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Numerical study on tensioned membrane structures under impact load

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Abstract. This paper presents the numerical simulation of membrane structure under impact load. Firstly, the numerical simulation model is validated by comparing with the test in Hao's research. Then, the effects of the shape of the projectile, the membrane prestress and the initial impact speed, are investigated for studying the dynamic response and failure mechanism, based on the membrane displacement, projectile acceleration and kinetic energy. Finally, the results show that the initial speed and the punch shape are related with the loss of kinetic energy of projectiles. Meanwhile, the membrane prestress is an important factor that affects the energy dissipation capacity and the impact resistance of membrane structures.

Keywords: tensile membrane structures; failure mechanism; dynamic response; impact load; parameter analysis

1. Introduction

As an important structural form, membrane structure is widely used in large span spatial structures and usually landmark of a city (Chen *et al*. 2016). At the same time, it is suffering from impact damage due to the thinner surface. During strong winds, wind-borne debris has a higher speed, which will collide directly with the membrane. Usually, the debris contains stones, branches and materials falling off the buildings. Some of the debris are rebounded owing to impact resistance of the membrane. However, some debris pierce the membrane because of the high speed and specific shape (Fig. 1). Not only the debris will hurt the people inside, but also the holes caused by it will propagate rapidly under the strong wind until the membrane structure lose function(Fig. 2) (Zhang *et al*. 2015). Therefore, it is important to study the dynamic response and impact resistance of membrane materials.

The physical test is the most effective way to analyze the impact problems (Moghim and Caracoglia 2012, Moghim *et al*. 2015). Through the impact test, we can obtain the experimental data and observe the failure morphology of membrane (Li *et al*. 2015, Ning *et al*. 2007, Moghim *et al*. 2015). However, there are few references on the tests on the impact response of membrane structures limited by experimental conditions. The impact analysis is affected by strong nonlinear characteristic (Grayson *et al*. 2012). Due to this complex process, it is impossible to be solved by the analytic method (Zhang *et al*. 2018). Model test and numerical simulations have been considered as the effective approach to investigate the mechanical performance of engineering structures (Yu *et al*. 2018 and Xu *et al*. 2018). The current researches are mainly on the theoretical analysis or the finite element analysis. But, the

Fig. 1 Damages under impact load

Fig. 2 Impact secondary damage

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numerical method is effective to solve these problems by simulating the whole process and carry out parameter analysis (Zhou *et al*. 2014).

York *et al*. (2015) studied the dynamic response problems under impact load of membrane structure by extending the material point method (MPM) to discrete membrane structure and studying the nonlinear vibration discrete membrane structure. Phoenix and Porwal (2013) developed an 2D membrane analysis model, which is able to analyse the ballistic impact load and can be applied to the design of fibrous materials such as body armor. Malla ang Gionet (2013) proposed a three-dimensional membrane structure model used for studying the barrier to protect the moon. Zheng and Guo (2014) studied the nonlinear vibration under impact load of membrane structure according to principle of virtual displacement, which can provide the accurate theory for the measurement of pretension. Liu *et al*. (2016) investigated the undamped nonlinear vibration response of membrane structure under impact load by analytical and numerical methods. The results obtained provide some theoretical basis for vibration control and dynamic design of membrane structure. Mostofi *et al*. (2016) carried out the theoretical analysis of fully clamped thin plates under impulsive load, in which the effects of both the load and the material on dynamic response are studied.

Some researches have been studied on the vibration response of membrane structure under impact load. Wang *et al*. (2015) used the finite element software to simulate the impact process of prestressed square planar membrane by a round column-shaped projectiles and studied the impact resistance under different membrane prestress. Zheng *et al*. (2012) studied the dynamic response of circular membrane structures under low speed impact load and studied the effects of material parameters and boundary conditions. Li *et al*. (2017) investigated the dynamic response of rectangular prestressed membrane under uniform loads and the stochastic dynamic response and reliability analysis of membrane structure under impact load conforms to the Gaussian distribution.

Besides, the dynamic response of membrane structure penetrated by the projectiles have been investigated by some researchers. Ding (2010) used the LS-DYNA software to analyze the whole process of ETFE membrane materials impacted by the wind-borne debris. The contact analysis method was used to analyze the penetration process of membrane materials. Li *et al*. (2016) carried out the high-speed impact test of composite plate by the Hopkins rod test, and used the numerical simulation to study the impact resistance of composite plate against the high-speed projectiles. Hao *et al*. (2016) (2015) used the pneumatic cannon system to launch timber projectiles to impact several types of structures, including PVC membrane, composite plate, aluminum plate, and sandwich panel etc.

