Research on Human Falling Protection Performance Based on Safety Net

Zongyu Chang[1,2] ,Jingwen He[1], Peizheng Hao[1], Zhongqiang Zheng[1]
1. College of Engineering
Ocean University of China
Qingdao, China
2. Key Laboratory Ocean Engineering Lab of Shandong Province
zongyuchang@ouc.edu.cn

***Abstract*—As a high-risk industry for safety accidents in the construction industry, falling from a height is the most likely one to be occurred. Based on the finite element analysis method, this paper combines the safety net model with the human body model to obtain the human body-net dynamic simulation model. Through simulation, the effects of different factors on the fall protection performance of safety net are analyzed from different aspects. The maximum contact force of the human body model can be used as an evaluation index to reflect the protective performance of the safety net effectively in the research process. The research results show that under the condition of meeting the protection requirements and economy, reducing the height between the safety nets, and choosing a safety net with a larger overall size and a smaller mesh side length can effectively improve the protection performance of the safety net. This study can provide a reference for choosing, arranging and installing the safety net during construction industry.**

Keywords-Safety net; Flexible net; Safety protection; High falling accident

I. INTRODUCTION

As the construction industry is a high-risk industry for safety accidents, falling from a height is the most likely one to be occurred. Safety net is widely used as an important safety protection product in high-rise operations. Safety net is a flexible web structure made of nylon, polyester or other fiber ropes.

A lot of works has been done in the research of structure of flexible mesh and the protection of human falling. Anghileri M et al. [1] models the safety net based on finite element method, and uses Hybrid III mannequin model to simulate the damage of skiers falling to safety net body at different speeds and angles. Gourinat Y et al. [2] discussed the nonlinear dynamic modeling of safety net systems at different scales, proposed an analytical two-dimensional model and a nonlinear finite element model simulation method for the preliminary design, established the safety net dynamic model, verified the qualification of the safety net model by dynamic test. The United Kingdom Health and Safety Laboratory [3] studied possible problems with the performance of safety nets and their accessories when they suffered undesirable impact loads, then can assess the effectiveness of safety nets in order to detect the risk of failure timely. Zhao G W et al. [4,5] established the dynamic model of flexible mesh based on the finite element method and lumped mass method and simulated the developing process. Considering the effects of air resistance and gravity and using the method of iteration calculation, Hu X N et al. [6,7] established the numerical models of single net rope, space fly net and gravity cage based on the finite element method, compared the simulation results with the formers, and verified the reliability of the method. Chen B J et al. [8] established a finite element model of cable impact protection network system based on finite element method. The force analysis of the fixed end of the protection net was analyzed by simulation that effectively solved the problem the collision force between flexible bodies which was difficult to calculate. Wan J N, Cao Q et al. [9,10] built the model of the wire rope of the police net gun based on the finite element method. The simulation and experimental study of the launching and unfolding process of the defensive net gun were carried out. To some extent, the nonlinear problem of the flexible net was realized. Zeng S Y et al. [11] built the numerical model of the highway slope passive flexible protection net based on the finite element method, calculated and studied its protection performance.

Based on finite element method and explicit nonlinear dynamic software LS-DYNA, the dynamic model of human body-safety net is established in this paper. The process of safety net intercepting human falling under different conditions is simulated, which provides a theoretical basis for choosing, arranging and installing the safety net during construction industry.

II. SAFETY NET

The horizontal safety net is a safety net which is installed in parallel with the horizontal plane or has certain angle with the horizontal plane, which is mainly used to avoid and reduce the falling of human body or object that causing falling and damage to objects, etc.

According to the national standard GB 5725-2009 [12], the safety net is generally composed of mesh ropes, border ropes,

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tie ropes and so on. The mesh rope is the main part of the safety net. The border rope is the rope which passes through each mesh at the perimeter of a net and determines the overall dimension of the safety net. Tie rope is the rope used for securing the border rope to a suitable support. The overall structure of the safety net is shown in Figure 1.

