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Early Warning System for Load Distribution in Automated Warehouse Based on Seismic Safety

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Abstract

As an integral part of the storage system in automated warehouse, the structural behaviors of steel rack structures have been extensively studied. However, little research has been conducted on the seismic performance evaluation of racks under different load distributions and also a warning system for safety evaluation of the load distribution that might cause unfavorable seismic performance. The objective of this study is to develop a method of evaluating seismic safety and an early warning system of over-limit load distribution for racks with spine bracings. The genetic algorithm was employed to seek and identify the influence of load distribution on the seismic performance of racks with spine bracing. Then, a formula for safety evaluation for racks with spine bracing was derived and its reliability was validated. An early warning system for over-limit load distribution was established and codified in a software package. Different safety statuses using a color system like Green, Red, and Yellow were employed in the software package as an indicator of the load distribution level of racks. Finally, the system developed was applied to the actual racks in an automated warehouse in Nanjing to demonstrate its applicability and reliability.

1. Introduction

With the development of the logistics industry and the massive increase of goods in warehouses, steel rack structures have been widely studied as an important part of the storage system. However, the current research on the optimization of load space mainly focuses on improving the efficiency of warehouse [1][2], while few studies focuses on the seismic safety of the structure. Existing studies generally consider that the stability of a structure is related to its gravity center and eccentricity: the lower the center of gravity of the rack [3] and the smaller the eccentricity [4], the higher the stability of the structure. Yin et al. [5] found that for steel racks with spine bracings, the gravity center of the goods has a significant effect, but the seismic performance of the structure does not decrease monotonically with the increase of the height of gravity center of the goods. EURICO et al. [6] pointed out that the movement of goods has an important effect on the racking system, especially under the effect of earthquakes. QARUD et al. [7] studied the effects of partial loading on the behavior of steel pallet racks with a six level, six bay model and found that most combinations failed by sway buckling. However, the seismic safety evaluation of racks mainly focuses on predicting the collapse mode of the racks [8]. The research on seismic performance evaluation of racks and safety warning for different load distribution is insufficient.

Yin et al. [9] used genetic algorithm to summarize the most unfavorable and most favorable load distribution based on seismic design. Probability statistics were performed on a large number of load distribution patterns generated and calculated in the process of genetic algorithm optimization to generate a probability distribution contour. According to the probability distribution contour and the optimization results of genetic algorithm, the load distribution risk model and load distribution safety model of racks with spine bracings and without spine bracings are obtained respectively. Based on these results, this paper explores the method of seismic safety evaluation and early warning of over-limit load distribution for racks with spine bracing.

Firstly, based on the influence of load distribution on the seismic performance of racks with spine bracings obtained by genetic algorithm, the safety evaluation formula for racks with spine bracing is derived and the reliability of the formula is verified. The program implementation process of the early warning system for over-limit load distribution is established. Finally, the above analysis steps are used to study the actual racks in an automated warehouse in Nanjing. The applicability and reliability of the safety evaluation of racks

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with spine bracings and the early warning system of over-limit load distribution are verified.

2. Model Description

According to the results of the optimal load distribution study by Yin's team [9], the seismic performance of the racking structure is mainly affected by the load distribution of column with spine bracing and its two adjacent columns. In this paper, based on this study, a calculation unit model of braced steel rack with 12 floors and 5 columns were established, as shown in Figure 1(a). Due to the symmetry of the structure, only the braced column and the column to its right or left are considered as the bracing unit for analysis in this paper. The non-bracing area of the calculation unit is assumed to be filled with goods. The influence of the load distribution of bracing unit on the left and right uprights of the braced column is analyzed. The number of load positions in right non-bracing area is shown in Figure 1(b).