As is shown above, the current studies are targeted at the flight characteristics of impact projectile and rebounding response of membrane structures against impact. There are few studies about the dynamic response of membrane structures after penetrated by projectile (Sun *et al*. 2014, Lin *et al*. 2007). As we know, the dynamic response and failure modes of membrane structures are important issues

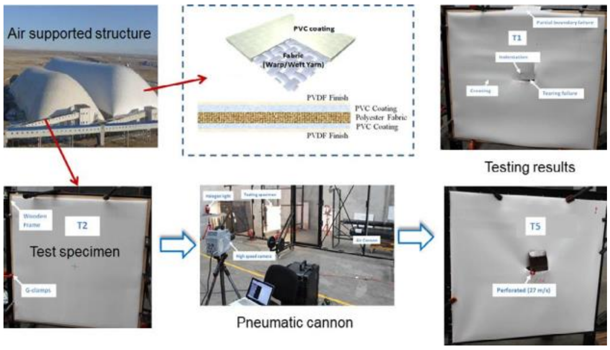


Fig. 3 Test over view (Chen *et al*. 2016)

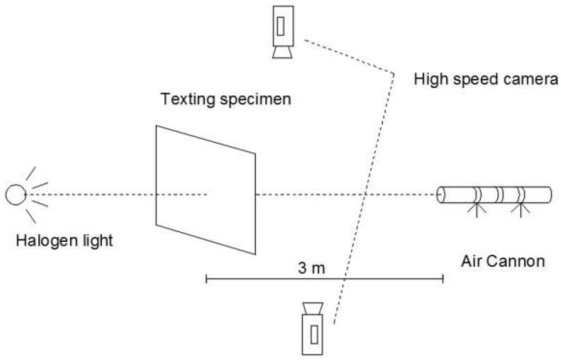


Fig. 4 Test plot of pneumatic gun system

of structural resistance of membrane structures. Therefore, it is necessary to study the dynamic response and failure mechanisms of membrane structures by simulating the complete process containing the part after penetration.

This paper presents the dynamic response and failure mechanisms of membrane structures. First, the simulation method is validated by comparing with the test data in paper Chen *et al*. (2016). Then, the parameters, including the shape of the projectile, the membrane prestress on the surface and the impact initial speed, are changed in the model for further studying the dynamic response and failure mechanism, which are analyzed from the aspects of membrane displacement, projectile acceleration and kinetic energy. Finally, the dynamic response and the failure mechanism are summarized based on parameter analysis.

2. Verification of finite element modeling

In this part, the test in the paper Chen *et al*. (2016) is introduced briefly. Then, the finite element model is set for simulating the penetration process of ballistic impact test. Besides, the parameters in the model is explained in detail. Finally, the latter part of this section contrasts the results between the test and the simulation.

In this paper, our aim is to realize mutual verification by finite element simulation and the test. Only verified accurately, this model can be conducted for studying membrane displacement, dynamic response and energy dissipation by changing parameter. So, we choose the two typical specimens for comparing, which are targeted at initial speed.

Table 1 Mechanical parameters in the finite element models

Property	Projectile	Ferrari 1202
Stiffness behavior	rigid	flexible
Young modulus（MPa）	200	200
Density（kg/m^3）	800	1250
Poisson ratio	0.3	0.3

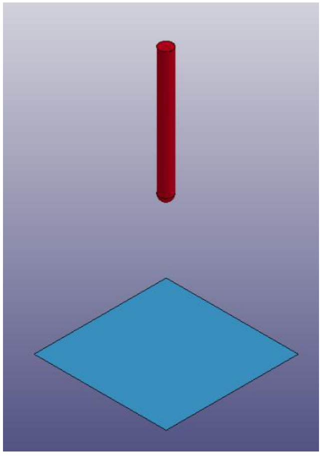


Fig. 5 Model of verification simulation

2.1 Test introduction

Hao *et al*. (2016) tested eight PVC coated polyester fabric specimens with dimension of 1000 mm by 1000 mm, according to AS/NZS 1170.2:2011(Fig. 3) (AS/NZS 2011). Fig. 4 shows the testing setup in Azuma Design laboratory. The fabric has the thickness of 1.2 mm and the density of 1250 g/m3. The testing specimens are different in impact location, membrane prestress and boundary conditions. Besides, two impact velocities, 22m/s and 32m/s, are considered in this test. Low-speed to high-speed impact tests have been carried out by using avail-able facilities such as pneumatic cannon, drop mass and pendulum. Through the test, he found the speed after penetration are dropped from 22m/s and 32m/s to 20m/s and 25m/s respectively.

2.2 Finite element analysis

The finite element modelling method is validated by comparing with this test. The membrane in the model is with the dimension of 1000 mm×1000mm, the thickness of 1.35 mm, and the density of 1250 kg/m^3. The projectile is with the section of 100 mm×50 mm, and the length is 1000 mm. The projectile is made by wood with the density of 800 kg/m^3.

The projectile is assumed as the ideal rigid material and the deformation is neglected (Zhang *et al*. 2018). The impact load from projectile is equivalent to 4 kg mass, as specified in AS/NZS, Structural Design Actions. Part 2: Wind Actions (AS/NZS 1170.2:2011). Same as the test, the properties of the projectile and the structure are shown in Table 1.

