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Seismic performance and most unfavorable and favorable Load distributions of steel storage rack: an optimization approach

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Abstract

In the current rack seismic design, the load distribution is generally considered to be placed uniformly on the rack, but the reality usually differ. In this paper, the objective is to identify the most unfavorable and favorable load distribution of the braced and unbraced racks under seismic loading through a stochastic optimization - Genetic Algorithm (GA). The GA optimization is performed with an established computational models of racks and the pushover analysis is integrated to evaluate seismic performance of the racks. It is analyzed that the distribution of load has a great influence on the seismic performance of steel racks. During the optimization, including the optimized solutions, there are other loading distributions that will make the racks fail with the seismic requirements. Statistical summary of these load pattern results create a cloud map. The cloud map from the optimization results show that the most unfavorable load distribution is in a '凸' shape of the 3D space of the racks and the safe load distribution holds a '凹' shape for braced racks. Meanwhile, unbracing racks have the characteristics of an unfavorable load distribution of a ' 卩' shape. The gravity center of the loading has an apparent impact on the braced rack's seismic performance such as the number of load carried by the columns in the back pulling zone, the total horizontal seismic force, and the distribution of local at the dangerous position. On the other hand, no obvious impact of the gravity.

1. Introduction

In recent years, the development of e-commerce has put forward higher requirements on the safety performance, work efficiency and economic benefits of logistics and warehousing. However, the current research on racks focuses on the structural performance while the research on the optimization of load space is insufficient. These studies simply assumed that structural stability was under an assumption of the center of the rack and the eccentricity of the load: the lower the center of gravity and the smaller the eccentricity, the higher the racking stability [1,2]. These conclusions are not rigorous. Moreover, in the current racking seismic design, load are generally considered to be uniformly arranged in the rack, but this is not the case in the actual storage process of load. The effect of center of gravity and eccentricity of load on the seismic performance of rack structure should be studied systematically.
Yin et al. [3,4] found that the center of gravity and eccentricity of load had no direct relationship with the seismic performance of racking structure. Yin's team conducted a partial study on the selection of structures and the determination of seismic analysis methods, as well as the effect of the center of gravity and eccentricity of load on the seismic performance of racking structures. Hence, the optimal method based on seismic design will be adopted to explore the distribution mode of the most unfavorable load and the most favorable load in this paper.

Firstly, based on seismic design, genetic algorithm is used to optimize the distribution modes of goods with 60%, 70% and 80% load on racks respectively. The common distribution modes of the most unfavorable load and the most favorable load are summarized respectively. According to the results, the influence of the distribution mode of the load on the seismic performance of the racking structure is studied. Finally, the probability statistics of a large number of load distribution patterns generated and calculated during the optimization process of genetic algorithm are carried out to generate the probability distribution cloud map. According to the probability distribution cloud graph and genetic algorithm optimization results, the load distribution risk model and the load

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distribution safety model with and without steel racks were obtained respectively.

2. Model Description

Yin et al. [3] studied the impact of load distribution on racking seismic performance. Based on this research, two types of steel rack models with and without bracings were established. In the actual warehousing process, a complete rack has a large storing capacity. A typical braced steel rack studied in this paper has 20,400 members and 3,600 load spaces. It is difficult to calculate all the Numbers, and there are a lot of similar force units, which will lead to low computational efficiency. Therefore, the overall model is simplified into a unit model in this paper. The braced rack unit is 12 floors and 5 rows, with a total of 60 load positions. The unbraced rack unit is 5 floors and 8 rows, with a total of 40 load positions. The front elevation, side elevation, column section and corresponding geometric parameters of the model are shown in FIG. 2.1 and 2.2. The specifications of other components are shown in Table 2.1.

Table 2.1 Model component specifications

Component	Upright frames	Beams	Spine bracing	Beams with Spine bracing
Component specifications	NH100×70×3	K100×50×1.5	C70×25×12×2	C70×25×12×2
Component	Webs of upright frames	Longitude horizontal bracing	Bracing brackets	Plan bracing
Component specifications	C40×29×6.5×1.3	C80×50×20×2.5	Rectangular steel tube 60×50×2×2	Rectangular steel tube 100×50×2.5×2.5