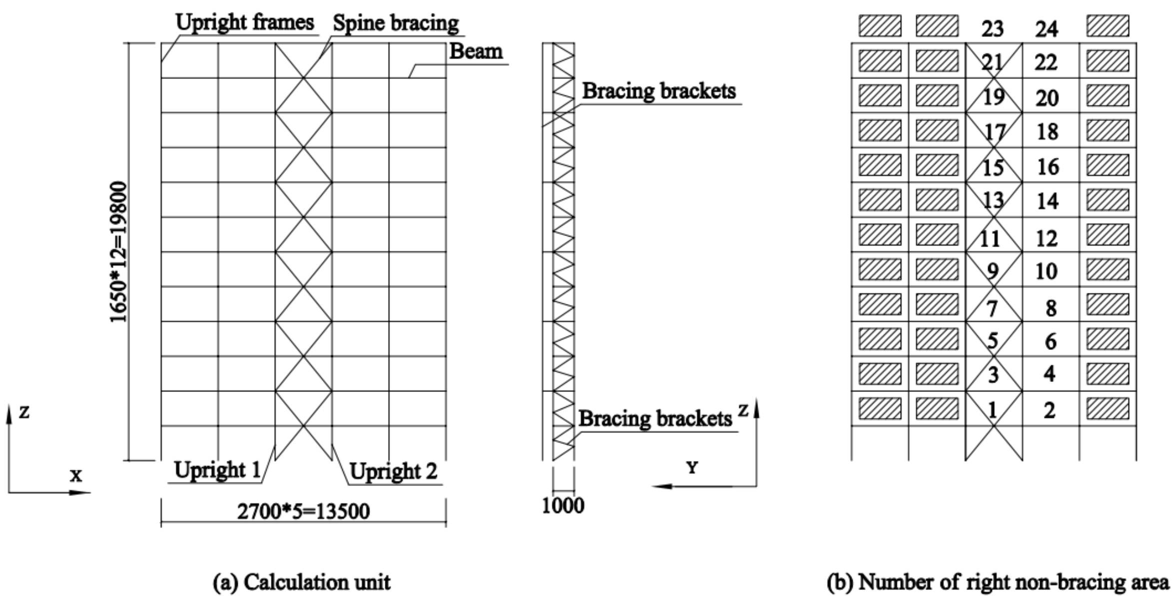

Figure 1: Calculation unit and bracing unit

3. Method

3.1 Safety evaluation

It is appropriate to set different maximum stress ratio limits for the uprights due to different importance of the racks. In this paper, two maximum stress ratios are set as 0.95 and 1.0. In the software, if the maximum stress ratio of the upright is less than 0.95, a green light will be shown. If the maximum stress ratio of the upright is more than 1.0, a red light will be shown. And if between 0.95 and 1.0, a yellow light will be shown.

3.1.1 Judgment process of red light

The judgment procedures of red light are shown in Figure 2.

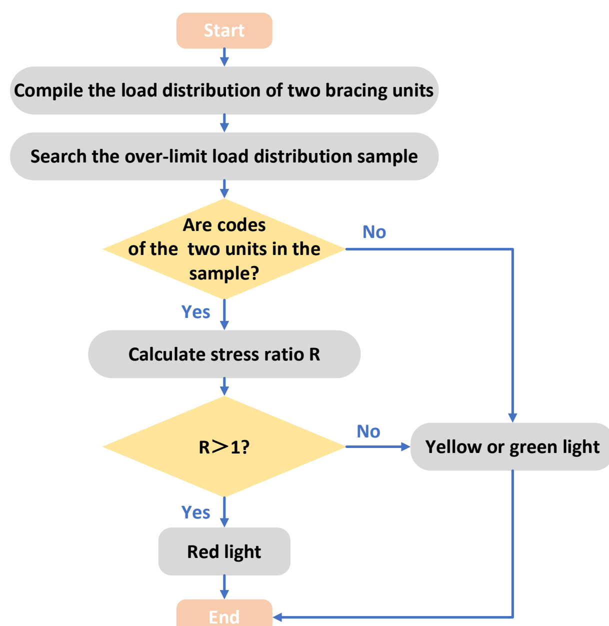

Figure 2: Red light judgment procedures

1) Compile the load distribution of two bracing units into a load position code.

2) Retrieve the over-limit load distribution samples and determine whether there are load position codes of the above two units. Compare the load position codes of the two bracing units compiled in process 1) with the over-limit load distribution samples of the bracing units obtained by the genetic algorithm. Determine whether there is the same code in the over-limit samples. If there is the same code, the maximum stress ratio of the upright may be greater than 1.0. Then the corresponding stress ratio is extracted and recorded as R_l' in the left bracing unit and R_r' in the right bracing unit. If there is no identical load position code, it is impossible to be a red light.

3) Calculate stress ratio R. The over-limit sample obtained from the bracing unit analysis is only for the case where all the other positions in the non-bracing area of the calculation unit is full of goods. In fact, the non-bracing area of the calculation unit may also be vacant. Hence, the actual stress ratio may be smaller than the stress ratio R_l' or R_r' obtained from the bracing unit analysis. Therefore, the maximum stress ratio of upright 1 and upright 2 needs to be subtracted from the influence of the vacant load position in the corresponding non-bracing area of the calculation unit. The number of the load position in the right non-bracing area of the calculation unit is shown in Figure 3.

