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Using MSC.Patran as a Tool for the Numerical Stress Analysis of a Shock-loaded Bullet-resistant Door

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There are two methods commonly used to determine the effectiveness of a bullet-resistant door: one involves the use of sensors attached to various locations to detect cracking following impact and the other employs software simulations. In this study, we utilized the finite element method (FEM) analysis software MSC.Patran to perform stress analyses on a designed bullet-resistant door, subjecting it to various external forces. Utilizing the FEM simulation method eliminates the need for attached sensors to detect the effects of impacts. The focus is on developing a shock-loaded door that can withstand various impacts with minimal visible damage or deformation. In this study, we primarily examine the effects of different impacts on a designed bullet-resistant door through simulation using MSC.Patran's FEM. The software was employed to simulate and compute stress and displacement distributions, as well as the response force of the entire door structure, while assuming various conditions such as steel structure, welding strength, and material, among others, under different impact conditions. The impacts were generated by a 125 kg and 8 inch armor-piercing projectile, a car, or a solid steel ball, and an earthquake with a magnitude of roughly 6.4 was added to the stress conditions to analyze and simulate the stresses. The results of different impacted objects were discussed. The findings revealed that, under the aforementioned conditions, the designed door structure could effectively withstand external impacts without damage. On the basis of the analysis results, it was determined that the steel panel, steel structure, and latch of the bullet-resistant door were capable of resisting the combined impacts of the specified foreign objects.

1. Introduction

A door is typically hinged but sometimes attached by other mechanisms such as tracks.(1) Usually, a door is designed to have multi-resistant functions, including bullet(2) and fire

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resistance.(3) When designing a bullet-resistant door, it is important to adhere to established specifications. The 1990 version of the US Army TM5-1300 is the most commonly used design specification. Several factors, such as deflection limit, rebound mechanisms, and fragment protection, must be considered. To analyze military bullet-resistant doors, engineers study the behavior of the door's plate under explosion pressure, as it will likely deform. As such, deflection is the primary criterion for determining the level of protection provided by military-grade blast-resistant doors, as outlined in the aforementioned specifications. The degree of deformation in the door's plate is measured by the rotation angle of the door bearing and can be divided into four stages. During the first stage, the door remains in the elastic range, and no permanent deformation occurs, allowing it to remain functional. During the second stage, the rotation angle of the door bearing is limited to two degrees, and while the door is no longer in the elastic range, it only experiences small permanent deformation that does not compromise its functionality. Moving to the third stage, the rotation angle of the door bearing is between two and four degrees, causing significant permanent deformation that renders the door unusable. In the fourth and final stage, the rotation angle of the door bearing exceeds four degrees but remains below twelve degrees, resulting in severe permanent deformation that restricts the door's capabilities to absorbing external forces.

From the above definitions, we can see that the larger the rotation angle of the door bearing, the greater the deflection of the door panel will be. The specifications recommend that the rotation angle of the door bearing should preferably be less than two degrees. This specification indicates that the door is capable of effectively blocking explosion pressure and fireballs from entering the structure, providing reliable protection for personnel and equipment. In addition, to avoid the difficulty in maintaining the door body in the future, it is better that the deformation is within the elastic limit. However, the cost of the fabricated door is high; therefore, a method of designing a door with a high safety factor and a low cost is worth developing. In terms of economic cost and efficiency, one of the benefits of computer simulation analysis is that it can simulate all types of dangerous conditions and has the potential to convert a design object from concept to reality in a computer without building a physical model and under safe conditions.(4–6) Simulation can improve the design, shorten the development cycle, and reduce the product cost. The core of the computer-aided engineering simulation process is that we can use computers to predict the structural response when the actual conditions are constrained by the external environment. Finite element method (FEM) analysis is a software method that can be used to determine how this model responds to the environment. Moreover, the simulation results can also be used to compare with the actual measured results.(7–9)