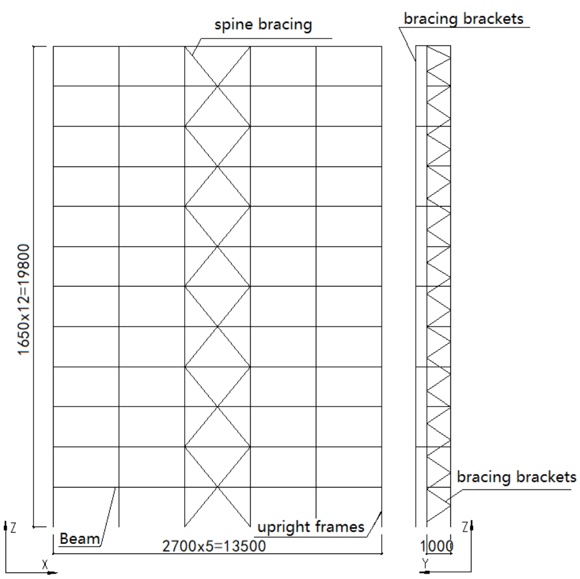


Figure 2.1 Elevation of braced racks

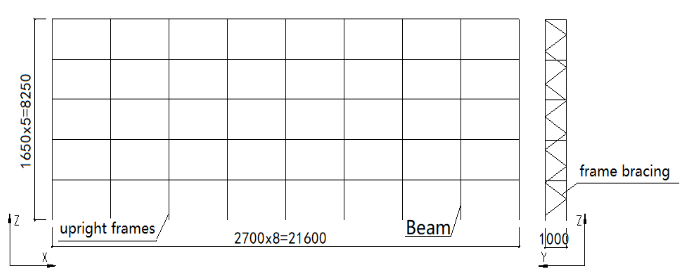


Figure 2.2 Elevation of unbraced racks

Seismic fortification intensity of 8 degrees, site soil category for Ⅱ classes, design earthquake are grouped into the first group. The characteristic period of the site is 0.40s, the designed basic seismic acceleration is 0.2g, and the damping ratio is 0.05. The weight of each pallet is 10.8kN, the live load is equivalent to 2.0kN/m for the wiring load of the beam, and the node stiffness is 116.3kN•m/rad according to literature [5]. The steel used here is Q235 steel, and the load combination taken into account in the strength checking calculation is the same as the braced steel rack.

The maximum stress ratio of the column is 0.941 when the rack is fully loaded, which meets the design requirements.

3. Genetic Algorithm

The essence of load position optimization [6] is to seek the mapping relationship between load and load position. There is a one-to-many mapping relationship between load and load space, that is, a maximum of one load is placed on the load space. There are only two cases of vacancy and full occupancy in each space. According to the above situation, the binary code is adopted, 1 represents the load in the load position, 0 represents the load in the load position. A chromosome represents an individual and represents a pattern of distribution of load. The unit model established in this paper has 60 load Spaces, so the algorithm encoding is represented by binary coding string of 60 bits. According to the selected load of 60%, 70% and 80%, 36, 42 and 48 codes 1 are arranged respectively, and the rest codes are returned to 0.

The genetic method implemented in this paper is to swap chromosomes of a random set of 60% load sequences according to the defined crossover strategy and mutation strategy. By interchanging zeros and ones, a new set of codes can be created. In the new code, eliminate the inferior sequences. After repeated several times, the optimized "survivable" code is obtained. Initialization population, selection, crossover and mutation in optimization process are realized by matrix operation in Matlab. SAP2000 was first used to calculate and analyze all individuals in the population, and the maximum stress ratio of each individual column was extracted. Then, the maximum stress ratio of each individual column extracted is returned to Matlab, and the adaptive value of each individual is obtained after conversion.

4. Result and Analysis

4.1 Detailed process

Two curves are shown in the genetic algorithm performance tracking graph. "Optimal individual column maximum stress ratio" refers to the curve formed by the maximum stress ratio of the optimal individual column (the most unfavorable distribution mode) among 150 individuals (the distribution mode) in each generation. "Population column maximum stress ratio mean" refers to the curve formed by calculating and extracting the maximum stress ratio of each individual column in 150 distribution modes represented by 150 individuals in each generation, and then calculating the average value of the maximum stress ratio of the obtained 150 columns. "Optimized distribution mode" is the most unfavorable distribution mode obtained through optimization, in which the maximum stress ratio position refers to the most dangerous position, namely the control position of structural safety. The process and result of optimizing the distribution of 80% most unfavorable load are shown in Figure 4.1 and 4.2. The relevant parameters such as the maximum stress ratio, the position of the maximum stress ratio and the load combination with the maximum stress ratio in the optimization results of load are listed in Table 4.1. This section introduces the detailed process of analysis by taking the optimization of the distribution of 80% most unfavorable load as an example.

