Numerical Simulation Study on Influence of Structural Interspace on Anti-penetration Performance of GFRP and Steel Composite Armor System

To cite this article: Yuanhao Zhang *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **562** 012038

IOP Conf. Series: Materials Science and Engineering **562** (2019) 012038 doi:10.1088/1757-899X/562/1/012038

Numerical Simulation Study on Influence of Structural Interspace on Anti-penetration Performance of GFRP and Steel Composite Armor System

Yuanhao Zhang[1,2], Zhongqing Cheng [2], Hailiang Hou [1], Xi Zhu [1], Jinghan Liu[1,2] and Lingfeng Li[1,2]

1. College of Surface Ship and Ocean, Naval University of Engineering, 713 Jiefang Road, Wuhan, Hubei, China.

2.Department of Coast Defence Engineering, Naval Logistics College of PLA, 1Hebei Road, Binhai, Tianjin, China.

Email: 158241904@qq.com

Abstract. In this study we investigated the influence of the structural interspace on the ballistic performance of GFRP and steel composite armor system, using finite element analysis by ANSYS/LS-DYNA to simulate, found out the failure modes of steel plates and GFRP plates, and analysed the anti-penetration mechanisms of the composite armor systems. The results indicated that impact by high velocity projectiles, the failure modes of GFRP plates change greatly by setting structural interspace, but less influence on the failure modes of steel plates. Impact by high velocity projectiles, structural interspace has little effect on the anti-penetration performance of steel-GFRP armor structure. Enough interspace can improve the anti-penetration performance of GFRP-steel armor structure, but the anti-penetration performance changes little with the increase of the interspace.

1. Introduction

After semi-armor-piercing anti-ship missiles invade the shipboard, the warhead implodes and produces fragments with velocities ranging from 1200 to 2000m/s, which damages the important cabins of the ship. In engineering, warships improve the anti-penetration ability by installing composite armor on bulkhead to maintain the vitality. How to assemble FRC plates in the engineering design to the critical parts of the ship and form a composite armor structure with the hull structural steel plate is a key research topic in the field of ship protection. Zhu Xi et al. [1] placed different FRC plates in front of hull structural steel plates to simulate naval composite armor structures, they carried out targeting experiments on the composite armor structures with interspace between two parts or not. It is considered that the increase of the interspace will be beneficial to improve the anti-penetration ability of composite structure. Chen Changhai et al. [2-3] placed steel plates in front of and behind aramid plates to simulate the outer and inner composite armor structures of shipboard, combining with low-speed ballistic impacting tests, it is pointed out that the anti-penetration ability of the structure which steel plate at front is better. Zhang Yuanhao [4] placed steel plates in front of and behind GFRP plates to simulate the outer and inner composite armor structures of shipboard. Combining with high-speed ballistic impacting tests, it is concluded that the anti-penetration ability of the structure which steel plate at back is better. Li Mao [5-6] taked aramid fiber reinforced composite laminates as sandwiches. According to whether there is 50 mm interspace or not between different parts, composite armor structures are divided into three types: non-interspace type, back interspace type and front and back interspace type. Through ballistic experiments, it is found that the anti- penetration performance is ranked as front and back interspace type > back interspace type > non-interspace type.

In this paper, we based on the experiments in reference [4], used finite element analysis by ANSYS/LS-DYNA to simulate, investigated the influence of the ballistic performance of GFRP and steel composite armor systems by setting structural interspace.

2. Finite Element Simulation

In order to study the effect of interspace on the anti- penetration performance of steel/GFRP composite armor structure, four different structural types were designed, which are non-interspace structures (structure I, III) and structures with interspace (structure II, IV). The finite element analysis program ANSYS/LS-DYNA was used to simulate four kinds of steel/GFRP composite structures. The model layout is shown in figure 1.

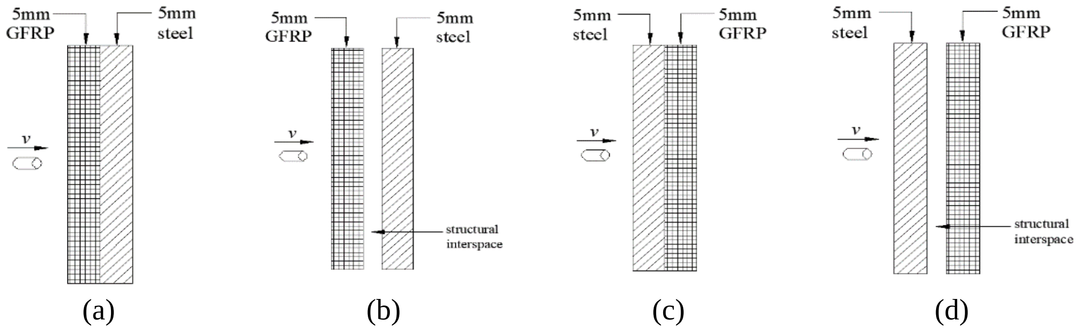


Figure 1. Sketch of armor structures: (a) Model I, (b) Model II, (c) Model III, (d) Model IV