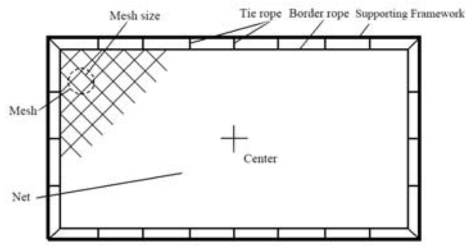
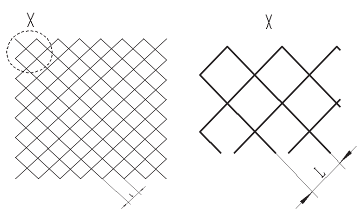
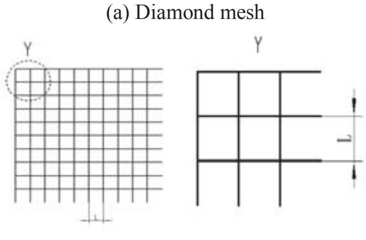


Figure 1. Overall structure of the safety net

The overall dimension of the safety net should not be less than 3m in width, and the commonly used overall dimension is 3×6m. According to the shape of the mesh, the safety net can be divided into diamond safety net and square safety net. The mesh shape of the safety net is shown in Figure 2. In the actual application, the diamond safety net is used more. As shown in Figure2, L denotes the mesh size of the safety net, L≤80mm, then the mesh side area is generally 30×30 to 80×80mm. The diameter of border rope and tie rope should be more than or equal to 2 times of the mesh rope, and should be more than 7mm. The tie rope is evenly distributed along the edge of the safety net. The distance between two adjacent tie ropes should be less than or equal to 0.75m, and the length of the tie rope should be more than or equal to 0.8m. After the safety net is installed, the distance between the edge of the safety net and the wall of the building should be less than 0.1m.



(a) Diamond mesh



(b) Square mesh

Figure 2. Mesh shape of the safety net

III. HUMAN BODY-SAFETY NET FALLING SIMULATION MODEL

A. Safety net model

In the element library provided by ANSYS/LS-DYNA software, Link167 element can only withstand tension, and this element can only produce tension but not pressure, which is consistent with the characteristics of flexible net. Therefore, the Link167 element is used to establish the safety net numerical model. According to the characteristics of Link167 element, the element material model is defined by Cable material.

The formula for calculating the axial force of LINK167 element is as follows:

$$F = K \max(\Delta L, 0) \tag{1}$$

where ΔL is the change quantity of length and ΔL = the current length - (initial length - *offset*). K is stiffness and its formula is as follows:

$$K = E \times A \big/ (10 - offset) \tag{2}$$

where A is the section area of the cable. *offset* is defined by defining the real constants of LINK167 element. When the element relaxes, the *offset* is negative and when the element is tense, the *offset* is positive.

The model for established safety net is shown in Figure 3:

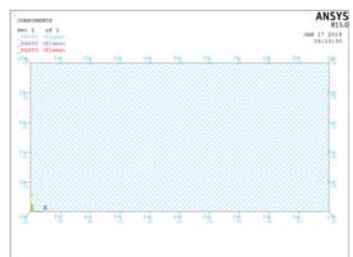


Figure 3. Safety net model

B. Human body model

Base on the fact that the US 50th percentile human body size parameter is equivalent to the Chinese 95th percentile human body size parameter [13], in order to describe the distribution of human body size comprehensively, this paper uses the US 50-percent dummy model to establish a human-safety net simulation model and perform calculation analysis. After comparison, the Hybrid III 50th percentile dummy model established by LSTC Company, which used the explicit nonlinear dynamics software LS-DYNA software and developed by the finite element method is shown in Figure 4. The model can accurately reflect the structure, force and deformation of various parts of the human body. This paper uses this dummy model to establish a human body-safety net falling simulation model.

C. Human body-safety net model

In the process of modeling, the dummy is located at the center of the safety net, and the fixed connection between the tie rope and the support frame is simplified by a constraint. In order to improve the speed of the simulation, the position of the dummy's centroid is set to be 0.1m away from the mesh surface, and the simulated safety net intercepts the process of human fall. The human body-safety net dynamics model is shown in Figure 5.

