Study on impact resistance of steel structural modular energy dissipation shed

Hang Xiao[a*], Zhi-Xiang Yu[b]

School of Civil Engineering, Southwest Jiaotong University, Chengdu, Sichuan, China

[a*]xiao.edu.cn@my.swjtu.edu.cn,[b]yzxzrq@swjtu.edu.cn

Abstract. In response to the low assembly level of the existing steel structure flexible shelter system, the use of welding as the connection method for supporting components, and the unreasonable arrangement of energy dissipation buffer layers, resulting in slow installation speed of the steel structure shelter, difficulty in replacing local components after being damaged by falling rocks, and low energy consumption levels, this paper proposes a steel structure modular energy dissipation shelter system based on a cable supported flexible buffer layer, This system replaces the flexible support in the cable supported flexible buffer layer with rigid support. A dynamic nonlinear numerical model of the shed tunnel was established, and the influence of different support conditions on the impact dynamic response of the shed tunnel was analyzed. The influence of impact velocity on the shed tunnel was studied. The results indicate that rigid support is more conducive to the stability of cable supported columns; Compared to the existing flexible shed tunnel with a protective energy level of 250KJ, the modular energy dissipation shed tunnel system of this steel structure can achieve protection of 2000KJ energy level, and the protective energy level of the system has been increased by 700%; The impact speed has a small impact on the buffering distance, but a significant impact on the impact force and internal force of the system support components.

Keywords: Impact and protection; Numerical simulation; Energy consumption; Shed.

1 Introduction

Rockfall refers to a dynamic process in which individual stones separate from the surface of a slope and rapidly move downwards along the slope through one or more combinations of actions such as falling, rebounding, jumping, rolling, or sliding, and finally come to rest near obstacles or gentle areas [1]. Rockfall pose a huge threat to the infrastructure and driving safety along the transportation route [2]. Shed tunnel are the main emergency rescue and protection measures for rockfall disasters in mountainous areas. Reinforced concrete shed tunnels have disadvantages such as large land area, heavy structural weight, long construction period, and high cost. The flexible steel shed tunnel

G. Zhao et al. (eds.), *Proceedings of the 2023 5th International Conference on Civil Architecture and Urban Engineering (ICCAUE 2023)*, Atlantis Highlights in Engineering 25,
https://doi.org/10.2991/978-94-6463-372-6_20

[3] utilizes the advantage of flexible protective nets to "overcome rigidity with flexibility" [4-5], reducing the impact force on the support structure. It has advantages such as light weight, prefabrication, fast construction, and easy maintenance. However, it has disadvantages such as blurred boundary between the support structure and buffer layer, frequent failure and damage of the overall structure, and low protection energy level. The existing flexible shed tunnel [3] has a protection energy level mostly lower than 250KJ.

At present, domestic and foreign scholars have conducted extensive research on reinforced concrete sheds and flexible steel sheds. Delhomme et al. [5-6] conducted damage experiments on rigid concrete sheds, and the results showed that the concrete roof had three damage modes: surface damage, punching damage, and bending damage. Wang Zhe et al. [7] studied the dynamic response of corrugated prefabricated corrugated steel shed tunnels, and the results showed that the thickness of corrugated steel had the smallest impact on the deformation and stress of the shed tunnel, followed by the waveform of corrugated steel, and the thickness of concrete had the greatest impact. Wang Min et al. [8] conducted full-scale impact experiments on three bay single span flexible steel shed tunnels. The results showed that the system can successfully intercept falling rocks under 250KJ impact, and the system can continue to be used after simple maintenance. At the same time, it was proposed that the configuration relationship of support components, support ropes, and energy dissipation components has a significant impact on the energy consumption of the system. S. Kawahara et al. [9] studied the impact dynamic response of buffer cushion dry density and thickness on rockfall. The results showed that as the dry density of the cushion increases and the thickness decreases, the impact force of rockfall decreases. Sun et al. [10] used rubber tires as cushioning materials to study the effects of rockfall mass, height, and filling materials on cushioning performance. Tan K et al. [11] proposed a cable supported flexible buffer structure based on the principle of cable supported structure, and studied the deformation characteristics and energy dissipation capacity of the structure. The buffer layer can be applied to various greenhouse tunnel structures. Liu Chengqing et al. [12] compared and analyzed that under the same protective energy level, width, and extension length conditions, the flexible shed tunnel system has significant advantages over traditional reinforced concrete shed tunnel systems in construction, structural stress, environmental protection, and economy. Wang Min et al. [13] used numerical simulation methods and combined experimental data to analyze the energy dissipation performance of internal components of flexible steel shed tunnels under rockfall impact, and proposed optimization measures for flexible steel shed tunnels.