In 2015, Kwon *et al.* suggested a simulation-based approach to predict the compressive strength of concrete used in the construction of nuclear power plant buildings during their early years.(10) This method involved selecting different solidification conditions and conducting tests. They identified three representative parameters for the mixed soil strengths of concrete, which were 6000 lbs (41.4 MPa), 4500 lbs (31.0 MPa), and 4000 lbs (27.6 MPa), on the basis of the experiments conducted. The tests were conducted at temperatures ranging from 10 to 40 °C and relative humidity levels ranging from 40 to 100%. They discovered that the concrete strength varied depending on the relative humidity and temperature. The simulation results indicated that the most effective approach to determining the appropriate strength of each concrete mixer was to adjust the humidity levels to the corresponding functional parameters. Previously, two methods were commonly used to evaluate the effectiveness of a designed bullet-resistant door. The first approach involved using sensors attached to various locations to detect cracking following a shot. For instance, Adrian conducted a study on a sensing system designed to detect threat data, which indicates the existence of a ballistic threat.(11) Additionally, some modern industrial products also use different sensors to sense the outcomes of being hit by bullets.(12,13) The other method uses software to simulate the effect of a shock impact on a bullet-resistant door, and in this study, we used this method.

The aforementioned research demonstrates that simulation methods are crucial for designing effective bullet-resistant doors. MSC.Patran (abbreviated as Patran), developed by MSC Software, was one of the first commercially available nonlinear finite element software programs investigated. It is a versatile and robust FEM analysis software program that can accurately model the behavior of products under various loading conditions, including static, dynamic, and multi-physics conditions. Patran's functions are versatile, and it can be used to model nonlinear material behaviors and transient environmental conditions. Therefore, it can be used to simulate and solve many complex design problems. In this study, Patran was used as the FEM software to analyze the failure mechanics of the designed bullet-resistant doors. The impact conditions in this study included a car, an armor-piercing projectile, and a solid steel ball, and the effect of an earthquake was also incorporated to analyze the stress distribution results using Patran simulation software. The complex impact loads were meticulously analyzed to evaluate their effects on the structure of the designed bullet-resistant doors using the principles outlined in FEM textbooks.(14)

2. Simulation Process and Parameters

The primary performance evaluation simulation was undertaken to gauge the stresses of a designed bullet-resistant door generated separately by an armor-piercing projectile, a car, or a solid steel ball, which were combined with the impact of an earthquake. Patran is the most widely used FEM analysis processing software in the world, and it is a toolset that can have the function to provide geometry construction and editing. When Patran is used, parts with 2D and 3D outlines, surfaces, and solid geometry can be created quickly. Patran can also provide the solid modeling, meshing, analysis setup, and postprocessing for multiple solvers, including MSC Nastran, Marc, Abaqus, LS-DYNA, ANSYS, and Pam-Crash. Patran provides a rich toolset, which simplifies the creations of analytical models for linear, nonlinear, explicit dynamics, thermal, and other finite element simulations. In this study, after using Patran to establish the geometric shape, the meshing tool is used to establish the finite element mesh, including the automatic meshing of curves, surfaces, and cubes, and to set the size of elements. Therefore, Patran allows subsequent analysis by different FEM analysis software programs to provide accurate results.

The door leaf was welded using a solid steel plate assembly structure, which conformed with the specifications of ASTM A240-316L. The door frame was also welded using a solid steel plate assembly structure, which conformed with the specifications of ASTM A240-316L. Door hinge fittings were fabricated using stainless steel, which conformed with the specifications of ASTM A240-316L. The handle was made of stainless steel, which conformed with the specifications of ASTM A240-316L. Latches were fabricated using stainless steel, which conformed with the specifications of ASTM A240-316L. Door resistance was fabricated using stainless steel, which conformed with the specifications of ASTM A666-316. Fixing bolts and pins were made of ASTM A108 alloy steel, and the embedded sheet metal was fabricated from ASTM A36 alloy steel. The allowable stresses of the materials used are listed in Table 1.