Figure 4. Human body model

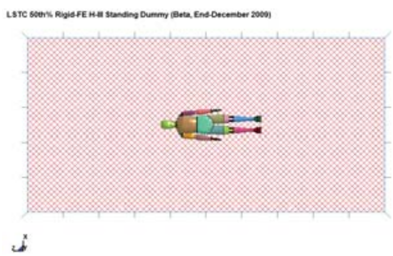


Figure 5. Human body-safety net model

IV. HUMAN BODY-SAFETY NET FALLING SIMULATION ANALYSIS

A. Parameter settings

Set the specific simulation parameters for the established human-safety net model. In construction and other engineering applications, the diamond-shaped safety net with the overall dimension of 3×6m is widely used. Therefore, this paper selects the safety net of this specification to establish the numerical simulation model. According to the size requirements of each part of the safety net, the basic size parameters are determined as shown in Table I.

TABLE I. BASIC SIZE PARAMETERS OF SAFETY NET

Overall dimension /m	*Tie ropes spacing /m*	*Mesh shape*	*Mesh size /mm*	*Length of tie rope /m*
3×6	0.6	Diamond mesh	70.71	0.1

According to the national standard GB/T 11787-2017 [14], the safety net made of three strands of polyester material which is the most used in construction is selected, and the material parameters of each component of the safety net are defined. The material parameters of the safety net model are shown in Table II.

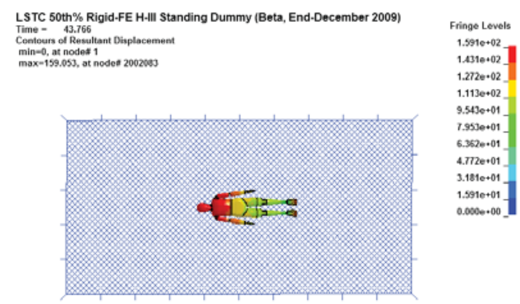
TABLE II. MATERIAL PARAMETERS OF SAFETY NET

Component	**E /Gpa**	**ρ /(kg/m3)**	**NUXY**	**Diameter /mm**	**Sectional area /mm2**	**Breaking force /kN**
Mesh rope	2.32	1130	0.34	4	12.56	2.8
Border rope	2.32	1130	0.34	8	50.24	10.6
Tie rope	2.32	1130	0.34	8	50.24	10.6

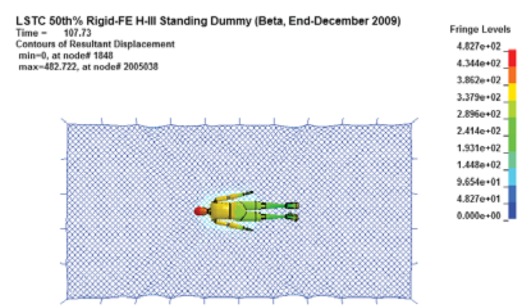
Assume that the human body falls from the 4m high working plane, and the falling process is regarded as freely falling body motion. The gravity acceleration is $9.8 m/s^2$, and the speed of the dummy in the model is 8.74m/s when it is 0.1m away from the mesh surface. The numerical simulation time is set to 500ms. Through simulation, the deformation of the safety net, the axial force of the components of the safety net and the contact force between the human body and the safety net are analyzed.

B. Safety net deformation analysis

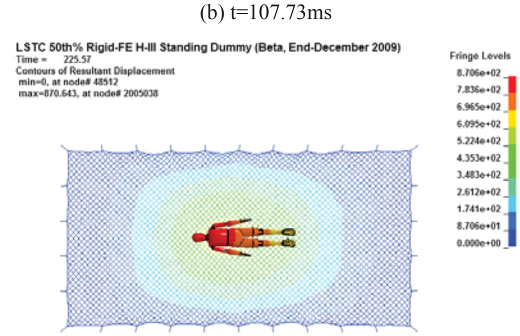
The deformation of safety net is a sign of safety net performance. Starting from human contact safety net, safety net uses its own deformation to play the role of interception. During the entire interception process, the safety net gradually reduces the speed of the human body to zero by the increase of its own deformation, thereby playing a role of safety protection. The deformation of the safety net is shown in Figure 6.