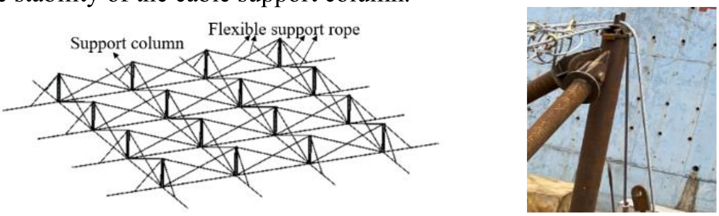
In response to the problems of low assembly level of existing steel structure flexible shed and tunnel systems, multiple welding methods for supporting components, unreasonable arrangement of energy dissipation buffer layers, slow installation speed of steel structure shed and tunnel systems, difficulty in replacing local components after being damaged by falling rocks, and low energy consumption levels, this paper proposes a steel structure modular energy consumption shed and tunnel system to achieve modular installation and fast construction speed of flexible shed and tunnel systems High energy consumption level, more suitable for emergency rescue of rockfall disasters . This article establishes a dynamic nonlinear numerical model of the shed, analyzes the impact dynamic response of the cable support column system under different support conditions, and studies the influence of impact speed on the impact dynamic response of the shed.

2 Design and working principle of the system

2.1 Design of the system

The key points in the design of modular energy dissipation shed holes in steel structures lie in modular installation and high energy consumption performance.

In the cable supported flexible buffer structure [11], a flexible support rope is used to connect the top of the support column (figure 1(a)). Due to the fact that the flexible support can only be tensioned, when the buffer layer is impacted by falling rocks, only the outer flexible support can provide tension to the top of the cable supported column, while the inner flexible support cannot function. Due to the fact that rigid supports can be both tensile and compressive, both the inner and outer layers of rigid supports can play a role in the system under the impact of falling rocks, and compared to flexible supports, rigid supports have a certain degree of out of plane stiffness. Therefore, the buffer layer of the steel structure modular energy dissipation shed system uses rigid supports to connect the top of the support column (figure 1(b)), which is more conducive to the stability of the cable support column.



(a) (b)

Fig. 1. Connection method at the top of the cable support column:(a) flexible support connection (b) rigid support connection.

(a) (b)

Fig. 2. Energy dissipator: (a) circular energy dissipator (b) u-shaped rod type energy dissipator.

The support components of traditional steel structure flexible shed holes are mostly connected by welding. The supporting components of the modular energy dissipation shed of the steel structure are connected by bolts (figure 3). The system components can be prefabricated in advance and directly assembled on the protective site, shortening the construction period and making it more suitable for emergency rescue in rockfall disasters.

Energy dissipators are important energy dissipation components of modular energy dissipation sheds in steel structures, which can achieve high energy consumption in the system. Common energy dissipators include pressure reducing rings [14] (figure 2(a)) and U-shaped rod type energy dissipators [15] (figure 2(b)).

Fig. 3. Bolt connection method for modular shed.

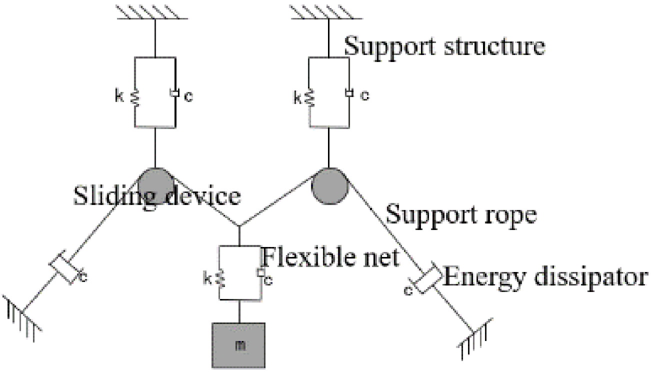


Fig. 4. Buffering principle of the system.

2.2 The working principle of the system

The modular energy dissipation shed of steel structure mainly achieves the energy dissipation of falling rocks through the friction damping and deformation of the energy dissipator, and the deformation of the flexible mesh. The energy consumption buffering principle of the system is shown in figure4.

3 Numerical simulation and analysis

3.1 Component of the model

Using LS-DYNA software, establish a dynamic nonlinear numerical model of the steel structure modular energy dissipation shed system (figure 5). The component specifications of the model are shown in table 1.

3.1.1. Finite element model description.

The annular network is established using the Hughes Liu discrete element method, and the material constitutive model is a segmented linear elastic-plastic model (MAT-PIECEWISE-LINEAR-PLASTICITY) [16]. The stress-strain data is referenced to the tensile experiment of the mesh ring steel wire [17]; The support components use BEAM units, and the support ropes use CABLE units; The energy dissipator adopts BEAM elements, and the material constitutive model uses a segmented linear elastic-plastic model (MAT-PIECEWISE-LINEAR-PLASTICITY). Its stress-strain curve refers to the restoring force model of the U-shaped rod energy dissipator [15], with a maximum elongation of 2m; The detailed parameters of the numerical model are shown in table 2.