In this analysis, one is corner penetration of prestressed membrane by the projectiles with the initial speed of 32m/s

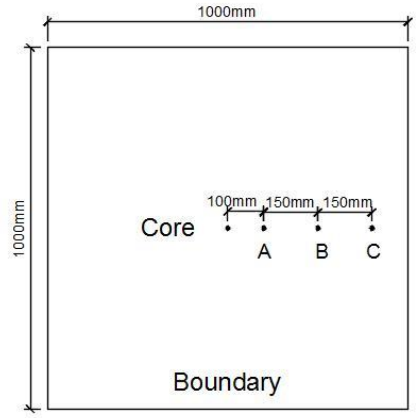


Fig. 6 Distributions of displacement measurement

Table 2 Comparison between numerical simulation results and experimental results

Index	Pretension force (kN/m)	Proposed debris velocity (m/s)	Residual velocity(m/s)		Errors
			test results	numerical results	
T1	0	32	*	*	-
T2-1	0	22	-9.6	-8.96	6.7%
T3-1	3	22	-7.8	-7.33	6.1%
T3-2	0	32	25	24.91	0.3%
T4-1	0	27	-7.5	-7.14	4.8%
T4-2	3	27	20	20.06	0.3%
T5-1	3	27	*	*	-

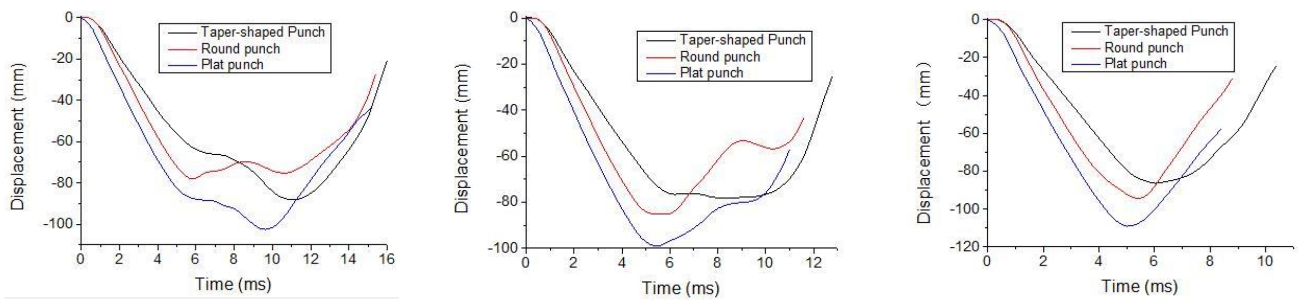
*: represents that the projectile pierced the membrane and was without the residual velocity

and the other is corner penetration of membrane without prestressed by the projectiles with the initial speed of 27m/s. In two specimens, four sides are fixed.

The membrane is meshed in Shell163 with triangle shape. The shell163 has the features of bending and membrane. Besides, the projectile is meshed in Solid164 with hexahedral shape. The element of solid164 is used in 3-D solid structure, which can be only used in dynamic display analysis. The meshing of the membrane and the projectile is both with the size of 5mm.

The Hashin criterion is chosen as failure criterion. The material shear strength can be obtained from the static test proposed in the European Design Guide for Tensile Surface Structures (Forster and Mollaret 2004). Considering the important effect of tensile strength, the impact tensile test by the Split Hopkinson Tensile Bar is conducted to consider the influence of high tensile rate.

It is assumed that the projectile is perpendicular to the surface of membrane and the interface between the projectile and the membrane is single-side contact. LS-DYNA will automatically determine which surface is in contact. It allows all outer surfaces of the model can be in contact. Besides, the friction between the projectile and the membrane has little effect on the movement of the projectile. Therefore, the static and dynamic friction coefficient between the material interfaces in the model is defined as 0.1 and 0.05.



(a)22m/s (b)27m/s (c) 32m/s

Fig. 7 Displacement variations against impacting under different punch shapes (membrane prestress: 3kN/m, Point A)

2.3 Finite element verification

The comparisons of the numerical simulations and experimental results are shown in Table 2. In the tests of T3-1 and T4-2, the membrane was penetrated in test. The projectiles moved along the direction before penetration. The numerical simulation shows that the residual speed of projectile changed from 27m/s to 20.06m/s. Besides, the one with residual of 32m/s changed to 24.91m/s. The simulation results are in good agreement with the test of T3-1 and T4-2. Besides, in the tests of T2-1, T3-1 and T4-1, the projectiles moved in the opposite direction when the deformation of membrane researched maxmimum. The errors are within reasonable range between simulation results and test results. Besides, the phenomenons in simulations are coincident to the phenomenons in tests. So, it can be seen in Table 2 that the numerical simulations are in good agreement with the test results. The simulation method is reliable and can be used for the following parameter analysis.

3. Parameter analysis

Based on the finite element model above, the relevant parameters are changed to study the dynamic response and failure mechanisms of membrane structures under impact load. The finite element model contains three different parameters, including the punch shape, the pretension and the initial speed. Among them, the punch shape includes taper, round and plat. The membrane prestress are set as 1kN/m, 3kN/m and 5kN/m respectively. The initial velocities of projectiles are 22m/s, 27m/s and 32m/s respectively.