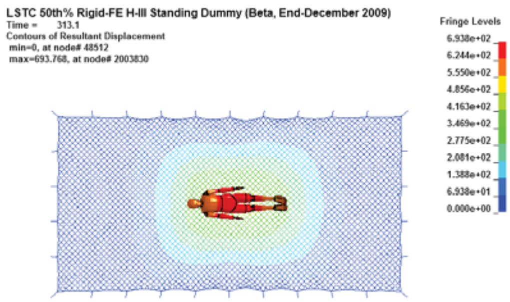
(a) t=43.766ms



(b) t=107.73ms



(c) t=225.57ms



(d) t=313.1ms

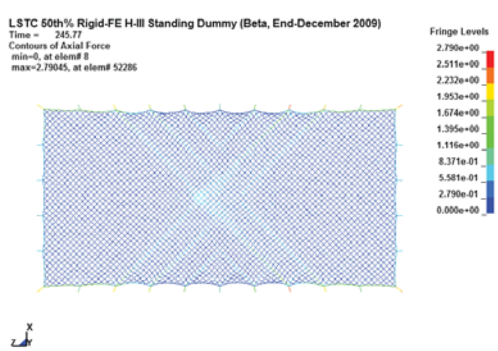
Figure 6. Deformation of safety net

In the modeling process, the dummy and the net surface have a certain distance. When t=43.766ms, the dummy starts to contact with the safety net, the deformation of the mesh is zero. During the time period t=43.766ms~225.57ms, under the impact of a dummy falling, the deformation of the safety net increases gradually and the mesh surface gradually sinks downwards, as shown in Figure 6 (b), which shows the deformation of the safety net when t=107.73ms; when t=225.57ms, the maximum deformation of the safety net is reached, and the speed of the dummy is reduced to zero. During the time interval t=225.57ms~500ms, there is a rebound phenomenon that the safety net drives the dummy to move upward due to the elasticity of the mesh itself.

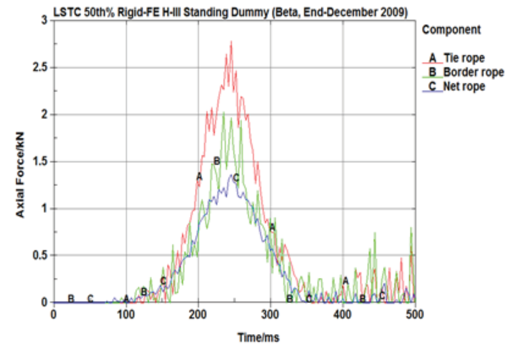
The maximum deformation of the mesh close to the center of the dummy's fall was achieved during the whole interception process, The deformation of the mesh is parallel to the four sides of the mesh along the center of the dummy's fall, and the deformation of the mesh near the edge is the least, and it extends and decreases gradually.

C. *Safety net axial force analysis*

The process of the human body falling into the safety net is actually an impact process. The impact force caused by the human body falling to the safety net is transferred to the border rope through the net rope and finally to the tie rope. Since the breaking force of each component of the safety net is different, each component must meet the strength requirement to protect the human body from falling. Therefore, the analysis results of the axial force of each component of the safety net are shown in Figure 7.



(a) Overall axial force distribution of safety net



(b) The history curves of axial forces

Figure 7. Axial forces distribution of safety net

Figure 7 (a) shows that the force on the mesh is mainly distributed in the center of the dummy's fall, and it is obliquely crossed from the center to the sides along the line. The maximum axial forces values of the border ropes and tie ropes are distributed at the four corners of the safety net and the extension of the force on the net rope.

Figure 7 (b) shows that the maximum axial force of each component of the safety net occurs near the time when the maximum deformation of the safety net occurs. Among the axial force of each component of the safety net, the tie rope is the largest, the border rope is the second, and the net rope is the smallest. Since the dummy falls in the center of the safety net during the modeling of the human-safety net, the axial force distribution of the components in the safety net is symmetrical.

D. *Contact force analysis*

High fall injury is a category of impact acceleration damage. The severity of high fall injuries is closely related to the average impact force on the human body when it is impacted. Due to the working plane of workers at high altitudes, the speed of the human body when contacting the safety net is large when the fall occurs, and the contact force between the human body and the safety net may cause certain damage to the human body. The contact force between the human body and the safety net is shown in Figure 8.