Table 1. Component specifications of the model.

The component name	Specifications	Materials	Length
Cross beam	HW400x400x13x21	Q345	4m
Longitudinal beam	HW400x400x13x21	Q345	12m
Extended beam	HW400x400x13x21	Q345	1.5m
Column	HW400x400x13x21	Q345	8.5m
Oblique strut 1	P180x8	Q345	1.8m
Oblique strut 2	P180x8	Q345	1.4m
Oblique strut 3	P219x8	Q345	8.7m
Support column	P219x8	Q345	1.5m
Support rope	φ22	6x19M-IWRC	——
Flexible support rope	φ28	6x19M-IWRC	
Flexible net	R16/3/300	1770MPa high strength steel wire	——
Rod type energy dissipator	3φ18, starting force 150KN	Q345	——

Table 2. Material properties of numerical model.

Component	Material type	Density (kg/m^3)	Elastic modulus (GPa)	Yield stress (MPa)
Shackle	Kinematic plastic	7850	206	1200
Support rope	Cable	7850	120	——
Stone	Rigid	2500	200	——

Component	Material type	Density (kg/m^3)	Elastic modulus (GPa)	Yield stress (MPa)
Support column	Ideal elastic-plastic	7850	206	345
Diagonal brace	Ideal elastic-plastic	7850	206	345
Beam、column	Ideal elastic-plastic	7850	206	345
Energy dissipator	Piecewise linear plasticity	7850	200	——
Flexible net	Piecewise linear plasticity	7850	206	1000

3.1.2. Contact and boundary conditions.

The rockfall ring network adopts automatic beam surface contact (CONTACT _AUTOMA-TIC_BEAMS_TO_SURFACE). The network ring, network ring, and net-work ring shackle use universal contact (CONTACT_AUTOMATIC_GENERAL). The shackle support rope adopts guided sliding contact (CONTACT_ GUIDE_ CABLE_SET). Fixed connection of steel column base.

The support rope and cable support column top are set as SEATBELT units [18], and the element is used_ SEATBELT_ SLIPLING simulates the sliding of the support rope at the junction.

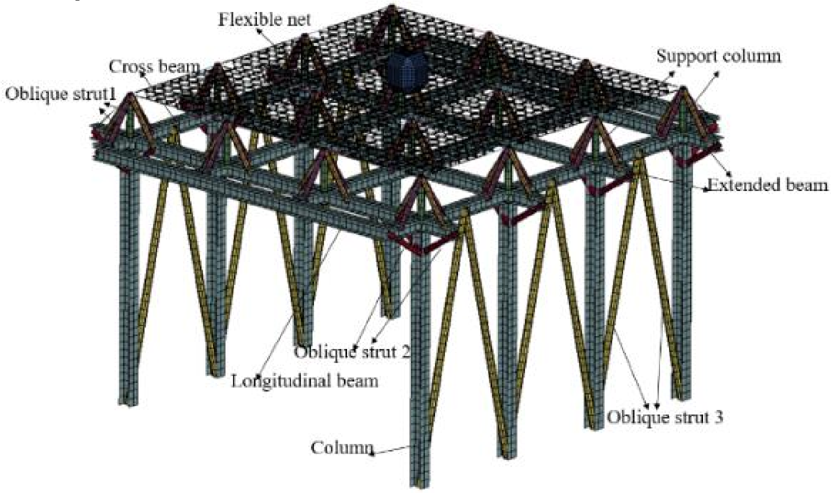


Fig. 5. Numerical model of steel structural modular energy dissipation shed.

3.2 Result analysis

Simulate a 1000KJ rockfall impact experiment based on a numerical model, with an initial velocity of 25m/s.

3.2.1. Experimental phenomena.

Extract the typical deformation of the steel structure modular energy dissipation shed system during the impact process, analyze the working behavior of the system, and show the deformation at each typical impact time in figure 6.