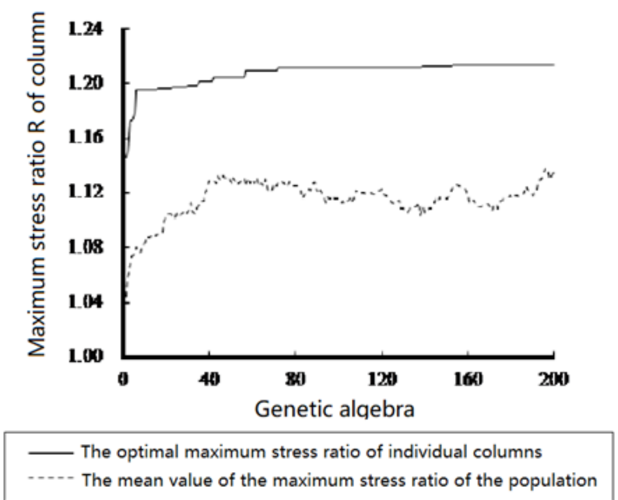


Figure 4.1 Optimal performance tracking graph obtained by genetic algorithm

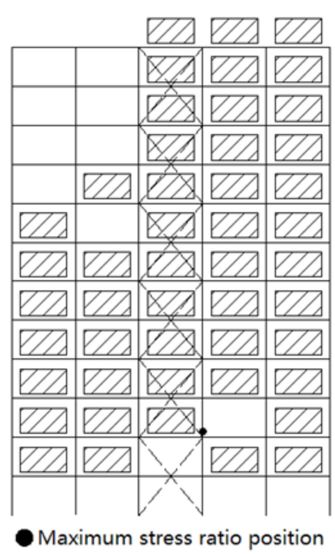


Figure 4.2 Distribution mode obtained by optimization(H=6.00，P=0.29)

Table 4.1 Parameters related to the adverse distribution pattern of the optimized load

Quantity of load	The center of gravity-*H*	Deviation from the center of gravity-*P*	Maximum stress ratio of column	Percentage increase in stress ratio	Member number	Maximum stress ratio position	Load combination
80%	6.00	0.29	1.214	18.4%	33	JD16	1.2G+1.3Ex
70%	5.90	0.36	1.153	12.5%	33	JD16	1.2G+1.3Ex
60%	5.67	0.08	1.085	5.9%	21	JD15	1.2G-1.3Ex

Note: G in the load combination represents the representative value of gravity load; Ex stands for X direction earthquake; The position of the maximum stress ratio, the position of the 33 bar is indicated in FIG. 4.2.

Probability statistical processing was conducted on the distribution mode of over-limit load generated in the optimization process of the above braced steel rack with 80% load to form the probability distribution cloud map, as shown in FIG. 4.3

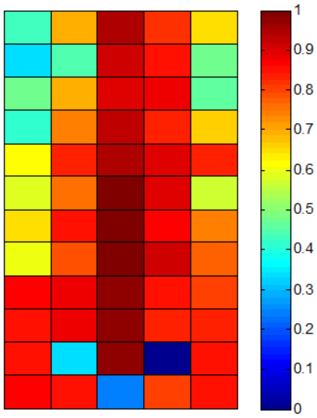
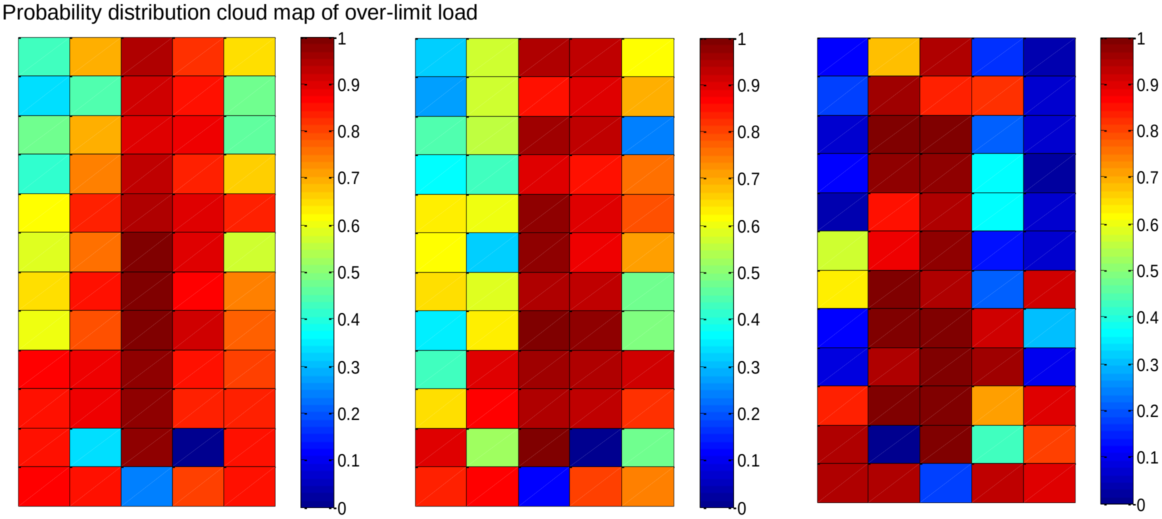