The load types are described in Table 2. The designed shock-loaded bullet-resistant doors were simulated by different impacts, including an 1800 kg car (hereinafter referred to as a car), a 125 kg and 8 inch armor-piercing projectile (an armor-piercing projectile), or a 1 inch solid steel ball (a solid steel ball). In addition, an earthquake effect was also considered, and therefore, there were three different loads for analyses.

The parameters of the designed door are listed below:

Label: AFB- MRD-01, door length: 2260 mm, door width: 1155 mm, material: A204-316L, surrender strength of A204-316L: 207.2733 MPa, and tensile strength of A204-316L: 93.271 MPa.

Impact of a car collision: $F = \mu \times [m(t)] \times V(t) = 91500$ nt, where $\mu = 1$, $m = 1800$ kg, and $v = 51$ m/s = 183.6 km/h.

Impacts of an armor-piercing projectile or a solid steel ball: $F = E/DF^2 = S \times (16000 \times T^2/F^2 + 375 \times WT/F^2)/46500 = 1994$ nt, where $S = 32.271$ Ma, $T = 8$ mm, $W = 0.15$, and $F = 5.4$.

Earthquake: horizontal acceleration design = 0.39 g, and vertical acceleration design = 0.31 g.

After setting the basic load types and parameters, a model of a bullet-resistant door was first constructed according to the geometric shape and structural material. Its internal structure was cut and welded from ASME A36 H-shaped steel to construct its skeleton structure, as shown in Fig. 1(a). After covering the ASME A240-316 plate and various components, the external structure of the designed door is as shown in Fig. 1(b). For the hinge, there was no displacement

Table 1
Allowable stresses of materials used.

ASTM	Young's equation E	Yield stress F_y	Tension $0.45F_y$	Shear force $0.4F_y$	Bending force $0.66F_y$	Bearing capacity $0.9F_y$	Compression force $0.75F_y$
Material name	kgf/cm^2	kgf/cm^2	kgf/cm^2	kgf/cm^2	kgf/cm^2	kgf/cm^2	kgf/cm^3
A36	2.04E+06	2536.4	1141.4	1014.5	1674.0	2282.7	1902.3
A108	2.04E+06	3500.0	1575.0	1400.0	2310.0	3150.0	2625.0
A283	2.04E+06	1690.9	760.9	676.4	1116.0	1521.8	1268.2
A240-316	2.04E+06	2113.6	951.1	845.5	1395.0	1902.3	1585.2

Table 2
Load types.

1	A car collision and an earthquake (about 6.4 Richter scale)
2	An armor-piercing projectile and an earthquake (about 6.4 Richter scale)
3	A solid steel ball and an earthquake (about 6.4 Richter scale)

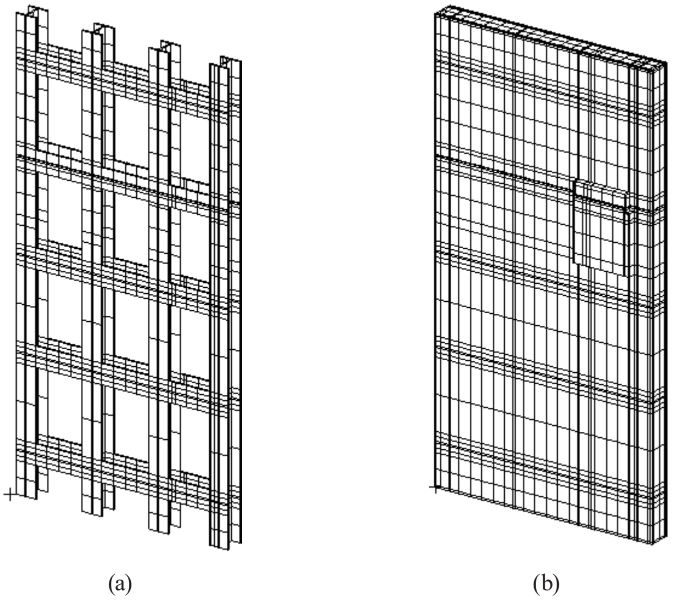

Fig. 1. Skeleton structures of (a) the bullet-resistant door and (b) the bullet-resistant door covered with a sheet.

or rotation between the door and the hinge. For the latch, only the x-direction was free, indicating that the door could move in the x-direction and the latch could be locked or unlocked.