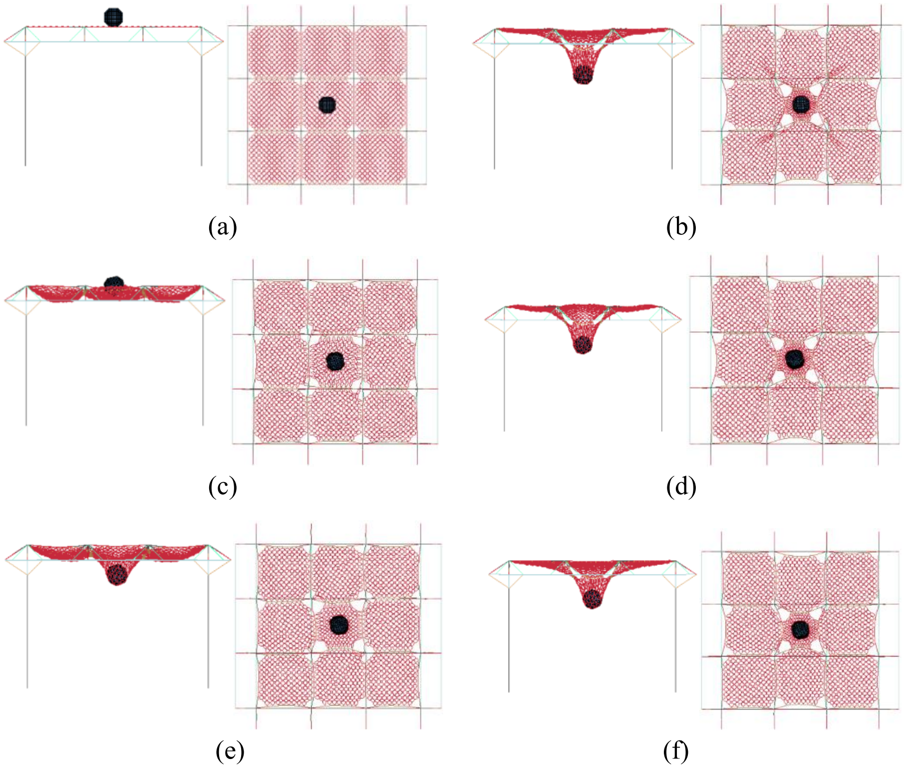


Fig. 6. Process of 1000KJ impact action: (a) t=0s falling stone touching the net (b) t=0.2s the first impact reached its lowest point (c) t=1.01s first rebound to the highest point (d) t=1.82s The second impact reached its lowest point (e) t=2.28s second rebound to the highest point (f) t=4.39s falling rocks remain still.

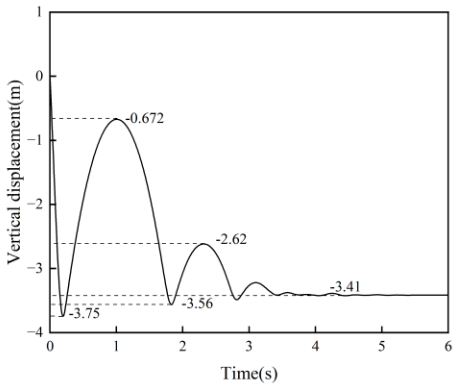


Fig. 7. Vertical displacement of rockfall.

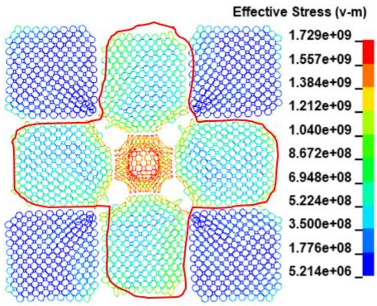
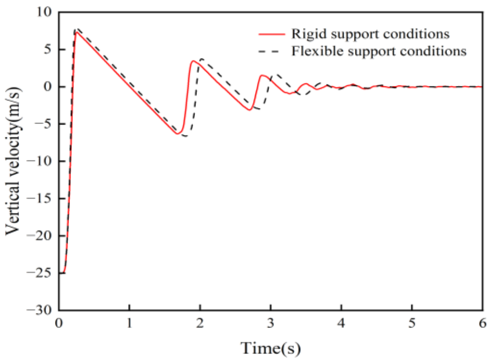


Fig. 8. "Cross shaped" tensile belt.

During the impact process, the vertical displacement of rockfall is shown in Figure 7. When t=0s, the falling rock hits the net and starts to impact downwards under the action of gravity at an initial velocity of 25m/s. T=0.2s, the first impact of the falling rock reaches its lowest point. During the 0-0.2s process, the falling rock moved downwards by 3.75m; The mesh continuously tightens, the stress increases, plastic deformation occurs, and converges towards the impact point of the falling rock into a funnel shape, forming a "cross" shaped tensile band (figure 8). T=1.01s, the falling stone rebounds to its highest point for the first time. During the process of 0.2s~1.01s, the falling stone rebounded upwards by 3.078m; The mesh releases the internal energy stored in the 0-0.2s stage, and the falling stone rebounds upwards under the action of a "cross" tensile belt. T=1.82s, the second impact of the falling rock reaches its lowest point. During the period of 1.01s to 1.82s, the falling rock moved downward by 3.188m. T=2.28s, the falling rock rebounds to its highest point for the second time. During the period of 1.82s to 2.28s, the falling rock rebounded upwards by 0.94m, which was less than the first rebound height of 3.078m. The rebound height decreased by 69.5%, indicating that the shed tunnel system consumed most of the energy at the end of the first impact process. T=4.39s, the falling stone remains stationary on the mesh. During the process of 2.28s to 4.39s, the falling stone experienced multiple small rebound, and under the damping effect, it finally remained stationary on the mesh. The final vertical displacement of the falling stone was 3.41m.