By analyzing the process of penetrating the membrane, the main factors are the tensile stress and the shear stress. The damage process begins with the fabric deformation, which is increasing with the moving of the projectile. The shear stress mainly appears from the extrusion between the membrane and the projectile. Along with the shear stress increasing, large transverse deflection across the whole membrane can be observed, which absorbs most of the impact energy. When the coupling effects reach the threshold value, small defects appear in the membrane surface. The projectile moves along, and the small defects will propagate until the projectile penetrate completely.

In order to understand the dynamic response and failure mechanism better, the variation membrane displacement, the acceleration and the kinetic energy are studied. Firstly, the membrane displacement is an important index to reflect the dynamic response of membrane structure. Three points on the membrane surface are taken as the research objects, as shown in Fig. 6. Then, the initial speed of projectiles before and after the penetration is recorded. According to the Newton principles, the acceleration of an object is proportional to the external force, and the direction of the acceleration is the same as the direction of the force. Therefore, the acceleration variation of the projectiles can directly reflect the variation law of structural resistance.

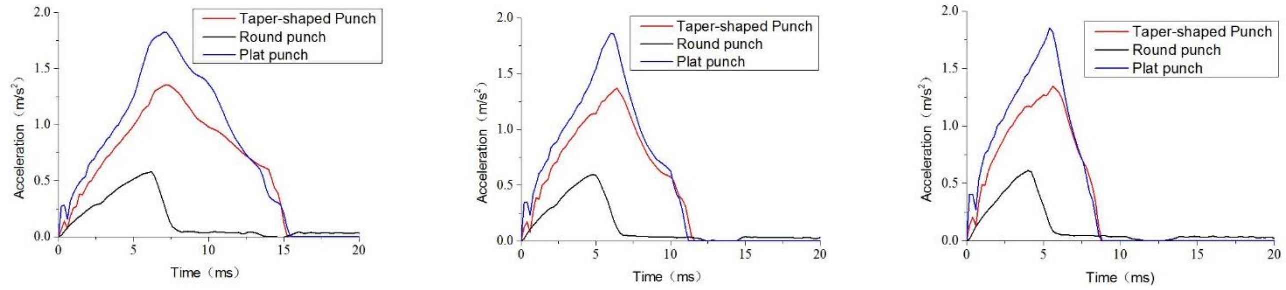
In order to show the interaction between projectiles and the membrane structure, the data before the impact process are removed and the initial time of impact process is regulated to zero.

3.1 Punch shape

(1) Membrane displacement

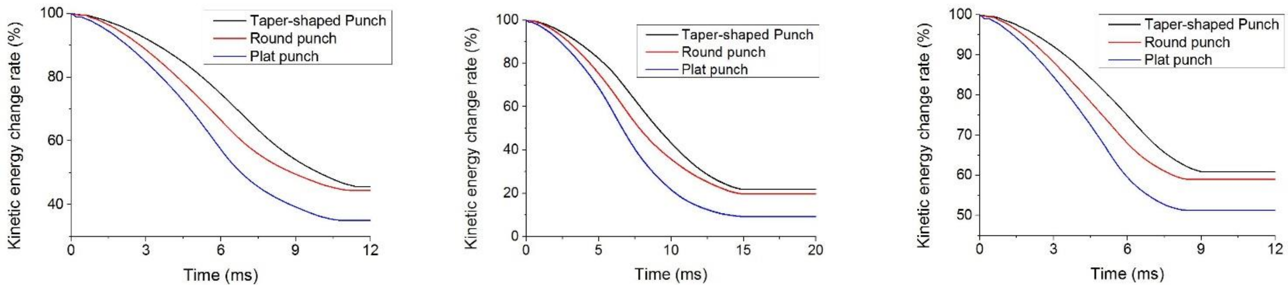
As shown in Fig. 7, when the punch is more flat, the maximum displacement increases and the deformation energy dissipation of membrane structure increases. When the punch is sharper, the stress concentration is more significant at the contact point and it is easier to achieve the failure strength of the membrane material. Then, the penetration time is shorter, and the deformation energy consumption is small. Therefore, the sharp of the punch has significant effects on the energy dissipation of membrane structures. Besides, it can be observed clearly that the displacement drop point of the flat punch is before the points of the other conditions. That is because the area of contact surface between flat punch and membrane surface is large, and the starting time is earlier than the round punch and tapper punch.

When the membrane prestress is 1kN/m, the variation law is not obvious. For the maximum displacement of membrane surface against impact, the round punch is the lowest, the tapper punch is second, and the flat punch is the largest. It is affected by the vibration superposition of membrane surface. Besides, in the numerical simulation, the impact point of round punch is consistent with the tapper punch. Due to small failure surface, the tapper punch penetrates firstly and the residual membrane surface can still perform good structural resistance.