3. Simulation Results

Because the stress on the structure leads to complex impact loads, the structural loadings or impacts of bullet-resistant doors were analyzed using software with FEM analysis as its core, and Patran software was used for analysis. Under the above impact conditions, the critical point of impact for the designed door is calculated by FEM simulations. When the impacts are applied as shock loads on the doors, reactive forces cannot be resolved theoretically or empirically. Therefore, in this study, the software with FEM analysis as the core was used to analyze the impacts causing the stress and deformation of the designed bullet-resistant door. In this designed door, the components included the hinges and snap locks. However, in the applications of different impacts, the reaction forces of the hinge and spring lock were still unknown, and they were not easy to solve theoretically. Therefore, the software with FEM analysis as the core was selected to analyze the effects of different impacts on the bullet-resistant door, and the analysis results were used to determine whether the strength of each part of the door was sufficient.

3.1 Load I: a car collision and an earthquake

A car of 1800 kg weight was used as the impact source, and the impact was v = 51 m/s = 183.6 km/h. The contact region of the door center was 20 ft^2, the impact was 91500 nt, and the total impact time was 0.2 s. For an earthquake, the horizontal acceleration design was 0.39 g and the vertical acceleration design was 0.31 g. Next, we discussed the effect of dispersing impacts on a symmetrical model. The maximum stress was less than the yield stress, and the displacement did not pose a risk of penetration to the door panel. However, it will cause a depression at the center of the structure, and the door was designed to be safe. The simulation results showed that the weld strength of the I beam in the designed door was sufficient. The maximum stress of the welded joint was 4.63 MPa, which was considerably less than the yield strength of the A36 material of 250 MPa. The simulation results also showed that the maximum stress of the door after the impacts of a car collision and an earthquake was 27.6 MPa (Fig. 2), the maximum displacement of the door was 0.076 mm (Fig. 3), and the maximum force of the door latch was 646.5 N (Fig. 4). These simulation results prove that the junction strength is reliable.

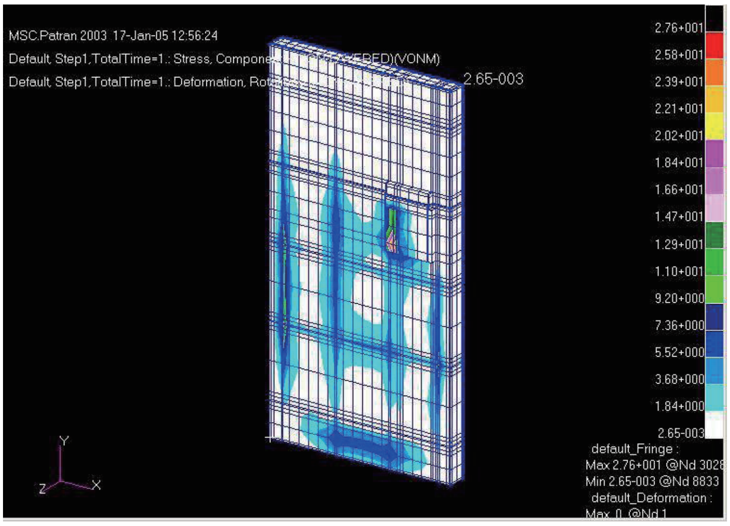

Fig. 2. (Color online) Stress distribution of the door after the impacts of a car collision and an earthquake; the maximum stress of the door was 27.6 MPa.