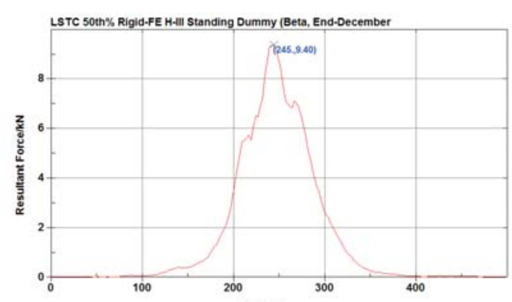


Figure 8. The history curves of contact force

Figure 8 shows that in the process of the safety net intercepting the human body falling, the contact force gradually increases from the contact between the human body and the safety net, and finally reaches the maximum of 9.40kN at

245ms. The contact force gradually decreases with the rebound of the safety net and finally tends to zero.

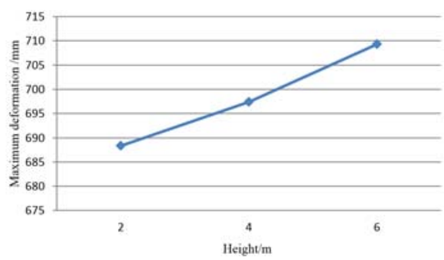
V. IMPACT ANALYSIS OF SAFETY NET PROTECTION PERFORMANCE

A. *Impact of different fall states*

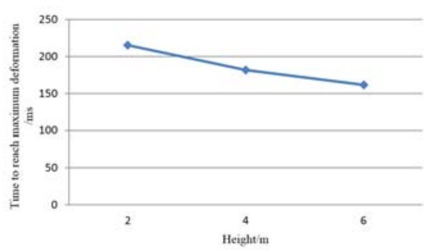
During the safety net interception of the human body fall, the reaction force which generated by the safety net acts on the human body, causing damage to the contact part of the body with the safety net, and the main injured part of the human body is the contact point and the impact part. Therefore, different heights and contact postures of falling have a certain impact on the severity of human injury.

1) *Different fall heights*

From the perspective of different fall heights, the human body fall height is 2m, 4m, 6m for simulation. Through simulation analysis, under different fall heights, the maximum deformation and the time to reach the maximum deformation of the safety net, the axial force of different type of rope, and the maximum contact force between the human body and the safety net are shown in Figure 9 to Figure 11.



(a)



(b)

Figure 9. Maximum deformation (a) and Maximum deformation time (b) at different heights

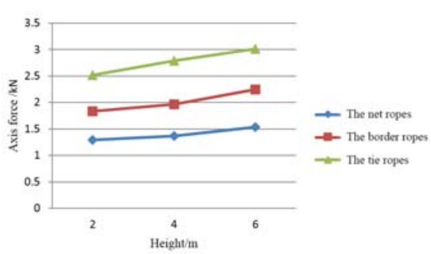


Figure 10. Axis Force at different heights

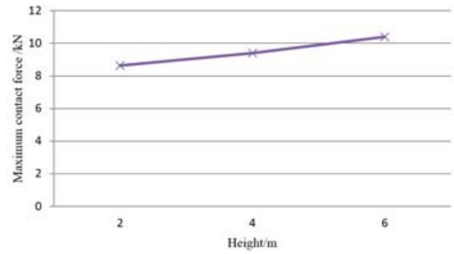
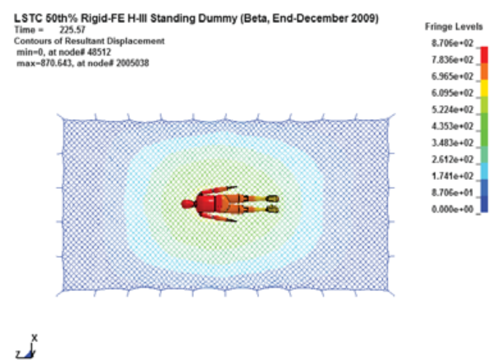


