both ends are created by the process due to the change in diameter of the aluminum liner. These zones provide an advantage to the barrel as a reinforcement to the stress concentration zones of the liner. The lean angle of these zones is also investigated by FEM simulation (Fig. 10). The lean angle of 30° appear to be an optimum choice. Even though the stress on composite is less at 45° but at a steep angle like 45°, carbon fibers will slip during winding process even with wet viscid resin.

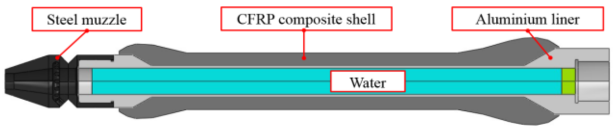


Figure 9. Model of composite disruptor barrel

For the composite shell, the fiber orientation and shell thickness are the key parameters to define its strength. Since there is only circumferential load which confirmed by hoop strain, the perfect fiber orientation would be 90° with respect to longitudinal axis. At this angle, all fibers will fully support the load corresponding to the philosophy of composite design. However, the best angle in practice limit to +/-88° due to a nature of filament winding. Concerning to the shell thickness, the prototype of composite barrel is intended to use with the test rig where its mounting clamp limit the maximum thickness of the composite shell to 8 mm. For this reason, the thickness of 8 mm. is chosen for FEM simulation. If this design cannot sustain the water jet firing predicted by simulation then other modifications will be suggested.

The CFRP composite properties (Table II) are from the previous work that dedicated mainly to a CFRP composite pressure vessel using a filament winding technique [14]. These properties are for a unidirectional CFRP composite which are base properties for composite shell. The local axis needs to be specified into the composite shell in finite element model. The primary direction is defined by a longitudinal axis and the perpendicular direction is defined locally normal to the surface of the barrel. The composite shell is then divided into 10 plies to simplify the composite structure fabricated by filament winding [14]. Each ply is additionally assigned to the primary direction a fiber orientation according to the winding angle of +/-88° measured from longitudinal axis and creates a composite stacking of $[2°, -2°]_5$. The direction 1 which represents fiber direction follows the local axis of this stacking and the direction 33 follows the perpendicular direction. These are typically the rule to define the local axis of composite. Fig. 11 demonstrates composite local axis for 90° winding angle which correspond to a composite stacking of $[0°]_{10}$.

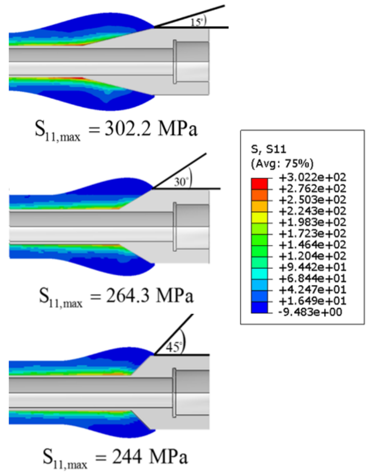


Figure 10. Fiber direction stress, S_{11} on composite shell with different lean angle

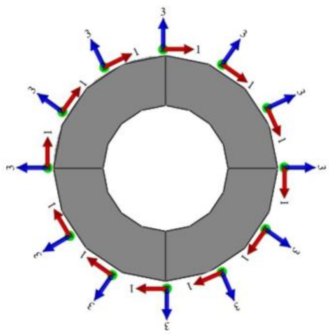


Figure 11. Local axis of composites for 90° winding angle (1 = fiber direction and 3 = laminate perpendicular direction)

TABLE II. PROPERTIES OF CFRP COMPOSITE WITH EPOXY RESIN [14]

CFRP composite: UD, V_f = 59% Density, ρ = 1.8 x 10^{-6} kg/mm^3	
E_{11} (MPa)	134220
E_{22} (MPa)	8175
E_{33} (MPa)	8175
ν_{12}	0.36
ν_{13}	0.36
ν_{23}	0.38
G_{12} (MPa)	4697
G_{13} (MPa)	4697
G_{23} (MPa)	2962
X_t (MPa)	2104