Figure 4.3 Probability distribution cloud map of over-limit load

4.2 Distribution cloud map

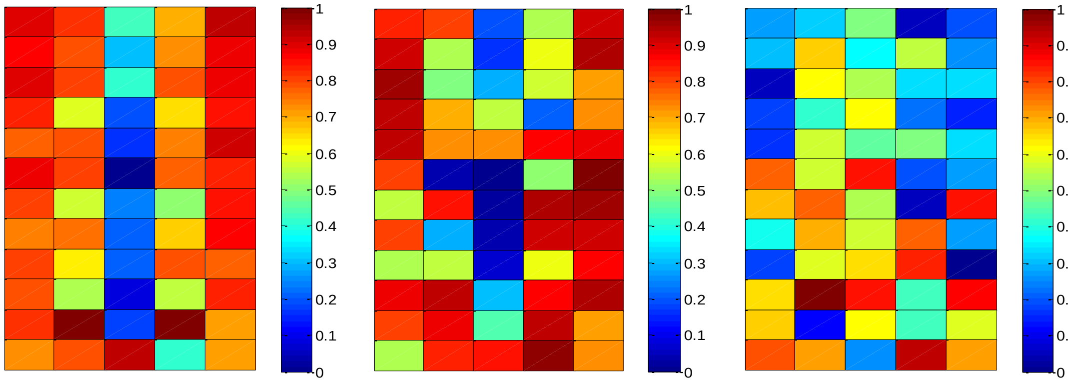
4.2.1 Braced racking systems

Probability statistical processing is carried out for the distribution mode of over-limit load generated in the optimization process of braced steel racks introduced in Section 4.1, and a probability distribution cloud map is formed, as shown in Figure 4.4.



(a) 80% load (b) 70% load (c) 60% load

FIG. 4.4 Probability distribution cloud map of over-limit load



(a) 80% load (b) 70% load (c) 60% load

FIG. 4.5 Probability distribution cloud map of unexpired load

According to FIG. 4.4 and the commonness of adverse distribution mode of load on braced racking systems, the distribution risk model of load on braced racking systems is concluded. As shown in Figure 4.6, it is defined as a "凸" distributed hazard model.

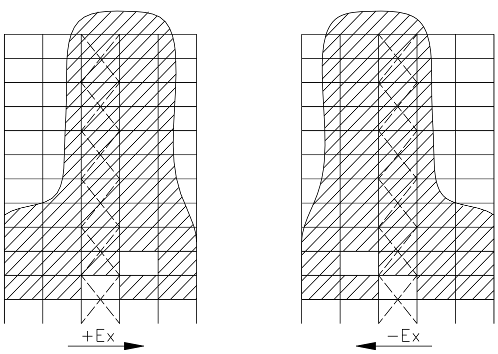


Figure 4.6 Load distribution hazard model for braced steel racks

According to the comparison between A, B and C in FIG. 4.5 and the optimized distribution modes of load, it is believed that the probability cloud plots under 80% and 70% load are very close to the most favorable distribution modes finally obtained by optimization. However, the probability cloud chart with 60% load is not very regular. The reason is that there are too many distribution modes that do not exceed the limit when 60% of the load are loaded, and many distribution modes that do not exceed the limit do not conform to the distribution commonness due to the small number of load value. The distribution safety model of load on steel racks with bracing is summarized as shown in Figure 4.7. It is defined as a concave distributed security model.