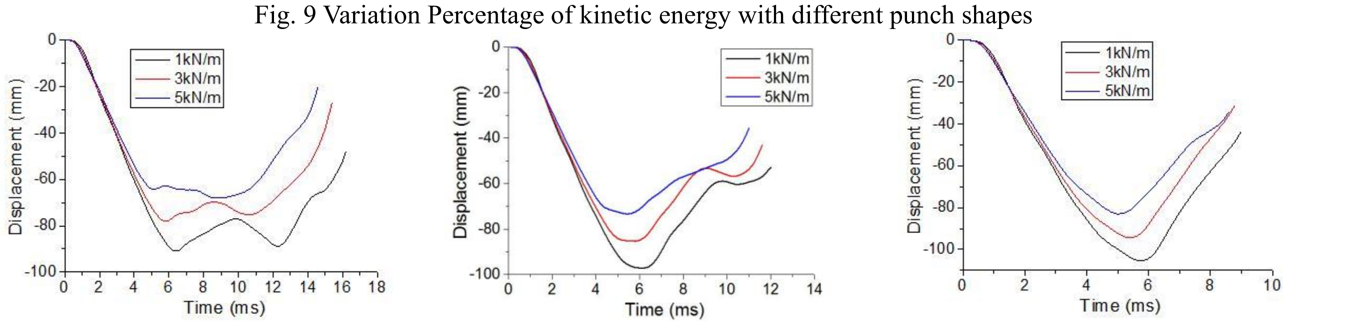
(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 8 Acceleration variation of projectiles under different punch shapes



(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 9 Variation Percentage of kinetic energy with different punch shapes



(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 10 Membrane Displacement under different stress with round punch (Point A)

When the punch shape is round, the contact surface is large, therefore, the membrane surface after penetration can't play a good role in structural resistance. It leads to the phenomenon that the maximum displacement of membrane surface penetrated by round punch is the smallest. After comprehensive consideration, this may be a special case, which is mainly related with the phenomenon of double peak value.

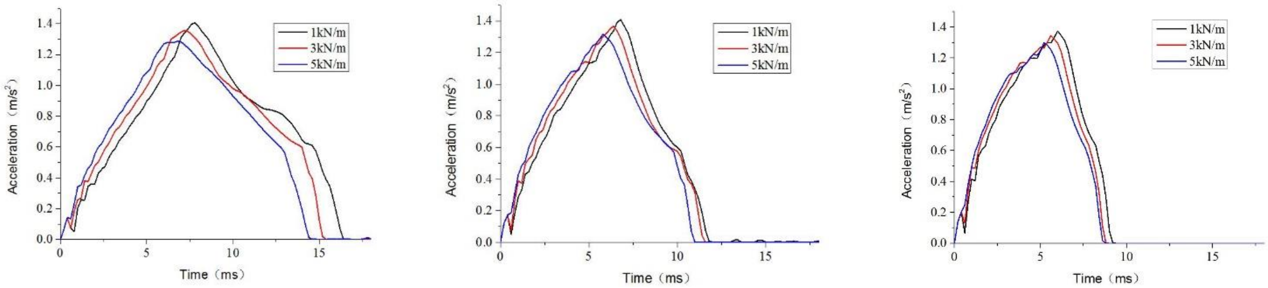
The vibration forms of membrane surface under different punch shapes are similar, it can be seen that during the impact process, there are two obvious peaks in the dynamic waves of membrane surface. The sharper punch shape is the larger second peak value turns. The maximum value of the flat punch appears at the first peak, and that of the tapper punch appears at the second peak. The reason is that the tapper punch penetrates the membrane surface, and it forms the first peak. However, the area of failure surface is small, so the membrane structure can continue to bear the projectiles and the second peak forms due to larger contact surface.

(2) Acceleration change

Fig. 8 shows the relationship between impact resistance of membrane structures and punch shape of projectiles. The flatter the punch, the greater the contact surface, the maximum acceleration of the projectiles, the maximum resistance of membrane structure is greater, the impact resistance of membrane structure is stronger. The reason is as follows. When the punch is relatively flat, it is difficult to achieve the corresponding failure stress, and greater contact force is needed. It will increase the maximum resistance of membrane materials and enhances the impact resistance of membrane structures. In summary, the punch shape has a great influence on impact resistance of membrane structure.

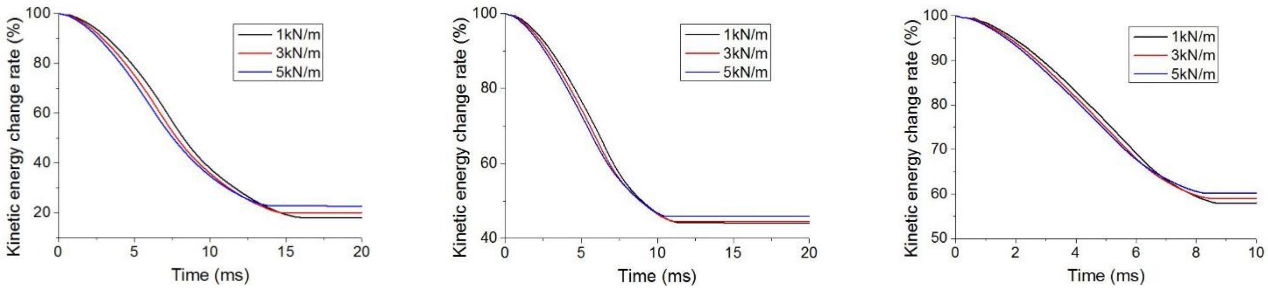
(3) Kinetic energy change

From Fig. 9, it can be seen that the speed loss of projectiles is closely related to the punch shape. When the punch is more flat, the area of contact surface increases and the variation percentage of the kinetic energy increases. It will lead to higher loss of kinetic energy and longer penetration time. Besides, in the numerical simulation, when the punch is sharper, significant stress concentration can be observed in the contact surface. It easily leads to the material failure. Then, no larger deformations appeared on the membrane surface and the penetration happened. Therefore, the punch shape has a great influence on the energy dissipation ability of membrane structures.