Figure 11. Maximum contact force at different heights

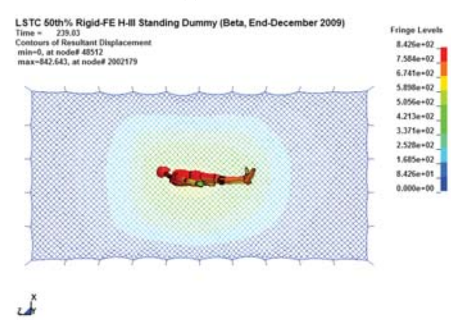
It can be seen from Figure 10 that the maximum axial force received by each component of the safety net does not exceed its limit value, that is, safety protection can be achieved. As seen in Figure 9 to Figure 11, with the increase of the height of the human body, the impact energy of the human body gradually increases, so that the impact force of the safety net when intercepting the human body falls, the maximum deformation of the safety net, the maximum contact force of the dummy and the safety net, and the maximum axial force experienced by the each component also increases, and the time to reach the maximum amount of deformation gradually decreases.

2) *Different contact postures*

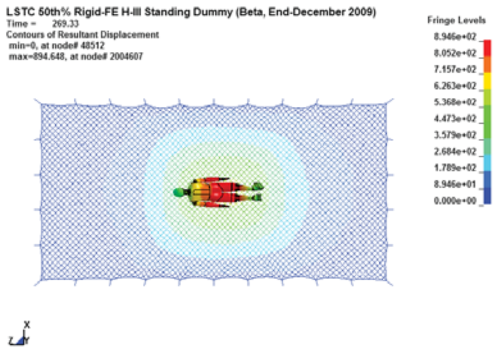
From the perspective of different contact posture, it is assumed that the human body falls from 4m, touch the safety net with the back, the side, and the chest of human body for simulation, as shown in Figure 12.



(a) The back



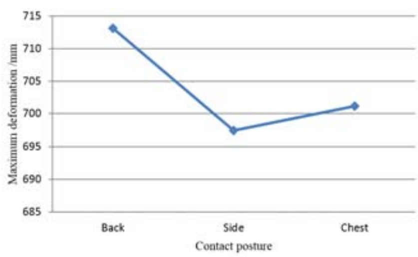
(b) The side



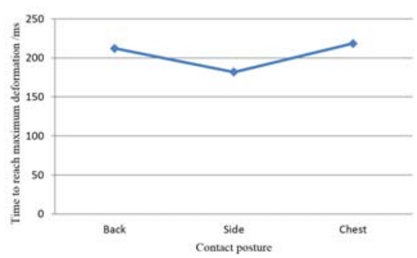
(c) The chest

Figure 12. Deformation of safety net at different contact postures

Through simulation analysis, under different contact postures, the maximum deformation and the time to reach the maximum deformation of the safety net, the axial force of different type of rope, and the maximum contact force between the human body and the safety net are shown in Figure 13 to Figure 15.



(a)



(b)

Figure 13. Maximum deformation (a) and Maximum deformation time (b) at different contact postures

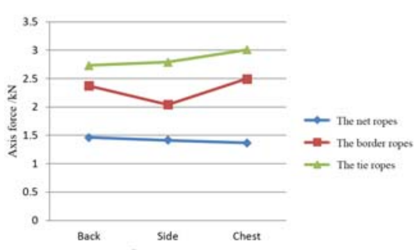


Figure 14. Axis force at different contact postures

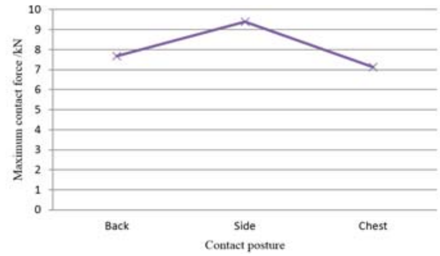


Figure 15. Maximum contact force at different contact postures

Similarly, it can be seen from Figure 14 that safety protection can be achieved. As seen in Figure 13 to 15, for the three fall postures, the maximum deformation of the safety net when the back is in contact is greater than the other two postures. The contact between the dummy and the safety net is greatest when the side body is in contact, the second is when the back is in contact, and the smallest when the chest is in contact. When the back contact is made, the contact area between the body and the net is smaller than the other two postures, so that the force of the net rope is the greatest when the side body is in contact, and the human body has the highest degree of injury. When the side body is in contact, the safety net reaches the maximum amount of deformation for the shortest time, and the chest contact takes the longest time. When the chest is in contact, the tie ropes and side ropes of the safety net are subjected to the greatest axial force.