3.2.2 Characteristics of rockfall movement.



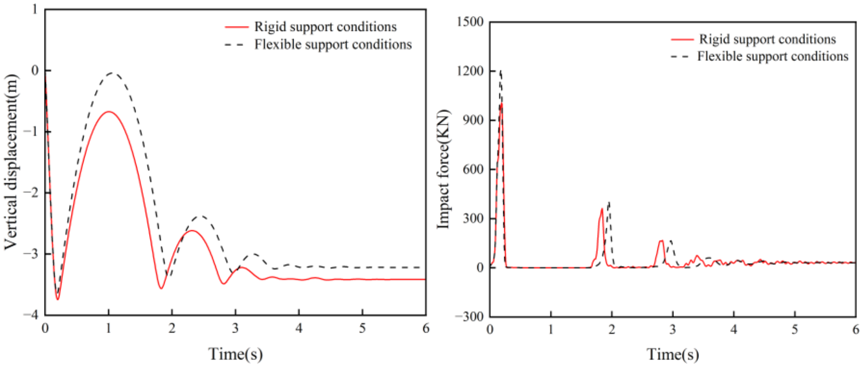


Fig. 9. Characteristics of Rockfall Movement: (a) vertical velocity (b) vertical displacement(c) impact force.

From figure 9 (a), it can be seen that when using rigid support, the peak and valley of the rockfall velocity are always faster than flexible support. This indicates that during the entire impact process, when using rigid support, the rockfall reaches various typical impact positions faster than flexible support. When supported by flexible support, when the falling rock is stationary, t=4.59s, which is slower than the rigid support by 0.2s. Rigid support is more conducive to the early end of the entire impact process.

From figure 9 (b), it can be seen that the peak and valley of Z-phase displacement are faster in the case of rigid support than in the case of flexible support. The first rebound height of the rigid support is 3.1m, and the first rebound height of the flexible support is 3.61m, an increase of 16.5%.

From figure 9 (c), it can be seen that the maximum impact forces of rigid and flexible supports are 1007KN and 1213KN, respectively, with an increase of 20%. This indicates that the circular mesh is subjected to greater force when supported by flexible support, and using rigid support is beneficial for reducing the internal force of the component. When supported rigidly, the peak impact force between the falling stone and the mesh during the second impact process was 362KN, a decrease of 64% compared to the first one. From this, it can be seen that the modular energy dissipation shed tunnel system has a significant energy dissipation ability, which can dissipate most of the energy of falling rocks during the first buffering process. Therefore, the subsequent analysis focuses on the first impact process of 0-1s.

3.2.3 Internal force of components.

During the impact process, the peak values of the axial force of the rigid support and flexible support mesh were 55KN and 80KN, respectively (figure 10), with an increase of 45%. From this, it can be seen that using rigid support is better than using flexible support.

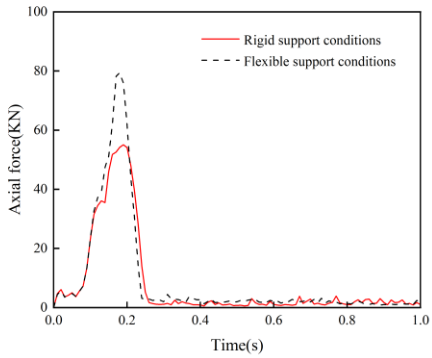


Fig. 10. Axial force of mesh ring.

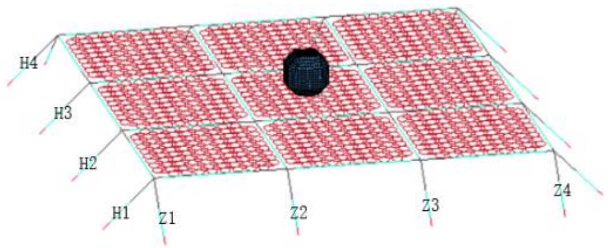


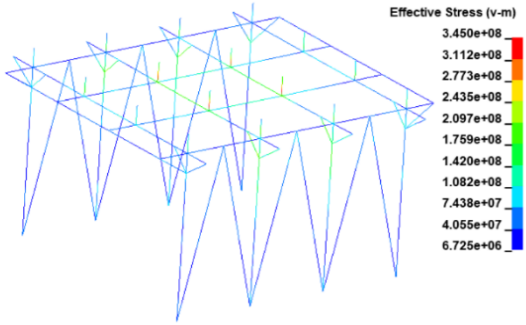
Fig. 11. Support rope and energy dissipator numbers.

Table 3. Peak internal force of support rope and elongation of energy dissipator.

