FBG testing on inside strain capturing of concrete blocks subjected to hard projectiles penetration

D C Gao¹, W J Yao¹, Y Ren², R Wang³, Q Wu³,⁴ and J Feng⁴,⁴

¹ School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China.
² China Research and Development Academy of Machinery Equipment, Beijing 100089, China.
³ State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
⁴ National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, China.

gaodacheng001@163.com

Abstract. This study evaluates the terminal ballistics and strain behaviors of normal strength concrete blocks penetrated by hard ogival-nosed projectiles. Fiber Bragg Gratings (FBG) sensors are utilized herein to measure the radial strain responses inside concrete target during penetration process. With precise location, a novel method of FBG sensors embedment inside concrete block is proposed. The penetration tests are conducted with ballistic gun whereby the FBG sensor reflected signals are recorded. Consequently, Holmquist–Johnson–Cook (HJC) model is used to describe the concrete material dynamic behaviors. The LS-Dyna numerical penetration model is validated by Depth of Penetration (DOP) prediction. The numerical radial strain inside concrete target matches well with the experimental data by FGB testing.

1. Introduction
Characterized with high compressive strength, easily shaping, good thermal properties and low cost, concrete material has been widely used in most of human civilization, including buildings, bridges, dam, bay and civil defense etc. Over past years, continuous interest in the design and construction of high performance protective concrete structures to resist impact and explosive loads has greatly contributed to the investigations of the impact of a hard projectile on a concrete target [1]. Moreover, requirement to assess the safety of concrete shelter against any possible projectile penetration considerably promotes the understanding of the concrete penetration mechanism. Extensive concrete penetration tests [2-6] have been performed to study the dynamic behavior of the concrete target.

The operation principle of fiber optic sensors is based on the feature that variations on external parameters can induce changes in the properties of the light guided by the optic fiber. These external parameters might include strain, displacement, pressure and temperature, between others. The fiber optic sensors have been employed in the measurement of several parameters of bridge structures, such as, strain, displacement, pressure, load, acceleration, rotation, temperature, concrete cracking and reinforcement corrosion monitoring, by means of both embedded and externally installed solutions. FBG technology is also the most frequently applied in civil structures. The application of these sensors
to steel bars embedded into concrete or to critical structural elements such as prestress tendons, FRP reinforcements, cables, ties or bracing bars has been the traditional solution for bridge local strain monitoring [7]. And the fiber Bragg grating (FBG) technology has demonstrated intrinsic and suitable characteristics adequate for structural monitoring, making it one of the most widespread and competitive optical technologies.

In the present paper, 30CrMnSiNi2A high strength steel alloy projectiles are used to impact the concrete targets to avoid erosion. FBG sensors are utilized herein to measure the radial strain responses inside concrete target during penetration process. With striking velocity ranging from 389.3 m/s to 565.5 m/s, it was found that the dimension change of projectile is negligible. Holmquist–Johnson–Cook (HJC) model is used to describe the concrete material dynamic behaviors. LS-DYNA is used to simulate the penetration process. The correctness of the model is verified by comparing the DOP data of experiment and numerical calculation. The strain behaviors obtained by numerical simulation are compared with the data measured by FBG sensor.

2. Experimental program

2.1. Projectile
Made of high strength steel alloy 30CrMnSiNi2A [11], the project was manufactured with 14.5 mm in diameter and 90 mm in length. The main chemical and mineral compositions of 30CrMnSiNi2A alloy are strictly controlled whereby iron accounts for 96.8% of the alloy while carbon is controlled at a low level. After heat treatment, the ultimate tensile strength of 30CrMnSiNi2A steel alloy was 1650 MPa and its Rockwell hardness was measured as 50 HRC. The ogival nose projectiles 3.0 calibre-radius-head (CRH) were investigated for penetration test. In order to improve the striking velocity, the projectile interior was hollowed out and sealed with nylon bottom to reduce the weight as depicted in figure 1.

![Figure 1. Projectile dimensions (unit: mm).](image)