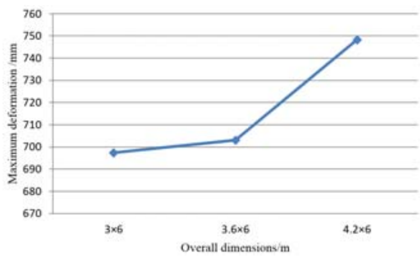
In summary, the most stressed part of the safety net is the tie rope, the side rope is the second, and the net rope is the smallest. This is because the impact force of the human body is shared by the interwoven mesh ropes, and is transmitted to the side ropes through a plurality of connection points, and finally a small number of tie ropes take up the resultant force of the safety net system. The smaller the distance between the human body and the safety net, the smaller the maximum axial force of each member and the smaller the contact force between the human body and the safety net, the better the protective effect. In order to improve the protection effect of the safety net and ensure that the safety net is not damaged, the number of erection layers of the safety net should be increased to reduce the distance between the two safety nets under the conditions of meeting construction and economic requirements. When a fall accident occurs, personnel should protect the vulnerable parts of the body while increasing the contact area with the safety net to reduce the degree of injury to the human body.

B. *Impact of different safety net specifications*

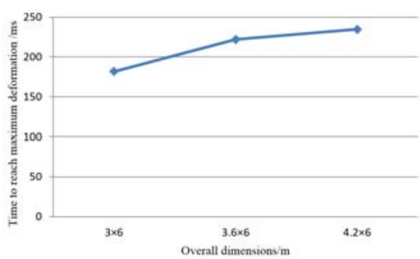
The difference between the overall dimension and the mesh length of the safety net will cause the change of the exposure area of the human body to the safety net, the number of human impact meshes, the axial force on the components of the safety net and the contact force between the human body and the safety net during falling process that the human body was intercepted by the safety net.

1) *Different overall dimensions*

From the perspective of different overall dimensions, the diamond safety net model with the overall dimension of 3×6m, 3.6×6m and 4.2×6m is established respectively. Based on the established safety net, a simulation model of human-safety net falling was established under different safety net specifications. Through simulation analysis, under different overall dimensions, the maximum deformation and the time to reach the maximum deformation, the axial force, and the maximum contact force are shown in Figure 16 to Figure 18.



(a)



(b)

Figure 16. Maximum deformation (a) and Maximum deformation time (b) at overall dimensions

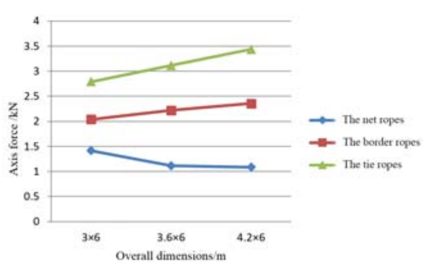


Figure 17. Axis Force at different overall dimensions

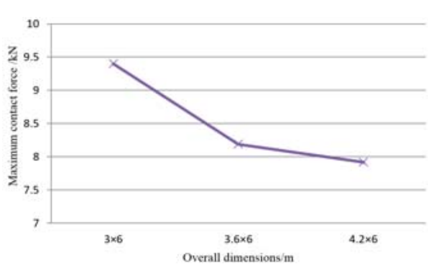
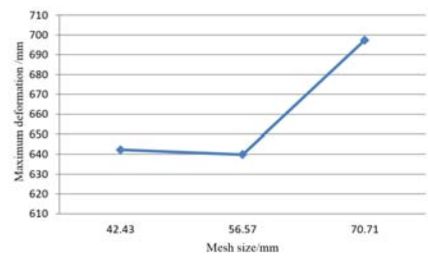