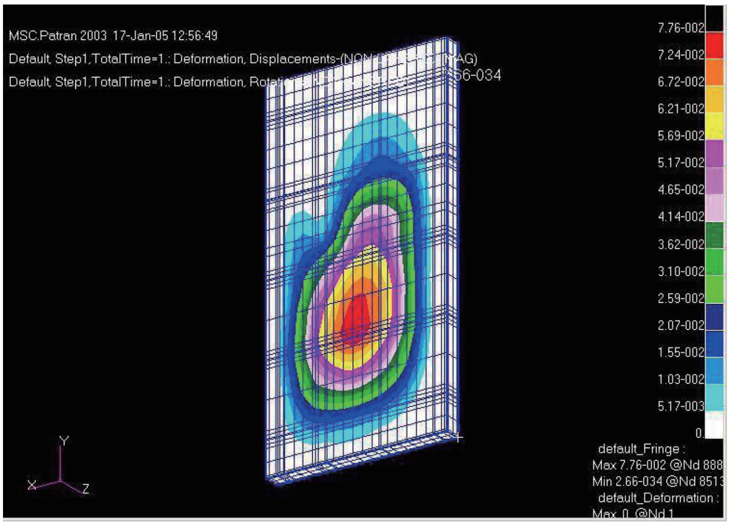

Fig. 3. (Color online) Displacement distribution of the door after the impacts of a car collision and an earthquake; the maximum displacement of the door was 0.076 mm.

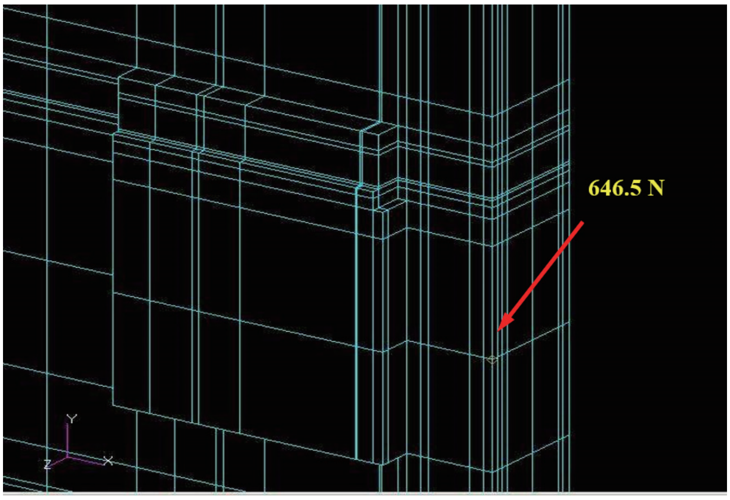

Fig. 4. (Color online) Response force of the latch after the impacts of a car collision and an earthquake; the maximum force of the door latch was 646.5 N.

3.2 Load II: an armor-piercing projectile and an earthquake

An armor-piercing projectile of 125 kg weight and 8 inch diameter was used as the impact source, and the impact was 1994 nt. The contact region of the door center was 0.42675 inch^2 and the total impact time was 0.01 s. For an earthquake, the horizontal acceleration design was 0.39 g and the vertical acceleration design was 0.31 g. As shown in Figs. 5 and 6, under this condition, the dispersing impacts of an armor-piercing projectile and an earthquake were discussed on the basis of an asymmetrical model. The simulation results also showed that the maximum stress of the door after the impacts of an armor-piercing projectile and an earthquake was 2.63 MPa (Fig. 5), and the maximum displacement of the door was 0.00829 mm (Fig. 6). However, the maximum stress was less than the yield stress, and the displacement of the designed door did not pose a risk of penetration to the panel. Therefore, the door is designed to be safe after the impacts of an armor-piercing projectile and an earthquake.