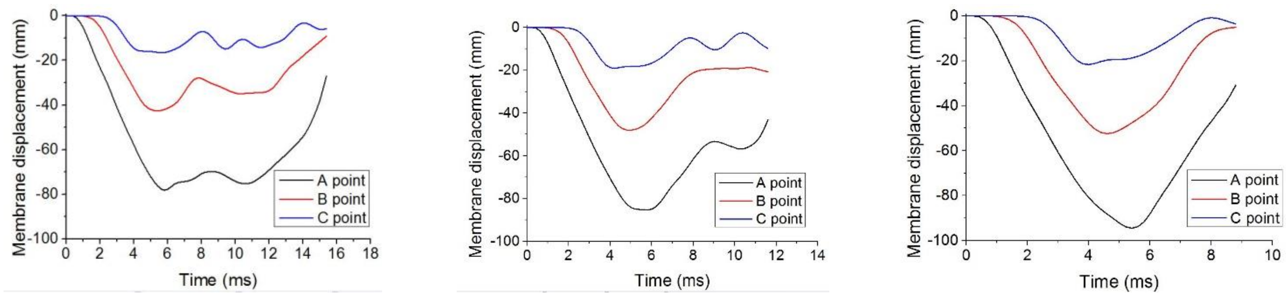
(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 11 Acceleration variation of round punch under different membrane prestress



(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 12 change Percentage of kinetic energy with round punch under different membrane prestress



(a) 22m/s (b) 27m/s (c) 32m/s

Fig. 13 Membrane displacement with round punch with the membrane prestress of 3kN/m

3.2 Membrane prestress

(1) Membrane displacement

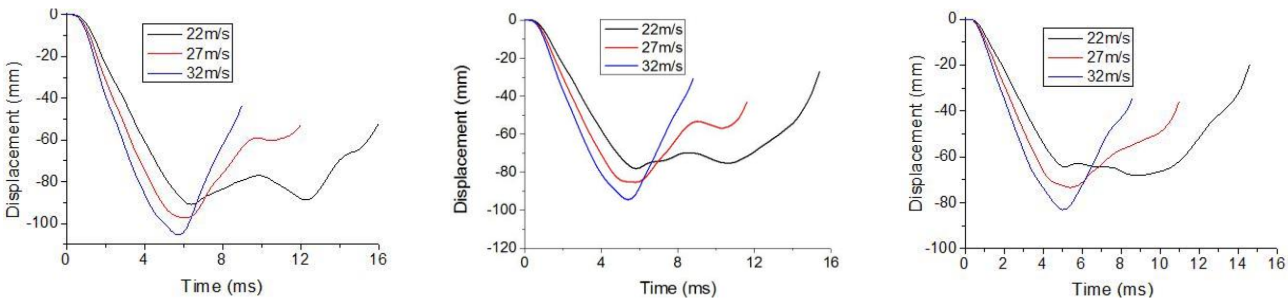
As shown in Fig. 10, with the same initial speed, with membrane prestress increasing, the maximum displacement of membrane surface decreases. The deformation and energy dissipation of membrane structure decreases. The reason is that the overall stiffness of membrane structure increases with the increasing of membrane prestress. Then, the deformation of membrane surface and the energy dissipation decreased when the projectiles penetrates the membrane surface. The vibrations of membrane surface with different membrane prestress are similar. With the membrane prestress increasing, the initial vibration time of C point appears ahead, which is similar to A point. The membrane prestress increases the structural stiffness of the membrane structure, which leads to the increase of wave propagation. With membrane prestress increasing, the vibration frequency of C point increases which is because C point is close to the boundary. Then, the amplitude is small, and the vibration superposition effect of membrane surface is obvious.

(2) Acceleration change

As shown in Fig. 11, with the increase of membrane prestress, the contact time decreases, which is not conducive to the energy dissipation of membrane structure. The maximum acceleration rate decreases with the increasing of membrane prestress. Besides, the magnitude of the decrease gradually increases. The membrane prestress increases the structural stiffness and decreases the impact resistance of membrane structures.