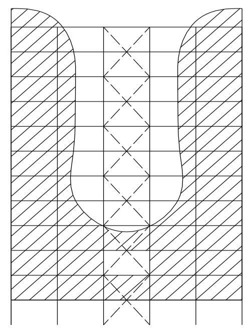
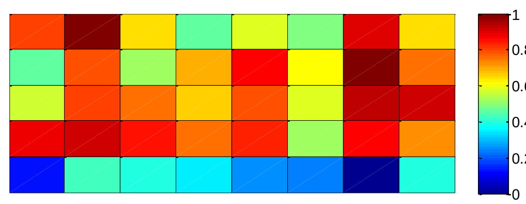


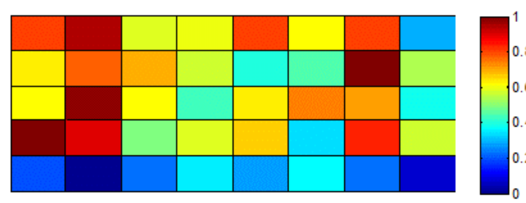
Figure 4.7 Danger model of load distribution on braced steel racks

4.2.1 Un-braced racking systems

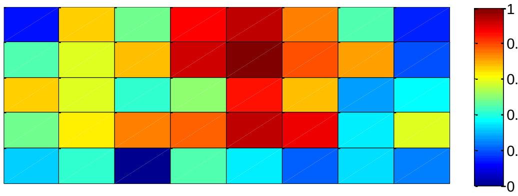
Probability statistical processing was carried out on the over-limit load distribution mode generated in the optimization process of steel rack without lateral bracing to form the probability distribution cloud map, as shown in FIG. 4.8.



(a) 80% load



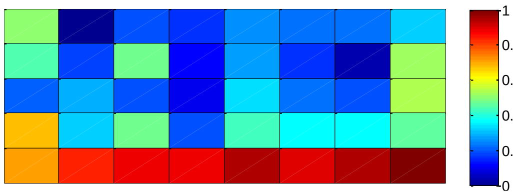
(b) 70% load



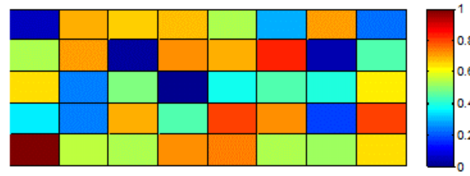
(c) 60% load

FIG. 4.8 Probability distribution cloud map of over-limit load

The probability distribution pattern of valid load generated during the optimization of unbraced steel racks was statistically processed to form a probability distribution cloud map. However, the maximum stress ratio of the column under 80% load of unbraced steel rack is bigger than that under full load (0.941). Therefore, only 70% and 60% of the probability distribution cloud maps of loads are listed, as shown in FIG. 4.9



(a) 70% load



(b) 60% load

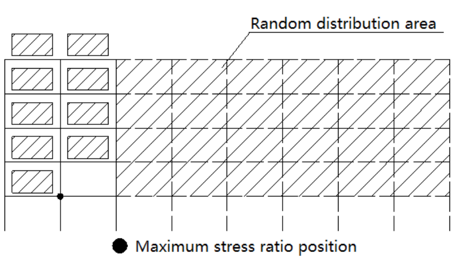
FIG. 4.9 Cloud map of probability distribution of unexpired load.

It can be seen from FIG. 4.8 that there is no strong regularity in the probability distribution of unbraced steel racks exceeding limits. The reason is that unbraced steel racks are different from braced steel racks. There is no bracing system and the horizontal seismic force is evenly distributed to each column. And according to the analysis of the results, it can be concluded that: If there are two columns carrying the same load in the 10 positions, the stress ratios of the two columns are similar to each other. Therefore, the maximum stress ratio may occur at each of the columns.

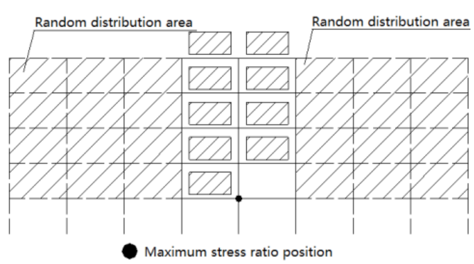
Table 4.2 Relation between the distribution mode of load and the stress of the column

The manner in which load are distributed	a	b	c
Position of maximum stress ratio	At the beam-column node of the first floor		
Maximum stress ratio	1.116	1.111	1.130
Total horizontal seismic force (kN)	11.3	11.3	25.3
The stress ratio due to axial force N	0.332	0.332	0.332
Stress ratio due to Mx (Not the axis of symmetry)	0.005	0.001	0.001
Stress ratio due to My (Axis of symmetry)	0.779	0.778	0.796
Load combination	1.2G+1.3Ex		