The numerical model consists of a cube bullet, a steel plate and a GFRP plate. The edge length of the cube bullet is 7.5 mm, and the dimensions of the GFRP plate and the steel plate are 200 mm x 200 mm x 5 mm. Solid 164 solid element with 8 nodes and Lagrange method was used to simulate the material model, each side of the projectile was equally divided into 8 equal parts. In the square impacting area with 50 mm in length at the center of the target plates, each side was divided evenly into 50 equal parts, the mesh was gradually sparsely away from the impacting area. Each side of target plates was equally divided into five equal parts along the thickness direction. The numerical model is based on the cm-g-us unit system. The size and parameters of the model are the same as those in the reference [4].

3. Numerical Calculation and Analysis

3.1. Validation of Numerical Results

In the experiments [4], a 7.5 mm cubic projectile penetrated the structure I with the initial velocity of 1194.4 m/s and the structure III with the initial velocity of 1291.7 m/s. Each working condition in the literature was numerically simulated to obtain the residual velocity of the projectile, as shown in table 1.

Table 1. Numerical models and experimental condition

Test number	Initial velocity (m/s)	Residual velocity (m/s)	Simulation number	Residual velocity of simulation (m/s)	Deviation (%)
1	1194.4	286.0	1	343	4.6
2	1291.7	462.7	2	628	1.7

From the table 1, it can be seen that the deviation between the residual velocity of the projectile obtained by using the aforementioned simulation material model and the residual velocity of each working condition in the tests [4] is less than 5%.

IOP Conf. Series: Materials Science and Engineering **562** (2019) 012038 doi:10.1088/1757-899X/562/1/012038

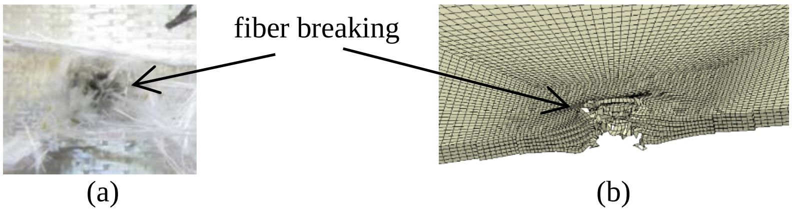


Figure 2. Failure mode of the front plane of GFRP plate: (a) Test1, (b) Simulation1

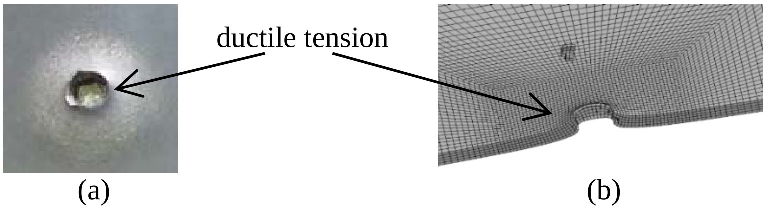


Figure 3. Failure mode of the rear plane of steel plate: (a) Test1, (b) Simulation1

Observe the figure 2, fiber breakage appears on the front plane of GFRP plate in simulation 1. Observe the figure 3, ductile expansion appears around the bullet hole of the rear plane of steel plate in simulation 1, which are similar to the test conditions in reference [4]. By comparing the residual velocity of the projectiles after penetrating and the damage modes of the targets in simulations and tests, it can be concluded that the model is reasonable.

3.2. Effect of Interspace on Target Type I

The velocity of high-speed fragments produced by missile warhead explosion is about 1200-2000m/s, and its impacting on the hull structure belongs to the problem of medium-high-speed impacting. In order to explore the influence of interspace on the anti-penetration performance of GFRP-steel armor structure, using the aforementioned simulation material model, considering the layout of the protective structure in the warship, the interspace sizes were defined as 3 mm, 5 mm and 8 mm, respectively. The initial penetration velocity of projectile was defined as 1200 m/s. The simulation results are shown in table 2.