3.3 Load III: a solid ball and an earthquake

A solid ball of 1 inch diameter was used as the impact source, and the impact was 1994 nt. The contact region of the door center was 20 inch^2, and the total impact time was 0.01 s. For an earthquake, the horizontal acceleration design was 0.39 g and the vertical acceleration design was 0.31 g. Under this condition, we investigated the effect of dispersing impacts on a symmetrical model, as shown in Figs. 7 and 8. The result with a solid ball and an earthquake showed that the maximum stress was also less than the yield stress, and the displacement of the designed door did not pose a risk of penetration to the panel. The simulation results also showed that the maximum stress of the door after the impact of a solid steel ball and an earthquake was 5.12 MPa (Fig. 7), and the maximum displacement of the door was 0.00812 mm (Fig. 8). Even if it also causes a depression at the center of the structure, the door is designed to be safe.

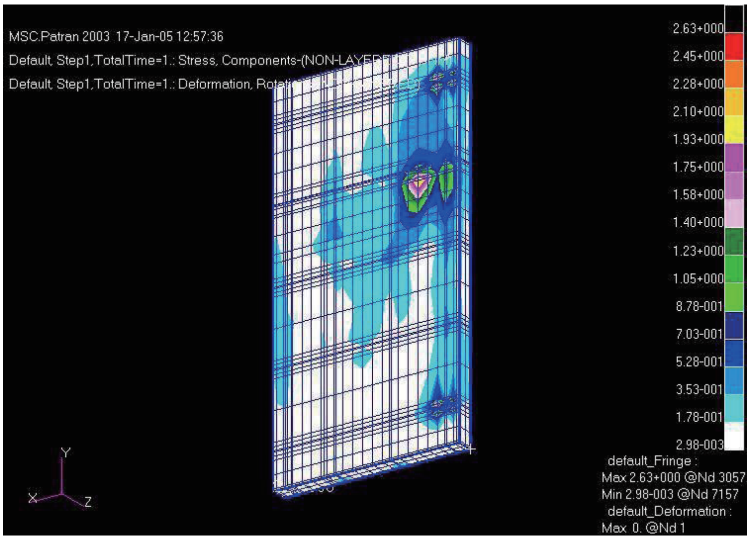

Fig. 5. (Color online) Stress distribution of the door after the impacts of an armor-piercing projectile and an earthquake; the maximum stress of the door was 2.63 MPa.

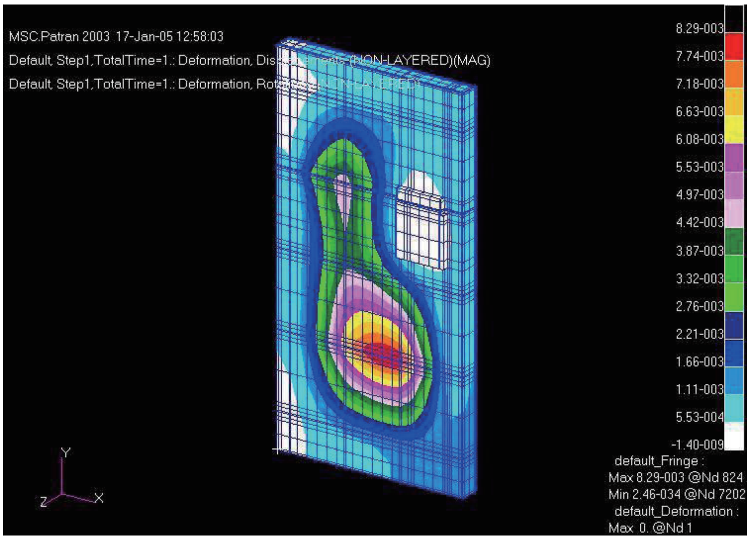

Fig. 6. (Color online) Displacement distribution of the door after the impacts of an armor-piercing projectile and an earthquake; the maximum displacement of the door was 0.00829 mm.