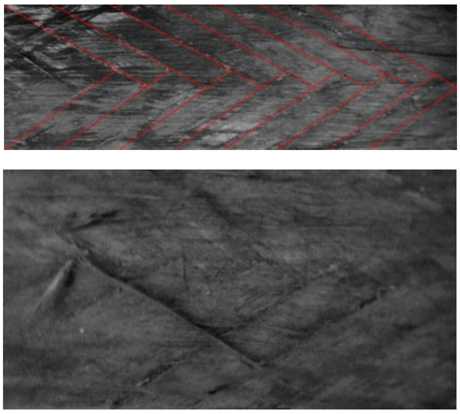
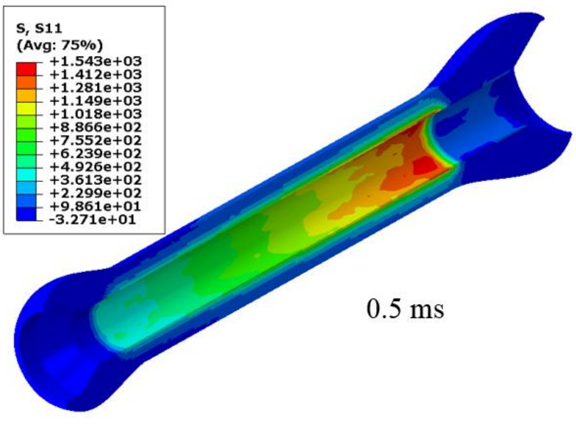
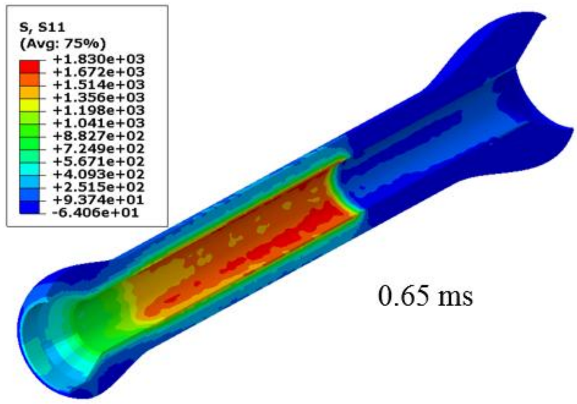


Figure 12. Fiber mesh interlocking from filament winding process

The damage of composite shell can be predicted by using failure criteria. With unidirectional loading (circumferential direction) applied entirely on a fiber direction of composite shell, the fiber break damage is expected. This damage mode in filament winding composite can be predicted using the simplest criterion, the maximum stress criterion in tension mode written as $\sigma_{11} < X_t$. The effect of shear stress will not be involved in fiber break mode as it does in Hashin criterion due to the interlocking of fiber mesh occurring specifically from filament winding process. Fig. 12 shows the close-up image of fiber mesh interlocking from $[30°, -30°]_S$ filament winding composite stacking where this effect is clearly visible than the stacking used in this work. This interlocking also plays an important role in other failure modes of composite namely a matrix cracking and inter-ply delamination. Unliked a conventional composite laminate which is a combination of unidirectional plies leading to a continuous interface for both inter and intralaminar. This continuous interface makes the other two modes (matrix cracking and delamination) significant to composite laminates since cracks from these two modes can be propagate across the laminates leading to a significant behavior degradation. For a filament winding composite shell, the fiber mesh interlocking discontinues that interface. Consequently, the crakes are no longer propagate across the section but creased within fiber mesh. This is also the other reason why in this work only the fiber break mode was considered.





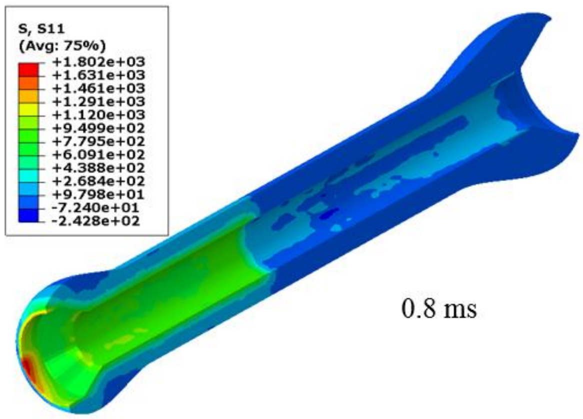


Figure 13. Simulation results of composite shell at 0.5, 0.65 and 0.8 ms after water jet firing (composite barrel)

For the aluminum liner, the simple elastic behavior is used ($E = 72$ GPa, $\nu = 0.32$ and $\rho = 2.8\text{x}10^{-6}$ kg/mm^3). The simulation with SPH technique is then performed. The result at 0.65 ms after firing is shown in Fig. 13, the stress in fiber direction is maximum at 1830 MPa less than the X_t of composite and corresponding to the factor of safety (FOS) of 1.15. This value appears to be on a lower side for composite. However, due to the fact that this simulation is backed up by a lot of experimental results, it seems to be very accurate so that the FOS of 1.15 is quite acceptable. The design of composite shell is then finalized at 8 mm. thickness with +/-88° winding angle.

V. Validation of Composite Barrel

The composite barrel prototype was fabricated using filament winding technique for validation tests (Fig. 14). It weighs 0.87 kg, almost 70% lighter than the steel barrel. Then, the water jet firing tests were performed on a specific test rig where only disruptor was mounted on a rigid steel stand for security reasons (Fig. 15). With several tests, the composite barrel was able to withstand the pressure load from water jet firing without any damage.