Table 2. Numerical simulation results

Simulation number	Target type	Interspace size(mm)	Initial velocity(m/s)	Residual velocity (m/s)
3	I	0	1200	295
4	II	3	1200	275
5	II	5	1200	260
6	II	8	1200	244

Table 2 shows that the residual velocity of the projectile is 295 m/s when there is no interspace between the target plates. With the increase of the interspace, the residual velocity of the projectile decreases slightly, and the overall anti-penetration performance of the target has not changed significantly.

Figure 4. Simulation mode 3-70μs

Figure 5. Simulation mode 4-70μs

Figure 6. Simulation mode 5-70μs

Figure 4, 5 and 6 respectively simulated the failure modes of GFRP plates and the rear plates after the projectile penetrated the target plates in simulation 3, 4, 5. Comparing figures 4, 5 and 6, it can be seen that when there is no interspace between the target plates, the “dynamic deformation cone” formed by the fibers being destroyed of the rear plane of GFRP plate can not be fully developed due to the restraint of the rear plate, with the increase of the interspace, the development space of the “dynamic deformation cone” can be increased, and when the interspace is large enough, the fibers in the deformation cone area reach the limit deformation state. So the existence of interspace is beneficial to improve the anti-penetration performance of composite structures.

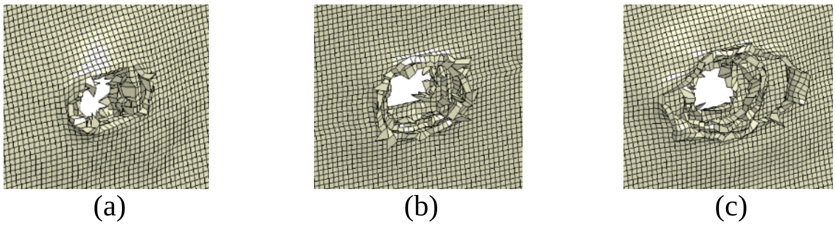


Figure 7. Failure modes of the rear plane of GFRP plates: (a) Simulation mode 3, (b) Simulation mode 4, (c) Simulation mode 5

Figure 7 shows the final failure modes of the rear plane of GFRP plates in each simulation. Due to the high velocity of the projectile, the failure mode of the GFRP plate is mainly shear failure, and a small amount of tensile failure occurs on the rear plane of GFRP plate. So GFRP plate can not play a good anti-penetration ability.

3.3. Effect of Interspace on Target Type III

In order to explore the influence of interspace on the anti-penetration performance of steel-GFRP armor structure, using the aforementioned simulation material model, the interspace sizes were defined as 3 mm, 5 mm and 8 mm, respectively. The initial penetration velocity of projectile was defined as 1200 m/s. The simulation results are shown in table 3.

Table 3. Numerical simulation results

Simulation number	Target type	Interspace size(mm)	Initial velocity(m/s)	Residual velocity (m/s)
7	III	0	1200	548
8	IV	3	1200	476
9	IV	5	1200	452
10	IV	8	1200	461

From table 3, it can be seen that the residual velocity of the projectile is 548 m/s when there is no interspace between the target plates, while there is interspace between the target plates (simulation 8, 9, 10), the residual velocity of the projectile is stable at about 460 m/s.

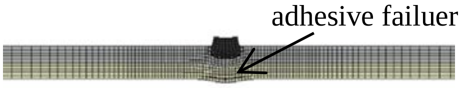


Figure 8. Simulation mode 7-9μs

Figure 9. Simulation mode 8-9μs

When there is no interspace between the front plate and GFRP plate, the compressive stress wave is formed when the projectile contacts the front plate, and propagates forward through the steel-GFRP interface (along the thickness direction of GFRP plate), resulting in local degumming and cracking of the rear plane of GFRP plate (figure 8), when there is interspace between the current plate and GFRP plate, the compressive wave can not propagate to GFRP plate (figure 9).

IOP Conf. Series: Materials Science and Engineering **562** (2019) 012038 doi:10.1088/1757-899X/562/1/012038

(a) (b)

Figure 10. Failure modes of the rear plane of steel plates: (a) Simulation mode 7, (b) Simulation mode 8

From figure 10, it is found that the failure modes of the steel plates in simulation 7 and 8 are adiabatic shear failure. There are small disc depressions and ductile stretching around the bullet holes on the rear plane, accompanied with small lateral displacement. The failure modes of the two steel plates is almost the same, the reason is when the GFRP plate is close to the steel plate, the deformation of the steel plate can not be restrained effectively because the rigidity of GFRP plate is small.