Figure 18. Maximum contact force at different overall dimensions

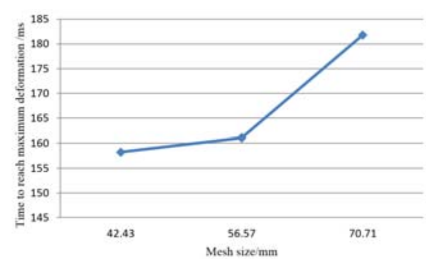
It can be seen from Figure 17, the three kinds of safety nets with different overall dimensions can be safe enough to protect the fall. As shown in Figure 16 to 18, with the increase of the overall dimension of the safety net, the maximum deformation, the time to reach maximum deformation, axial force of the net ropes, axial force of the border ropes and the tie ropes, maximum contact force are decreased gradually.

2) Different mesh sizes

From the perspective of different mesh sizes, the diamond safety net model with the overall dimension of 3×6m, and the mesh edges of 42.43mm, 56.57mm, and 70.71mm is established respectively. Through simulation analysis, under different mesh sizes, the maximum deformation and the time to reach the maximum deformation, the axial force, and the maximum contact force are shown in Figure 19 to Figure 21.



(a)



(b)

Figure 19. Maximum deformation (a) and Maximum deformation time (b) at different heights

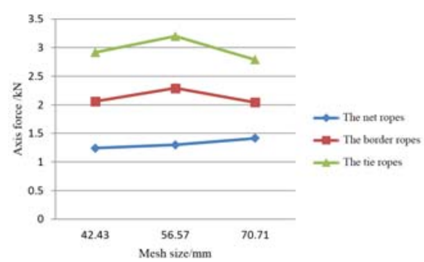


Figure 20. Axis Force at different heights

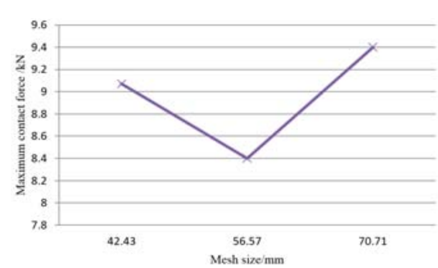


Figure 21. Maximum contact force at different heights

It can be seen from Figure 20, the three kinds of safety nets with different mesh sizes can be safe enough to protect the fall. As shown in Figure 19 to 21, with the same overall dimension of the safety net, as the safety net mesh length increases, the maximum deformation of the safety net and the time to reach the maximum deformation also increase. Among the three mesh lengths, when L=56.57mm, the axial force of the border ropes and the tie ropes is the largest. When L=70.71mm, the contact force between the dummy and the safety net is the largest, and when L=56.57mm, it is the smallest.

To sum up, the maximum axial force is suffered by the tie ropes, the next is the border rope, and the minimum is the net ropes. In order to improve the protective effect of safety net and to reduce the harm to human body, under the condition of satisfying the protective effect, construction requirement and economy, we should choose the safety net with larger overall dimension and smaller mesh edge length.

VI. Conclusion

Based on the finite element method, this paper combines the model of safety net with the model of human body to establish a human-safety net dynamics simulation model. From the angle of the deformation of the safety net, the force of each member and the contact force between the human body and the safety net, the effect of the height of human falling, the contact position and the safety net specification on the safety net protection performance are analyzed. The simulation results show that:

(1) The higher the fall height, the larger the deformation of the safety net, the greater the force of each component, the more the contact force between the human body and the safety net, the worse the protection effect. When an accident occurs, increasing the contact area of the body with the safety net can reduce the damage. Therefore, in order to mitigate human injuries and enhance the protective effect of the safety net, increase the number of layers of the safety net as far as possible and reduce the height between the two layers of safety net, provided that the requirements of protection and economy are met, When a crash occurs, the body should maintain a larger contact area with the safety net based on the protection of the vulnerable parts of the body, in order to allocate the contact between the body and the safety net, thereby reducing the extent of the physical damage.

(2) The larger the overall dimension of the safety net, the smaller the mesh edge, the better the safety protection effect. Therefore, in order to reduce the harm and enhance the protective effect of the safety net, the safety net should choose a larger overall dimension and smaller mesh length under the condition of meeting the requirements of protection and economy.

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