2.2. FBG sensor
The FBG sensors are based on the possibility of photo inducing a permanent periodic modulation of the core refractive index in a small extension of a single-mode optic fiber. An FBG sensor acts as a selective wavelength reflection filter that reflects just the spectral part satisfying the Bragg condition with the wavelength of the peak reflectivity, $\lambda_b$, expressed as,$$
\lambda_b = 2n_0dA
$$
where $n_{0f}$ is the effective refractive index of the fiber core at the free-space center wavelength, and $A$ is the grating period. The remaining spectral portion of the input light crosses the FBG sensor without any significant disturbance [8-10]. Inherent to the Bragg condition, both strain and temperature variations will change the effective refractive index and the grating period, leading to variations in the peak wavelength reflected by the sensor. Therefore, the reflected peak wavelength, when submitted to a strain variation, $\Delta \varepsilon$, and a temperature variation, $\Delta T$, shifts by a magnitude of $\Delta \lambda_b$, which can be expressed as,$$
\Delta \lambda_{b\text{eff}} = P_e\Delta \varepsilon + \frac{P_e(a_{t\text{eff}} - a_{t})}{\xi} \Delta T
$$
where $P_e$ is the strain-optic coefficient, $a_{t\text{eff}}$ and $a_{t}$ are thermal expansion coefficients of the base structure material and of the optic fiber itself, respectively, and $\xi$ is the thermo-optic coefficient.
2.3. Concrete target preparation
C30 industrial concrete was used herein as the target material which was cast with ordinary portland cement (PO42.5), sand, aggregate, water and additive. The detailed mixture proportion was listed in table 1. The aggregate size varies from 5 mm to 15 mm. The compressive strength of 15 cm³ cubic concrete was measured as 30.8 MPa after 28 days curing. The $f'_{c}$ defined as the unconfined uniaxial compressive strength for cylinder with 4 inches height and 2 inches diameter was estimated as 28.8 MPa. Hence, $f'_{c} = 28.8$ MPa was utilized for the sequent numerical simulations.

| Table 1. Proportion for concrete per m³. |
|----------------------------------------|
| Cement (kg)  | Sand (kg)  | Aggregate (kg) | Water (kg) | Additive (kg) |
|-------------|------------|----------------|------------|---------------|
| 348         | 764        | 1083           | 180        | 5.22          |

Given the influence of concrete boundary effect, the target cross section dimension was selected as 400 mm × 400 mm which was much larger than 25 times of shank diameter [12]. To ensure the deep penetration condition, the thickness was designed as 400 mm. The fresh concrete matrix was cast into the steel formwork welded by 4 pieces steel plates with 5 mm thickness. On each side of the formwork, a hole was drilled so that the steel pipe can cross the target body. By threading the optical fiber through the steel pipe, the FBG sensor was precisely located at the center of the cross section with 10 cm buried depth from the impact surface, as shown in figure 2. After FBG sensor allocation, the steel pipe was pulled out and the fresh concrete was carefully vibrated to guarantee compaction but avoid sensor damage.

The uniform Fiber Bragg Grating with the simplest structure is formed by the periodic change of the refractive index of the fiber core. The change of external stress, strain, temperature, concentration and other conditions results in the change of parameters such as effective refractive index and grating period, which results in the change of resonance wavelength of Fiber Bragg Grating. The external response information is obtained by measuring the change of resonance wavelength. Put one end of the FBG sensor pigtail into the steel sleeve, and then put the steel sleeve into the positioning hole on the template. The distance between tools such as vibrator and steel pipe shall be controlled during manual pouring. The steel sleeve shall be drawn out immediately after the pouring, and the concrete shall be tapped locally to ensure good contact between the concrete and FBG sensor.

2.4. Penetration test setup
Launching with a 14.5 mm caliber ballistic gun, the penetration test was carried out in the middle range ballistic laboratory as diagramed in shown in figure 3. On the right side of trajectory, a high-speed camera was used to capture the flying projectile whereby the projectile striking velocity
can be further calculated using the ruler scale at \( t_0 \) and \( t_0+dt \) time, as depicted in figure 4. The back support was utilized to prevent the possible displacement of the target body during projectile penetration. Behind the backing edge, a sandbag was also prepared to recover the projectile body that may perforate the target.

2.5. Penetration test results

To investigate the penetration with various striking velocities, the high strength steel alloy projectiles were fired with different amount of propellant. Shots labeled with S1 to S4 were conducted with 17.0, 16.0, 15.0 and 11.2 g propellant in sequence. The striking velocity was measured as 565.5, 505.0, 498.0 and 389.3 m/s (listed in table 2) according to foregoing projectile velocity estimation method.

After ballistic gun shooting, all the targets were not perforated, and no collapse observed on the rear surfaces. A square contour as well as several radial cracks occurred on the target impact surface as shown in figure 5. As listed in table 2, the DOP value for each shot was achieved by measuring the depth of terminal ballistic tunnel + the projectile length. By coring the target zone near ballistic tunnel, the projectile was retrieved by removing the surrounding concrete matrix. The length and mass of the recovered projectiles were measured and negligible changes occurred, although obvious scratches happened.
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Figure 5. Target damage and projectile recovery.