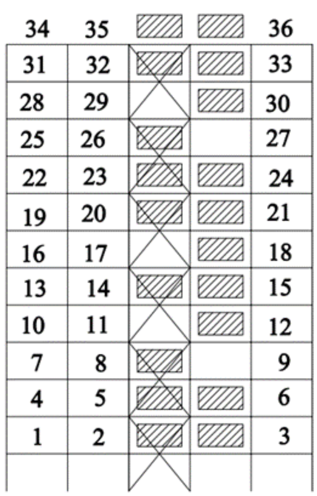

Figure 3: Number of right non-bracing area

The calculation of stress ratio R is shown in Formula 1, Formula 2 and Formula 3.

$$R_l = R_l' - \sum_{i=1}^{36} \left[R_{i,l} \times \left(1 - T_{i,l}\right) - R_{i,l}' \times \eta \right] \tag{1}$$

$$R_r = R_r' - \sum_{i=1}^{36} \left[R_{i,r} \times \left(1 - T_{i,r}\right) - R_{i,r}' \times \eta \right] \tag{2}$$

$$R = \max\left(R_l \, , R_r\right) \tag{3}$$

The variables related are shown in Table 1.

Table 1: Variables

Variables	Definitions
R_l'	The maximum stress ratio of the left upright in the bracing area according to the analysis of the bracing unit
R_r'	The maximum stress ratio of the right upright in the bracing area according to the analysis of the bracing unit
R_l	The maximum stress ratio of the left upright in the bracing area
R_r	The maximum stress ratio of the right upright in the bracing area
$R_{i,l}$	The stress ratio contribution of the ith position to upright 1 by numbering in the left non-bracing area
$R_{i,r}$	The stress ratio contribution of the ith position to upright 2 by numbering in the right non-bracing area
$R_{i,l}'$	The difference in stress ratio contribution of the ith position caused by two types of load position analyses (one empty position only and one full position only) for upright 1, by numbering in the left non-bracing area.
$R_{i,r}'$	The difference in stress ratio contribution of the ith position caused by two types of load position analyses (one empty position only and one full position only) for upright 2, by numbering in the right non-bracing area.
$T_{i,l}$	The status of ith position by numbering in left non-bracing area. If the position is loaded, $T_{i,l} = 1$. If not, $T_{i,l} = 0$.
$T_{i,r}$	The status of ith position by numbering in right non-bracing area. If the position is loaded, $T_{i,l} = 1$. If not, $T_{i,l} = 0$.
η	Vacancy rate of load position in calculation unit

4) Determine whether the stress ratio R exceeds the limit. If the stress ratio R is greater than or equal to 1, the light is red; if it is less than 1, the light is yellow or green.

3.1.2 Judgment process of yellow and green light

Since there are too many samples of load distribution in the bracing unit analysis where the maximum stress ratio of the upright is from 0.95 to 1.0, it is impossible to obtain all of them by calculation. Therefore, the analysis needs to be conducted according to Figure 4.

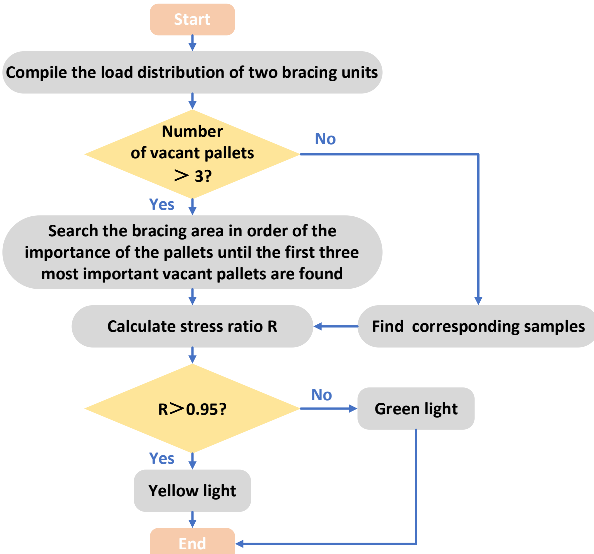

Figure 4: Yellow and green light judgment procedures

1) Compile the load distribution of two bracing units into a load position code.