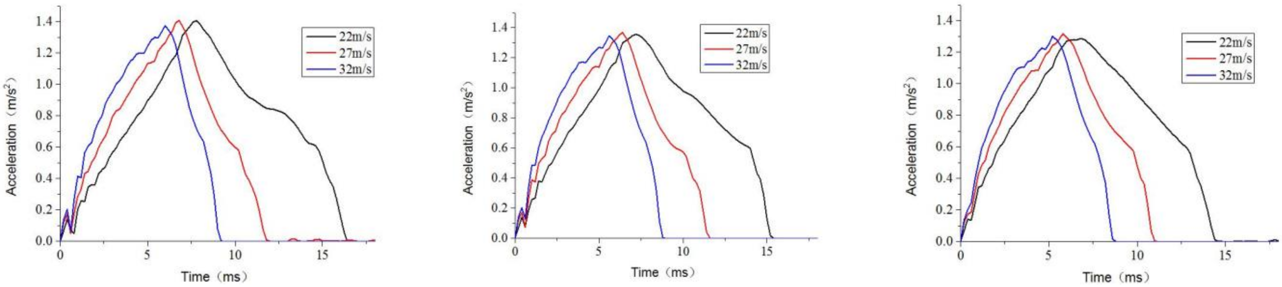
(3) Kinetic energy change

As shown in Fig. 12, with membrane prestress increasing, the percentage of kinetic energy of projectiles increase and the kinetic energy loss decreases, which indicates that the energy dissipation capacity of membrane structure decreases. With the membrane prestress increasing, the initial speed decreases fast and the structural resistance decreases. The increasing of membrane prestress improves the whole stiffness of membrane structure and reduce the limit failure stress value and deformation energy dissipation. Therefore, the energy dissipation capacity of membrane structure decreases slightly.



(a) 1kN/m (b) 3kN/m (c) 5kN/m

Fig. 14 Membrane displacement under different velocities impacted with round punch (Point A)



(a) 1kN/m (b) 3kN/m (c) 5kN/m

Fig. 14 Acceleration of round punch at different speed

3.3 Initial impact speed of projectile

(1) Membrane displacement

As shown in Fig. 13, when the point is further away from the impact point, the vibration amplitude is smaller. Due to the fixed boundary, the displacement of membrane surface is lower. Besides, there are the same vibration modes for the three points. Their vibration waves lag behind the impact center. Besides, the vibration frequency of C point is higher than A point and B point and it increases with the increasing of the distance from the center. The reason is the vibration superposition of membrane surface. For C point, the amplitudes of the vibration are small, so the vibration law of C point is more affected by the vibration superposition and its vibration frequency is higher. For A and B points, the effects of vibration rebound is not significant, because its own vibration is high. Therefore, although there is vibration superposition, the effect of superposition is not obvious, and the vibration frequency is lower.

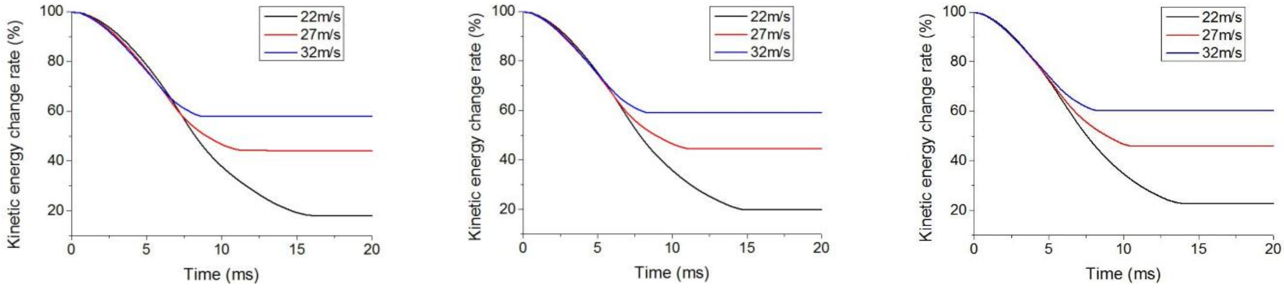
From Fig. 13, with the increase of initial speed, the maximum displacement of membrane surface increases at the same time. Besides, the membrane surface deformation increases and the energy dissipation of membrane structure increases. When the initial speed is 22m/s, obvious vibration phenomenon and two peaks can be observed. When the initial speed is 32m/s, there is only one peak. In the penetration process, when the initial speed decreases, the vibration of the membrane structure is more significant. The reason is that when the speed is low, the penetration time is longer and there is sufficient vibration time. Besides, when the speed is lower, the vibration amplitude is smaller, and the effect of vibration superposition is more obvious.

However, the displacement of 22m/s is the largest and the difference between 27m/s and 32m/s is small. The maximum displacement of 27m/s is the lowest and the attenuation law is not obvious. The reason is the vibration superposition of membrane surface. As we know, in the solid, the speed of longitudinal wave is about 5km/s. In this model, the length of membrane surface is only 1m, it needs only 0.2ms to spread to the border. The membrane displacements of 27m/s and 32m/s are similar, which is related with the jamming of vibration propagation rebound. This is only a special case only existing in tests with the flat punch, perhaps related to the punch shape.