4. Discussion

In this work, a numerical study was conducted on a shock-loaded door, and simulations at different impacts were conducted to calculate the maximum stresses and maximum displacements of the designed door. Through numerical simulations, the effects of the shock loads caused by a car collision and an earthquake, an armor-piercing projectile and an earthquake, or a solid steel ball and an earthquake on a bullet-resistant door are well studied. From the simulation results, we can observe that the stress after the collision is distributed in a

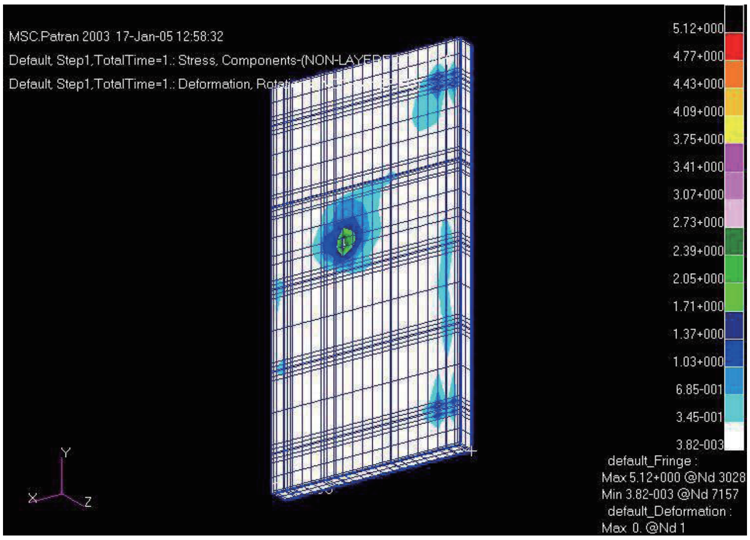

Fig. 7. (Color online) Stress distribution of the door after the impacts of a solid steel ball and an earthquake; the maximum stress of the door was 5.12 MPa.

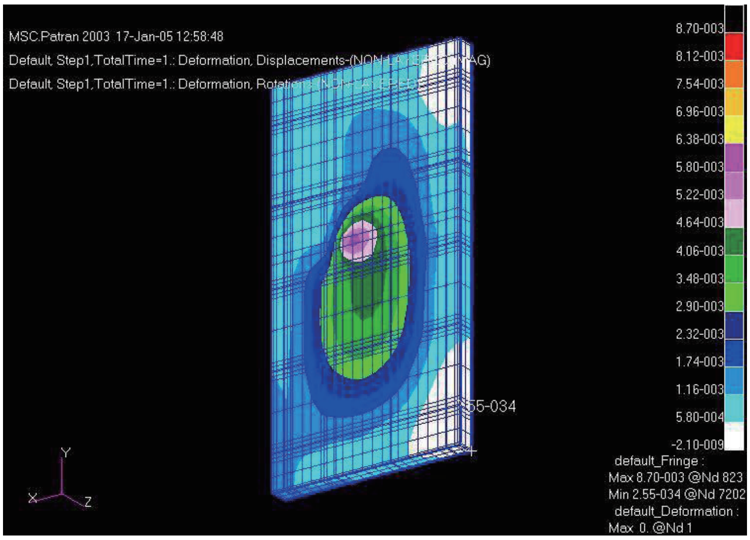

Fig. 8. (Color online) Displacement distribution of the door after the impacts of a solid steel ball and an earthquake; the maximum displacement of the door was 0.00812 mm.

small region, but the displacement is distributed in a large area. Therefore, the designers need to use many stress and displacement sensors to detect both the generated maximum stress and displacement, respectively. When the impacts were caused by a car collision and an earthquake, an armor-piercing projectile and an earthquake, and a solid steel ball and an earthquake, the maximum stresses were 27.6, 2.63, and 5.12 MPa, and the maximum displacements were 0.076, 0.00829, and 0.00812 mm, respectively. Apparently, when a car collision and an earthquake are used as the impact, the generated maximum stress and displacement on the designed door are much larger than those caused by an armor-piercing projectile and an earthquake and a solid steel ball and an earthquake. The reason is that a car has a larger weight than both an armor-piercing projectile and a solid steel ball, so a car collision and an earthquake will have a larger momentum to generate a larger impact; thus, they can cause a larger maximum stress and a larger maximum displacement.