2) Determine whether the number of vacant positions in the left and right bracing unit is greater than 3. If the number of vacant positions does not exceed 3, the corresponding stress ratio can be obtained from the existing samples of bracing unit analysis according to the load position code. If the number of vacant positions in the bracing unit exceeds 3, it is necessary to search the bracing area in order of the importance of positions until the first three most important vacant positions are found. Search for the corresponding samples of all the bracing area analysis samples with 3 vacant positions to obtain the upright stress ratio.

3) Calculate stress ratio R. If the number of vacant positions in bracing unit does not exceed 3, the calculation method of stress ratio R is the same as that in the red light judgment process. See Formula 1, Formula 2 and Formula 3 for details. If the number of vacant positions in the bracing area exceeds 3, the calculation of stress ratio R is basically the same as Formula 1, Formula 2 and Formula 3. The difference is that the maximum stress ratio of upright 1 and upright 2 needs to be subtracted from the impact of the vacant positions in the remaining 57 positions in addition to the first three most important vacant positions that have been found in the calculation unit.

4) Determine whether the light is yellow or green. If the stress ratio R is greater than or equal to 0.95, the light is yellow; if it is less than 0.95, the light is green.

3.2 Reliability analysis

Yin et al. [9] used genetic algorithm to optimize the distribution modes of goods with 60%, 70% and 80% load on racks respectively and obtained large numbers of samples. In this paper, these samples were randomly selected to verify the reliability of the safety evaluation. The maximum stress ratio R calculated by Formula 1 to Formula 3 is compared with the theoretical value of the maximum stress ratio of the uprights.

3.3 Early warning system

To implement the automated safety evaluation and early warning system, the above process must be compiled into a program and form a data interface with the rack management software WMS. A database management system (SQL Server) is used as the data transfer station for this program and the WMS.

The basic flow of this program is shown in Figure 5.

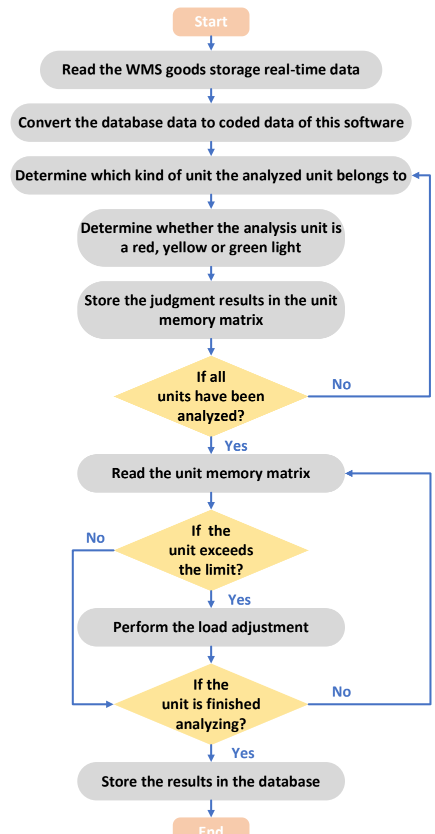

Figure 5: Flowchart of safety evaluation and early warning system

1) Connect to the database and read the WMS goods storage real-time data.

2) Convert the database data to coded data of this software.

3) Determine which kind of unit the analyzed unit belongs to. Since double entry racks and single entry racks need to be judged separately for safety, it is necessary to determine

whether the unit being analyzed is a double entry rack unit or a single entry rack unit.

4) Determine whether the analysis unit is a red, yellow or green light.

5) Store the judgment results in the unit memory matrix. This process deposits the judgment results into the memory matrix for the convenience of determining whether the unit is over-limit when adjusting over-limit loads.

6) Determine whether all units have been analyzed. If yes, continue with the following process; if not, continue with process 3).

7) Read the unit memory matrix in turn. This process needs to read out the unit safety information and basic load position information in the unit memory matrix.

8) Determine whether the unit exceeds the limit.

9) Perform the load adjustment. Record the load adjustment information to the unit memory matrix.

10) Determine if the unit has been analyzed. If yes, proceed to process 11); if not, proceed to process 8).

11) Store the results in the database and wait for the WMS system to call. Compile the load distribution status (red, yellow or green light) and load adjustment information into the data format required by WMS and store it into the database for WMS to read and perform the corresponding adjustment operation.