(2) Acceleration change

From Fig. 14, it can be seen that the acceleration can well reflect the changing of the structural resistance during the impact process, and the impact time decreases with the increase of initial speed. Besides, the maximum value of the acceleration rate remains almost unchanged, which indicates that the initial speed of the projectiles has no effects on the structural resistance of membrane structures. This is mainly related with the failure criterion of membrane materials. The effect of initial speed on the energy dissipation capacity of membrane structure is mainly related with to the area of impact surface, which has little effects on the impact resistance of membrane structure.

There is a big sudden jump at the initial, while the variation of flat punch is more obvious than the round one. It can be also observed for the taper punch. It is the contact energy dissipation between projectiles and membrane structure which is the kinetic energy transfer of momentum theorem. This is related to the shape of contact surface. When the punch is sharper, the surface area of the contact decreases and the quality of the collision involved decreases and the energy loss is not significant.



(a) 1kN/m (b) 3kN/m (c) 5kN/m

Fig. 15 Percentage of kinetic energy with a round punch at different velocities

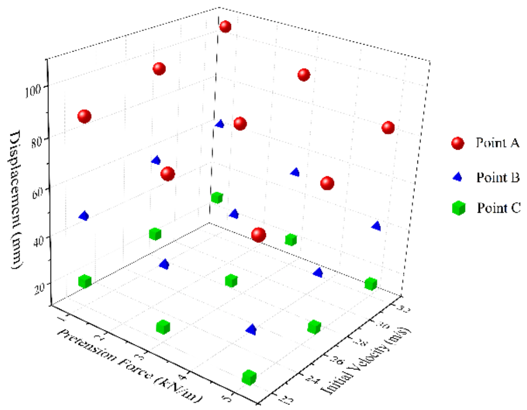


Fig. 16 Membrane displacements under diffierent initial velocities and membrane prestress

(3) Kinetic energy change

The variation of the kinetic energy of the projectiles is related to the initial speed of the projectiles. With the initial speed increasing, the variation percentage of kinetic energy of the projectiles increases, and the loss percentage of kinetic energy decreases. It is found that the energy dissipation ability of membrane structure is reduced, with initial speed increasing. The increasing of the total loss of kinetic energy means the increasing of energy dissipation capacity of membrane structures. The reason is that the failure of membrane surface against the projectiles is tearing failure and the energy absorption depends mainly on large deformations of membrane structure. With initial projectile speed increasing, the area of impact damage increases and the kinetic energy loss increases. There is a sudden jump in the variation of kinetic energy at the initial of contact process. It is the contact energy dissipation of membrane structure, which is related to the contact surface. The sharper the punch, the smaller the surface area of the contact, so the contact energy loss is less.

Fig. 16 shows the variations of maximum displacement along with membrane prestress and initial speed at Point A (upper), B (middle) and C (bottom) (Li *et al*. 2017), which is a typical three-level distribution. The graphics are close to the rectangular plane, so that maximum displacement has approximately linear relationship with initial speed and membrane prestress (Li *et al*. 2017). When the initial speed of the projectiles is 32m/s and the membrane prestress is 1kN/m, the displacement value of Point A is the maximum. When the point is further away from the impact point, the maximal displacement is smaller. Therefore, the maximal displacement and the distance of the point on structure also have linear correlations (Zhang *et al*. 2019).

4. Conclusions

This paper mainly researches on the parameters, including the shape of the projectile, the membrane prestress on the surface and the impact initial speed, are changed in the model for studying the dynamic response and failure mechanism, which are analyzed from the aspects of membrane displacement, projectile acceleration and kinetic energy. The following conclusions can be drawn:

- The energy dissipation of membrane structure against impact is composed of three parts, the deformation energy dissipation, fracture energy dissipation and frictional energy dissipation. Tearing failure turns to be the main failure mode under impact load, which is the most important way of energy dissipation. During the impacting process, the membrane structure can absorb most of the impact energy through large deformation, and it requires a certain time response. The friction energy dissipation is not an important part due to the small friction between the projectile and the membrane surface.
- The initial speed is related with the loss of kinetic energy of projectiles. The increasing of initial speed leads to the area of failure surface increasing. The failure energy dissipation of membrane structures and the loss rate of kinetic energy of projectiles both increase. However, impact resistance of membrane structure is not affected.
- The pretension force is an important factor that affects the energy dissipation capacity and the impact resistance of membrane structures. With the increasing of membrane prestress, the structural stiffness of the membrane structure increases. However, the limit stress value and the impact resistance decreases. At the same time, the maximum membrane deformation and energy dissipation capacity of membrane structure decreases.
- The punch shape is an important factor that affects the kinetic energy loss of projectiles. If the punch shape is more flat, the area of failure surface is larger and the failure energy dissipation of membrane structure is higher. Besides, when the punch shape is more flat, the maximum impact resistance of membrane structure increases, in which condition it is difficult to achieve the ultimate failure stress.
- The dynamic response of membrane surface is

related with the membrane prestress, punch shape and dimensions of membrane structures. Significant lagging of vibration transferring can be observed on the membrane surface, which is related to the distance between the point and the impact position. With the initial speed and the membrane prestress decreasing, the maximum displacement increases, which is related with the shape of the punch.

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