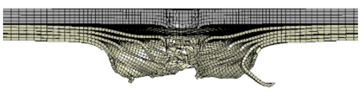


Figure 11. Simulation mode 7-200μs

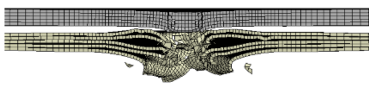


Figure 12. Simulation mode 8-200μs

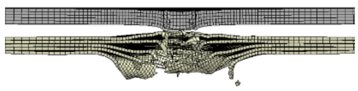
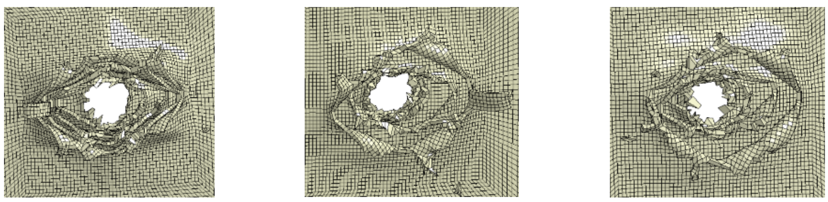


Figure 13. Simulation mode 9-200μs

Figures 11, 12 and 13 are the final failure modes of the target plates. The interspace of the target plate is 0 mm, 3 mm and 5 mm, respectively. Comparing with figure 11, 12 and 13, it can be seen that, due to the restraint of the front plate, the fibers breaking around the bullet hole of the front plane of GFRP plate can not be ejected backward. When the interspace is large enough, the fibers and matrix damaged on the front plane can rebound freely. Further observation of figures 11, 12 and 13 shows that the basic failure mode of the front plane of GFRP plate is shear failure, while the fibers on the rear plane are tensile fracture, which accounts for a higher proportion. It is also found that there are a large number of interlaminar degumming cracks in the penetration zone, accompanied with obvious folds, no obvious delamination and almost no deformation of the target outside the penetration zone.



(a) (b) (c)

Figure 14. Failure mode of the rear plane of GFRP: (a) Simulation mode 7, (b) Simulation mode 8, (c) Simulation mode 9

Figure 14 shows the final failure modes of the rear planes of GFRP plates. The main failure modes of the fibers of the rear plane are tensile failure, a large number of fibers valgus showing petal-shaped. The coverage areas of valgus fibers in simulation 7, 8 and 9 are 28.3 mm x 42.3 mm, 34.1 mm x 41.8 mm and 36.4 mm x 43.1 mm respectively, accounting for more than 80% of the penetration area. Further observation shows that the coverage area of fibre eversion increases with the increase of target interspace. The reason is that the existence of target interspace makes the fragments a certain initial divergence angle after the projectile penetrates the front plate, which enlarges the impacting range when they penetrate the GFRP plate, and the mass distribution of fragments is random, which disperses the kinetic energy of fragments penetration and is beneficial to improving the ballistic performance of composite structures.

IOP Conf. Series: Materials Science and Engineering **562** (2019) 012038 doi:10.1088/1757-899X/562/1/012038

4. Conclusion

In this paper, ANSYS/LS-DYNA software was used to simulate the ballistic performance of four kinds of steel/GFRP composite structures. The effects of target interspace and interspace size on the overall anti-penetration performance of GFRP plate with steel plate front and rear composite armor structures were discussed respectively. The main conclusions are as follows:

(1) The failure mode of steel plate is shear plugging failure. Shear failure is the main failure mode of GFRP fibers in GFRP-steel structure, while shear failure and tensile failure are the main failure modes of GFRP fibers in steel-GFRP structure.

(2) Impact by high velocity projectiles, the failure modes of GFRP plates change greatly by setting structural interspace, but less influence on the failure mode of steel plates.

(3) Impact by high velocity projectiles, structural interspace has little effect on the anti-penetration performance of steel-GFRP armor structure. Enough interspace can improve the anti-penetration performance of GFRP-steel armor structure, but the anti-penetration performance changes little with the increase of the interspace.

The conclusions obtained in this paper provide a reference for the installation of steel/GFRP composite protective structures on ship bulkheads. The actual ship skeleton structure should be taken into account in the specific interspace arrangement.

5. References

[1] Xi Z, Zhiyuan M and Runquan L 2003 *J. Explosion and Shock Waves* **23** 61
[2] Changhai C, Xi Z and Hailiang H 2012 *J. Acta Armamentarii* **33** 1473
[3] Changhai C, Xi Z and Hailiang H 2012 *J. Journal of Ballistics* **24** 51
[4] Yuanhao Z, Changhai C and Xi Z 2017 *J. Chinese Journal of Ship Research* **12** 93
[5] Mao L, Hailiang H and Xi Z 2017 *J. Acta Armamentarii* **38** 1797
[6] Mao L, Xi Z and Hailiang H 2015 *J. Chinese Journal of Ship Research* **10** 61