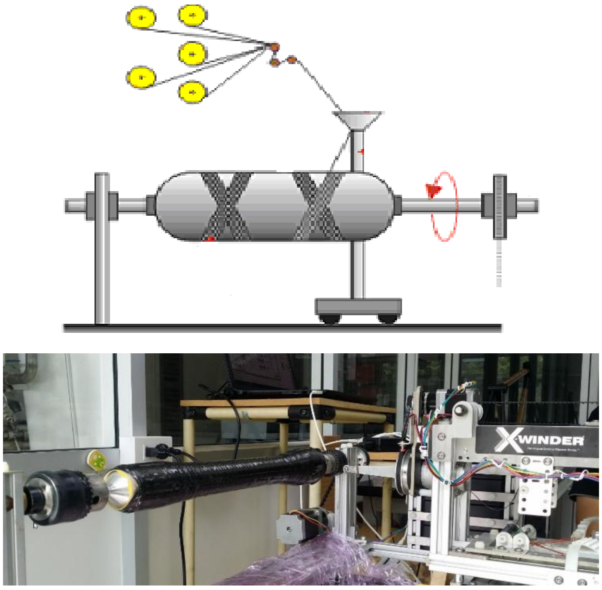


Figure 14. Composite barrel frabrication using filament winding

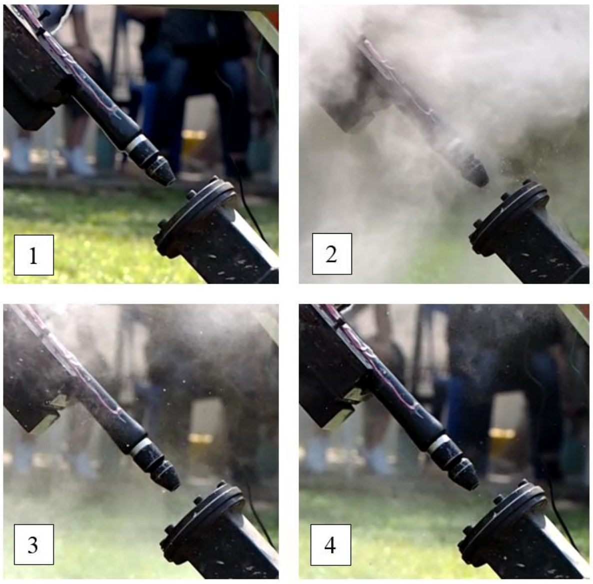


Figure 15. Water jet firing test on composite barrel prototype

For the two-last test, the strain gauges are installed in the middle of the barrel at the angle of 90 ° and 45 ° taking the advantage to compare the hoop strain with simulation results. The results from strain gauges at 90 ° and 45 ° confirm again a non-axial strain assumption (1650 vs 894 µm/m).

The hoop strain comparison with the simulation is shown the Fig. 16, a good agreement is found when considering the peak value. However, the simulation shows a noticeable longer time of action. This explains the contradiction of peak pressure from waterjet firing and air firing mentioned previously. The air firing will have a lower peak pressure due to the fact that it only needs to push a few grams of bullet head while in water jet firing, the pressure needs to be built up higher in order to push a mass of water stored in the barrel. Concerning to the gun powder leftover after water jet firing, it means that the water jet firing has less total energy comparing to air firing. This assumption relates to the shorter time of action which is clearly proved in the comparison in Fig. 16. Since the simulation took the pressure profile of air firing and scaled with only peak pressure, it performs longer time of action than the experimental results.

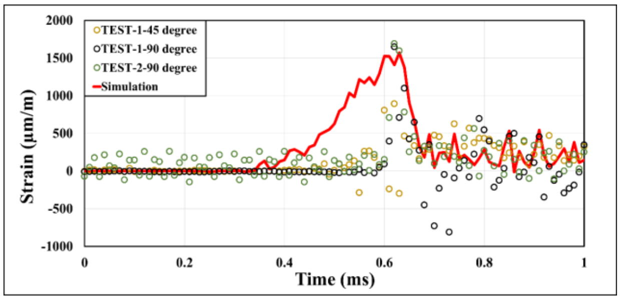


Figure 16. Hoop strain from simulation comparing to experimental results (composite barrel)

VI. Conclusion

The design of lightweight composite barrel was successfully completed. The weight reduction is almost 70% comparing to the current design steel barrel. The numerical approach using FEM simulation with SPH technique to model a water jet firing test show a good agreement with experiment results. It also clarifies the high peak pressure identified by strain gauge measurement and gun powder leftover observed in water jet firing. To improve the simulation results, the pressure profile of water jet firing needs to be characterized with direct measurement such as piezoelectric method which require the modification of disruptor barrel. Concerning to the composite barrel prototype, even it passed several water jet firing tests, the long-term damages which usually occur in microscopic scale still needs to be studied in order to estimate its lifetime. This parameter is crucial for the commercial scale production of this composite barrel.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mr. Veeraphat Tangtongkid as first author to conduct the research under the supervision of Asst. Prof. PhD. Baramee Patamaprohm (corresponding author), a chief of the research team, who finalized a manuscript. Mr. Kerati Suwanpakpraek 2nd authors contributed in performing the experiments and preparing simulation needs. All authors contributed in writing the manuscript and had approved the final version

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