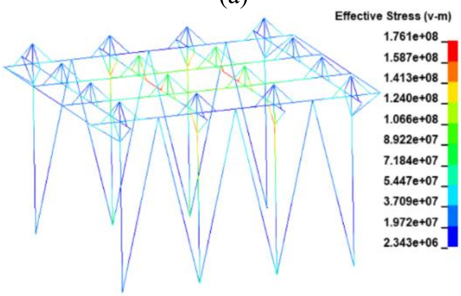
Number	Peak internal force of support rope /KN		Energy consumption elongation /cm	
	Rigid support conditions	Flexible support conditions	Rigid support conditions	Flexible support conditions
H1	89.2	74.8	5.4	4.5
H2	196.7	223.4	53.1	47.5
H3	194.4	224.7	52	43.3
H4	88.5	75.8	5.1	4.6
Z1	85.7	73.9	4.9	4.1
Z2	197.2	240.1	53.5	45.2
Z3	195.8	245.6	51.7	48.1
Z4	85.8	74.0	5.2	4.3

To describe the internal force of the support rope and the deformation of the energy dissipation device, it is numbered (figure 11). According to table 3, for the internal forces of the H2, H3, Z2, and Z3 support ropes, the flexible support is greater than the rigid support, but the elongation of each energy dissipator of the rigid support is greater than the flexible support. This indicates that using rigid support is more conducive to fully utilizing the energy dissipation effect of the energy dissipator. The internal force of the support rope adjacent to the impact position is significantly greater than that of the non adjacent support rope, and there is a consistent relationship between the elongation of the energy dissipator corresponding to the internal force of the support rope. From this, it can be seen that throughout the entire impact process, the support rope adjacent to the impact position plays a greater supporting role, while the energy dissipator adjacent to the impact position plays a major energy dissipation role, which corresponds to the "cross shaped" tensile belt.

The stress cloud diagram supported by the steel structure (figure 12) shows that when flexible support is used, the stress of the middle cable support column reaches 345MPa (figure 12 (a)), and all the middle cable support columns yield; When using rigid support, the maximum stress of the component is 176MPa (figure 12 (b)), which is much smaller than the material yield strength of 345MPa. The reason for this is that flexible supports can only withstand tension, while rigid supports can withstand both tension and pressure. When the structure is impacted by falling rocks, all rigid supports play a supporting role, with the outer support providing tension and the inner support providing pressure, which is conducive to the stability of the cable support column; Adopting flexible support method, the outer flexible support provides tension, while the inner flexible support cannot provide pressure and function, resulting in the buckling of the support column. From this, it can be seen that using rigid support is superior to flexible support, avoiding buckling failure of the support structure during the impact process.



(a)

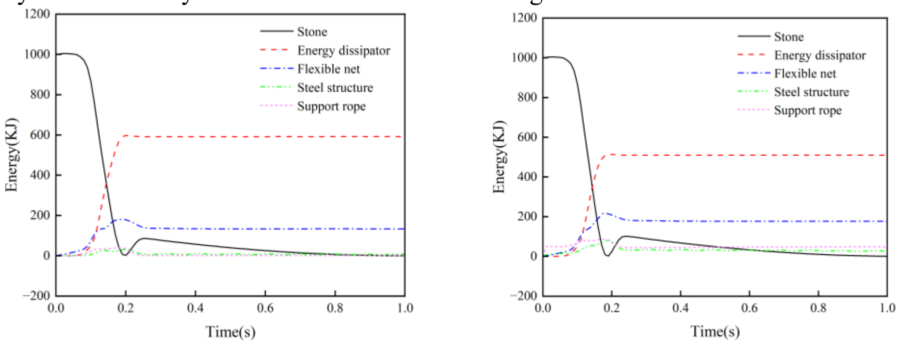


(b)

Fig. 12. Cloud chart of steel structure support stress: (a) flexible support conditions(b) rigid support conditions.

3.2.4 Energy consumption distribution.

To analyze the energy consumption distribution of the system, the energy time history curve of the system is extracted as shown in figure 13.



(a) (b)

Fig. 13. Energy time history: (a) rigid support conditions (b) flexible support conditions.

Table 4. Energy consumption distribution of the system.

		Energy dissipator	Flexible net	Steel structure	Support rope
Rigid support conditions	Energy /KJ	592	133	3.5	1
	Proportion	59.2%	13.3%	0.35%	0.1%
Flexible support conditions	Energy /KJ	510	177	22	47.4
	Proportion	51%	17.7%	2.2%	4.74%

From table 4, it can be seen that under rigid support conditions, the energy consumption of the energy dissipator is significantly higher than that under flexible support conditions, which corresponds to the elongation of the energy dissipator in table 3. Under flexible support conditions, the energy consumption of steel structures and support ropes is significantly higher than that of rigid support conditions. The reason for this is that under flexible support conditions, the buckling of the cable support column dissipates more energy, which is unfavorable for the system. Therefore, replacing flexible support with rigid support is more reasonable.