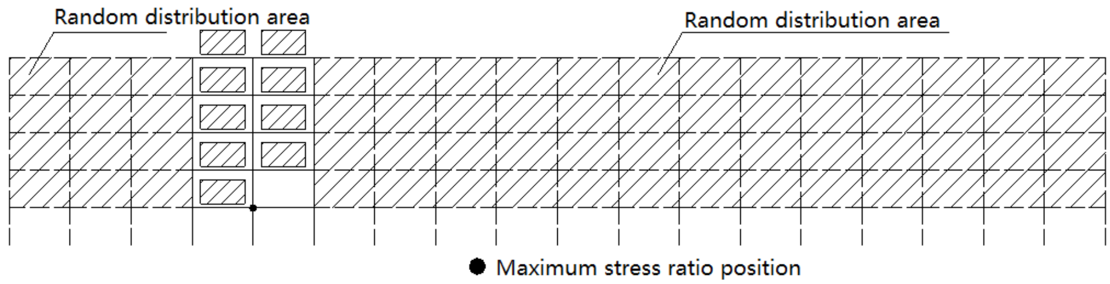
Note: The load combinations listed are those that guide the occurrence of maximum stress ratios, G is the representative value of gravity load, Ex is the x-direction earthquake; The locations of related components are shown in FIG. 4.10.



(a)



(b)



(c)

Figure 4.10 Comparison of two distribution modes of load

As can be seen from the results in Table 4.2, the results of the three distribution modes are very similar, so it can be considered that the distribution risk model of load with unbraced steel racks shown in Figure 4.11 should be avoided. The pattern of load distribution shown in Figure 4.11 is defined as a ‘ 卩 ’ model of load distribution. In the normal use of unbraced steel racks, a warning should be issued if a column has a " 卩 " distribution of load.

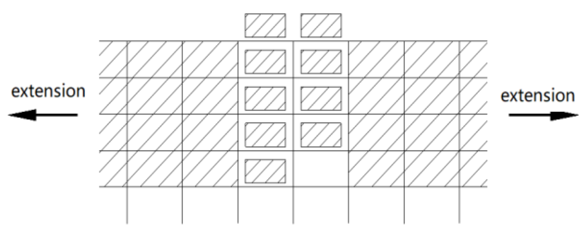


Figure 4.11 Hazard model of load distribution on unbraced steel racks

For unbraced steel racks, it can be seen from Figure 4.9 that the regularity of probability distribution of unexceed load is also weak. The reason is the same as the probability distribution of the over-limit load. However, it can still be seen from the figure that the probability of occurrence of load on the first floor is relatively high, especially when the load is relatively large (70%). This is the reason to avoid uneven distribution of load in the first tier when optimizing for the most favorable distribution pattern of load.

There is no specific load distribution safety model for unbraced steel racks. The characteristics of the load distribution safety model are as follows: the load are evenly distributed in each row, and there is no uneven distribution in the first layer.

6. Conclusion

Through the analysis of the optimal distribution of two types of steel racks, the main conclusions are as follows:

(1) The columns in the back pulling zone that brace the rack are dangerous columns, and the maximum stress ratio occurs at the junction of the column and the first layer of separated beam. The position of maximum stress ratio of un-braced racking systems appears at the joint position of a column and the first floor beam.

(2) Eccentricity of load has an effect on the seismic performance of braced steel rack structure, but it does not play a decisive role.

(3) Four factors of the most unfavorable distribution pattern of load on steel rack with bracing are summarized as follows: The position state of the column in the back pulling zone is close to full load; The two load positions near the maximum stress ratio position are unevenly distributed; The load space on the first floor of the pilar zone is empty; Ensure that the first three based on the distribution of load at the bottom of the load space and side columns.

(4) Four factors of the most favorable distribution pattern of load on steel rack with bracing are summarized as follows: The load in the back pulling zone is little; There is no load in the second deck of the back yard; There are more load in the two sides; The distribution of load is basically symmetrical.

(5) Two factors of the most unfavorable distribution pattern of load on unbraced steel racks are summarized as follows: The columns carry more load; The load distribution at the first beam-column node is unbalanced. Two factors of the most favorable distribution pattern of load on unbraced steel racks were obtained: Load are evenly distributed in each column; There is no uneven distribution of the first-
floor load space.

(6) According to the probability distribution cloud map and the factors summarized above, the characteristics of "凸" distribution hazard model and "凹" distribution hazard model with bracing steel rack, " 卩" distribution hazard model with no bracing steel rack and "load distribution safety model are obtained.

7. Acknowledgments

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