Figures 2–8 illustrate the static interactions of a car collision and an earthquake, an armor-piercing projectile and an earthquake, or a solid steel ball and an earthquake on the designed door at the point where the different impact objects cease striking the door. The results show that there was no penetration through the designed door despite the impacts generating energy that caused a large area displacement over the door. When exposed to explosion pressure, the door panel produced positive and negative resistance forces, with the latter being referred to as the rebound resistance force. During the springback process, changes in the door's boundary conditions occurred, and different hinge and door latch configurations resulted in varying boundary conditions, which, in turn, led to different rebound resistance forces. It was observed that flexible structures, such as steel structures, were subject to higher elastic forces, resulting in a faster response. Thus, in the analysis of a designed bullet-resistant door, the configuration of hinges and latches was crucial owing to the rebound effect. An appropriate configuration was critical, as the hinges and latches had to withstand the impacts during the rebound effect. Accordingly, the impact of different forces on the door frame was also simulated and analyzed. Simulation results for the maximum stress on the door frame of the designed bullet-resistant door were obtained. As depicted in Fig. 9, the analysis revealed that the maximum stress on the fixed point was 7.2 MPa, which was lower than the yield stress. The analysis results confirm that this door frame was designed to safely withstand the impacts of different forces.

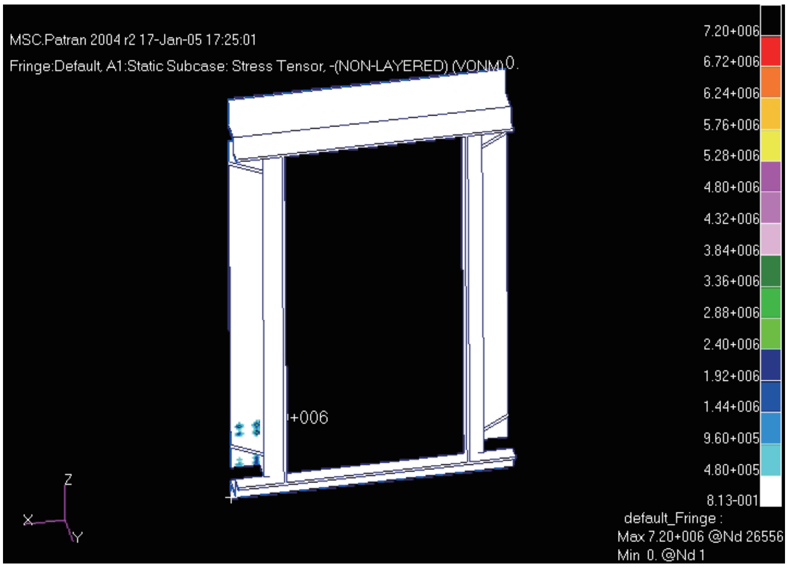

Fig. 9. (Color online) The maximum stress of the door frame was 7.2 MPa.

5. Conclusions

In this study, we utilized FEM software to simulate and analyze the impacts of various materials on the deformation and stress of a bullet-resistant door composed of an accessory door leaf, frame, latch, and hinge. The door was subjected to impacts from a car, an armor-piercing projectile, or a solid steel ball, under stress conditions equivalent to an earthquake of approximately 6.4. We also analyzed stress and displacement distributions resulting from these impacts. Under the impacts of a car collision and an earthquake, an armor-piercing projectile and an earthquake, or a solid steel ball and an earthquake, the maximum stresses experienced were 27.6, 2.63, and 5.12 MPa, while the corresponding maximum displacements were 0.076, 0.00829, and 0.00812 mm, respectively. The maximum stress experienced by the door frame was 7.2 MPa. On the basis of these analysis results, it was determined that the steel door frame and its accessories, including the steel structure and latch, could safely withstand the impacts of foreign objects as specified. Thus, we confirmed that utilizing FEM software for the design of high-strength ballistic doors can eliminate the need for many stress and displacement sensors.

Acknowledgments

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