Under the condition of rigid support, the energy consumption of energy dissipators, annular nets, and support ropes in the buffer layer accounts for 59.2%, 13.3%, and 0.1%, respectively, while the energy consumption of steel structure supports accounts for 0.35%. The energy consumption of energy dissipators accounts for the largest proportion, with a buffer layer energy consumption of up to 72.6%. The steel structure support mainly plays a supporting role and hardly consumes energy. The energy consumption distribution of the system is more reasonable.

4 Parametric analysis

Based on the numerical model in Section 2, conduct parametric analysis to study the impact resistance performance of modular energy dissipation sheds in steel structures. The component parameter settings of the model are the same as in Section 2.

4.1 The impact of energy

In order to discuss the impact of impact energy on the modular energy dissipation shed of steel structures, using Condition 1 as the reference working condition, changing the initial speed to provide different initial impact energy for rockfall, five working conditions were set, as shown in table 5.

Table 5. Impact energy

Working condition	Impact energy /KJ	Impact velocity /(m/s)
1	1000	25
2	1250	27.951
3	1500	30.619
4	1750	33.072
5	2000	35.355

4.1.1 Comparison of buffer distance and impact force.

From figure 14, it can be seen that as the impact energy increases, the energy dissipation buffer distance of falling rocks and the impact force on the circular network significantly increase. The reason is that the modular energy dissipation shed of the steel structure mainly achieves energy dissipation through the friction damping and deformation of the energy dissipator, as well as the deformation of the flexible mesh. The increase in impact energy will inevitably lead to an increase in buffering distance and impact force, resulting in an increase in the deformation of the circular mesh and energy dissipator, thereby increasing the total energy consumption of the system.

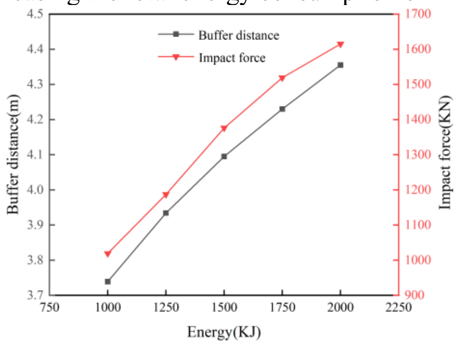


Fig. 14. Comparison of buffering distance and impact force.

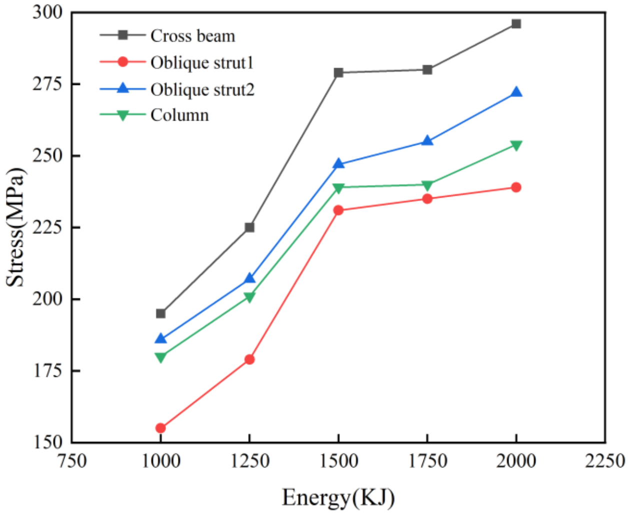


Fig. 15. Comparison of internal forces of supporting components.

4.1.2 Comparison of structural forces.

It can be seen from figure 15 that as the impact energy increases from 1000KJ to 2000KJ, the internal forces of longitudinal beam, diagonal brace 1, diagonal brace 2 and column increase by 51.8%, 54.2%, 46.2% and 41% respectively. The reason for this is that the supporting structure of the system will transmit external forces to the foundation. As the impact energy increases, the impact force on the flexible net significantly increases (figure 14), leading to an increase in the force transmitted by the flexible net to the supporting structure and an inevitable increase in the internal force of the supporting components. It can be seen from this that the impact energy has a greater impact on the force of the system's supporting components. The core supporting force components of the system are the longitudinal beam, diagonal brace 1, diagonal brace 2, and column, which should be emphatically considered in the actual design.

4.1.3 Energy consumption comparison.

From table 6, it can be seen that as the non main energy consuming components of the system, the energy consumption proportions of the support rope and support steel structure increase from 0.1% and 0.6% to 0.13% and 0.8% respectively with the increase of impact energy, and the impact is relatively small; As the main energy consuming components of the system, the energy consumption of the energy dissipator and the ring network decreased from 56.8% to 50.2%, and the energy consumption of the ring network increased from 13.2% to 15.8%. This indicates that the energy consumption effect of the energy dissipator has been fully utilized, and the proportion of energy consumption in the ring network has increased.

Table 6. Energy consumption comparison.