Table 2. Penetration experimental results.

| Test No. | Propellant (g) | Striking velocity (m/s) | Mass loss (g) | DOP (mm) |
|----------|----------------|-------------------------|---------------|--------|
| S1       | 17.0           | 565.5                   | 0.6           | 177    |
| S2       | 16.0           | 505.0                   | 0.8           | 150    |
| S3       | 15.0           | 498.0                   | 0.6           | 147    |
| S4       | 11.2           | 389.3                   | 0.5           | 108    |

Fortunately, the FBG signals were all captured for all four penetration tests. The strain history results were plotted in figure 6 where negative value denotes the compressive response for the concrete material near the sensor. The S1 has a pulse to plateau (exceeding the range) which was then followed by a gradual decrease. S2 and S3 seemed to overlap each other except for the peak difference. S4 shows the smallest response since its striking velocity is the minimum.

Figure 6. FBG data.

3. Numerical modeling and validation

3.1. Numerical model for penetration

This work used LS-DYNA solver for penetration simulation. The projectile and target were both modelled by 3D solid 164# element. Considering the symmetry of the structure, only 1/2 of the model was created, and the grid of the interaction area between the missile body and the target body is remeshed, as shown in figure 7.
In the experiment, it was found that the dimension change of projectile is negligible. Therefore, *MAT_RIGID* is used in the simulation, and \( \rho = 7.83 \text{ g/cm}^3 \), \( E = 216 \text{ GPa} \), \( \nu = 0.3 \). The widely recognized Holmquist-Johnson-Cook (HJC) model was used to describe concrete material mechanical responses, the constitutive laws were shown in figure 8.

*MAT_ADD_ERODING* keyword was used to delete failure element. The contact between the projectile and the concrete is the face-to-face eroding contact. The HJC model parameters for concrete material were shown in table 3.
Table 3. HJC parameters for concrete material.

| RO  | $G$  | $A$  | $B$  | $C$  | $N$  | $FC$  | $T$  | $EPS0$ | $EFMIN$ |
|-----|------|------|------|------|------|-------|------|--------|---------|
| 2.3 | 0.1486 | 0.79 | 1.6  | 0.007 | 0.61 | 2.88E-4 | 2.88E-5 | 1E-6   | 0.01     |

| $SFMAX$ | $PC$  | $UC$  | $PL$  | $UL$  | $D_1$ | $D_2$  | $K_1$ | $K_2$  | $K_3$  |
|---------|-------|-------|-------|-------|-------|--------|-------|--------|--------|
| 7.0     | 1.6E-4 | 0.001 | 0.008 | 0.1   | 0.04  | 1.0    | 0.85  | -1.71  | 2.08   |

3.2. Numerical results discussion

The detailed result data of penetration simulation can be obtained during projectile penetration process. The final DOP value for each penetration was compared with the test data for numerical model validation. The DOP relative errors were controlled within 9% indicating good prediction of test DOP as shown in table 4.

Table 4. Numerical results of DOP.

| Simulation No. | Impact velocity (m/s) | DOP for simulation (mm) | DOP for experiment (mm) | Relative error |
|----------------|-----------------------|-------------------------|------------------------|----------------|
| S1             | 565.5                 | 187                     | 177                    | 5%             |
| S2             | 505.0                 | 164                     | 150                    | 9%             |
| S3             | 498.0                 | 163                     | 147                    | 2%             |
| S4             | 389.3                 | 114                     | 108                    | 6%             |

Based on the penetration experimental results, it was revealed that the impact location is less than 1 cm distance from the designed impact location i.e., the center of the impact surface. The strain evolution of target inside concrete material was numerically obtained by selecting the element 1.0 cm away from the ideal ballistic tunnel. The comparison between numerical strain data and test results was shown in figure 9 where the good agreement was achieved in terms of amplitude and tendency during 1.2 ms. Both experimental and numerical data suggested that the compressive strain has little change until about 0.18 ms the projectile nose part start to create the tunnel near the sensor. After the pulse, the strain remained almost constant during penetration process.

The final status of target with project stopped inside was shown in figure 10 where the Von-Mises stress contour was plotted in $10^{11}$ Pa. A mushroom-shaped damage zone with $>26$ MPa Von-Mises stress was depicted in figure 10, which phenomenon was also captured by [8].
Figure 9. Comparison of strain data between simulation and experiment.

Figure 10. Mises stress contour (unit: $10^{11}$ Pa).

4. Conclusion
This work experimentally and numerically instigated the hard projectile penetration into thick concrete target. A novel approach was proposed to embed the tinny FBG sensor into the concrete target body. The DOP values were captured by the FEM penetration simulations. While the tested strain history was also matched by the numerical modelling which in turn validates the sensor collected strain results. This work provides a proper method for penetration researchers to measure the target inside information which may shed some lights on the mechanism of penetration in concrete.

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