Working condition	Energy dissipator energy/KJ	Flexible net energy/KJ	Support rope energy/KJ	Steel structure energy/KJ
1	592	133	1	3.5
2	700	165	1.54	7.7
3	803	209	1.9	11
4	903	260	2.3	12
5	1004	315	2.6	16.5

5 Conclusion

(1) Using rigid support to support the cable support column is superior to flexible support, avoiding the buckling of the cable support column.

(2) The modular energy dissipation shed system of this steel structure can achieve protection of 2000KJ energy level, which is 700% higher than the existing flexible shed system.

(3) The impact speed has a small impact on the buffering distance, but a significant impact on the impact force and internal force of the system support components; The core load-bearing components of the system support components are longitudinal beam, column, diagonal brace 1 and diagonal brace 2, which should be considered in the actual design.

Acknowledgments

The authors are grateful for the support provided by the Key Research and Development Program of Sichuan Province (Grant No. 2022YFG0414), the National Key R&D Program of China (Grant No.2018YFC1505405), the Natural Science Foundation of China (Grant No. 51678504).

References

1. Huang, Y., Sun, Q.D., Xu Q., (2010) New progress in research on the motion characteristics of rolling stones. J. Vibration and Impact, 29 (10): 31-35(in Chinese).
2. Luo, Z., Wang, Y.H., (2017) Experiment on dynamic response of piers subjected to rolling stone impacting. J. China Journal of Highway and Transport,30(9):78-85(in Chinese).
3. Wang, M., Shi, S.Q., YANG, Y.K., (2013) Experimental study on a new type flexible rock-shed under impact of rockfall. J. China Civil Engineering Journal, 46(9):131-138(in Chinese).
4. Yu, Z.X., Qiao, Y.K., Zhao, L., et al. (2018) A simple analytical method for evaluation of flexible rockfall barrier part 1: working mechanism and analytical solution. J. Advanced Steel Construction, 14(2):115-141.

5. Wang, M., Shi, S.Q., YANG, Y.K., (2012) Comparative analysis for capacity of energy dissipation of a ring net with two different connection forms. J. Journal of Vibration and Shock, 31(02):55-61(in Chinese).
6. Delhomme, F., Mommessin, M., Mouugin, J.P., et al. (2004) Behavior of a structurally dissipating rock-shed: experimental analysis and study of punching effects. J. International Journal of Solids and Structures, 42(14):4204-4219.
7. Delhomme, F., Mommessin, M., Mouugin, J.P., et al. (2007) Damage Mechanisms of a Reinforced Concrete Rock-Shed Slab Impacted by Blocks. J. Journal of Structural Engineering, 133(10):1426-1433.
8. Wang, Z., Zang, Q.Z., Pan, Q., et al. (2020) Research on the Construction Method and Stress Characteristics of Prefabricated Corrugated Steel Shed Tunnel. J. Journal of underground space and Engineering, 16(S1):185-193+207(in Chinese).
9. Wang, M., Shi, S.Q., Cui, L.M., et al. (2018) Experimental Study on Three Bay Single Span Flexible Shed Tunnel under Rockfall Impact [J]. Civil Engineering Journal, 51(05):37-47(in Chinese).
10. Kawahara, S., Muro, T., (2005) Effects of dry density and thickness of sandy soil on impact response due to rockfall. 43(3):329-340.
11. Sun, J.H., et al. (2016) Performance of Used Tire Cushion Layer under Rockfall Impact[J]. Shock and Vibration.
12. Tan, K., (2018) Multi flexible body dynamics simulation of cable supported flexible anti rockfall buffer structure. D. Southwest Jiaotong University (in Chinese).
13. Liu, C.Q., Chen, L.Y., Chen, C., et al. (2015) Research on the application of flexible steel shed tunnel structure in the prevention and control of rockfall disasters. J. Journal of Southwest Jiaotong University, 50 (1): 110-117(in Chinese).
14. Wang, M., Shi, S.Q., Liu, Y.F., et al. (2018) Energy consumption performance analysis and optimization design of rockfall flexible shed tunnels. J. Vibration and Shock, 37 (1): 216-222(in Chinese).
15. Qi, X., Xu, H., Yu, Z.X., et al. (2018) Experimental Study on Dynamic Mechanical Performance of Pressure Reducing Ring in Flexible Interceptor Net Structure. J. Engineering mechanics, 35(9):188-196(in Chinese).
16. Du, N.N., (2019) Research on Mechanical Properties of Rod Energy Dissipators in Flexible Protective Structures D. Southwest Jiaotong University (in Chinese).
17. Hallguist, J.O., USA. (1991) LS-DYNA-3D theoretical manual. https://lsdyna.ansys.com.
18. YU, Z.X., QIAO, Y.K., ZHAO, L., et al. (2018) A simple analytical method for evaluation of flexible rockfall barrier part 1: working mechanism and analytical solution J. Advanced Steel Construction, 14(2):115-141.