4. Results and Discussions

In this section, the actual racks of an automated warehouse in Nanjing are studied using the above safety evaluation method and over-limit load warning system.

4.1 Model description

The overall model of the automated warehouse is shown in Figure 6. There are 7 racks in total, including 2 single entry racks and 5 double entry racks, with totaling 12 rows. The total length of the racks is 59.5m. The width is 25m and the height is 15.2m. The width of each load position is 2.38m and the height is 1.575m.

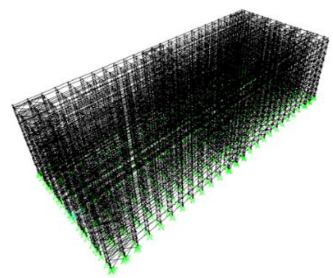

Figure 6:Three-dimensional diagram of overall model

The weight of each pallet is 12kN. The live load is equivalent to 2.471kN/m for the wiring load of the beam and the node stiffness is 116.3kN•m/rad [10]. The seismic intensity is 7 degree with site class of II. The classification of design earthquake is the first group. The characteristic period of the site is 0.35s and the designed basic seismic acceleration is 0.1g. The damping ratio is 0.05. The steel used is Q235 steel. The specifications of components are shown in Table 2.

Table 2: Model component specifications

Component	Upright frames	Beams	Spine bracing	Beams with Spine bracing
Component specifications	Ω90×70×2	Rectangular steel tube 100×50×2×4	C70×25×12×2	Rectangular steel tube 50×50×2×2
Component	Webs of upright frames	Longitude horizontal bracing	Bracing brackets	Plan bracing
Component specifications	C45×25×10×2	C45×25×10×2	Ω90×70×2	Rectangular steel Tube 50×50×2×2

4.2 Safety evaluation

The safety evaluation of this rack is conducted according to the color system. On the basis of calculation, the single entry racks always show green light, while the side units of double entry racks are only possible to show yellow or green lights. The middle units of double entry racks are possible to show all the 3 colors. Therefore, only the middle units of double entry rack need to be judged by red light. The side units of double entry rack will be judged by yellow light.

The safety evaluation reliability analysis was performed for the double entry rack unit. The results of the side unit are shown in Table 3 and the results of the middle unit are shown in Table 4. The maximum stress ratio calculated for the side and middle units of double entry racks is within

±0.005 from the theoretical value, which can ensure the accuracy and reliability of the safety assessment.

Table 3: Comparison results of the side unit

Sample number	Vacancy rate of load position	Maximum stress ratio Occurrence Location	Calculated value of maximum stress ratio	Theoretical value of Maximum stress ratio	Stress ratio difference
1	95%	Upright 2	0.988	0.990	-0.002
2	95%	Upright 2	0.981	0.981	0.000
3	95%	Upright 2	0.970	0.970	-0.001
4	95%	Upright 1	0.960	0.960	0.000
5	95%	Upright 1	0.951	0.950	0.001
6	95%	Upright 1	0.941	0.940	0.001

Table 4: Comparison results of the middle unit

Sample number	Vacancy rate of load position	Maximum stress ratio Occurrence Location	Calculated value of maximum stress ratio	Theoretical value of Maximum stress ratio	Stress ratio difference
1	90%	Upright 4	0.953	0.950	0.003
2	90%	Upright 3	0.965	0.960	0.005
3	90%	Upright 3	0.974	0.970	0.004
4	90%	Upright 4	0.982	0.980	0.002
5	90%	Upright 3	0.992	0.990	0.002
6	90%	Upright 4	1.004	1.000	0.004
7	90%	Upright 3	1.010	1.010	0.000
8	90%	Upright 3	1.024	1.020	0.004
9	90%	Upright 3	1.035	1.030	0.005
10	90%	Upright 3	1.040	1.040	0.000
11	95%	Upright 4	1.007	1.003	0.004
12	95%	Upright 4	1.022	1.020	0.002
13	95%	Upright 4	1.033	1.030	0.003
14	95%	Upright 4	1.043	1.040	0.003

4.3 Over-limit load adjustment

According to the analysis of the bracing unit, if there are two empty positions above the third floor of the first column, the load distribution status of the double entry rack side unit can be guaranteed green light. If there are 6 empty positions above the third floor of the two columns of the bracing area, the load distribution status of double entry rack side unit can be guaranteed green light. The number of load position in calculation unit is shown in Figure 7.

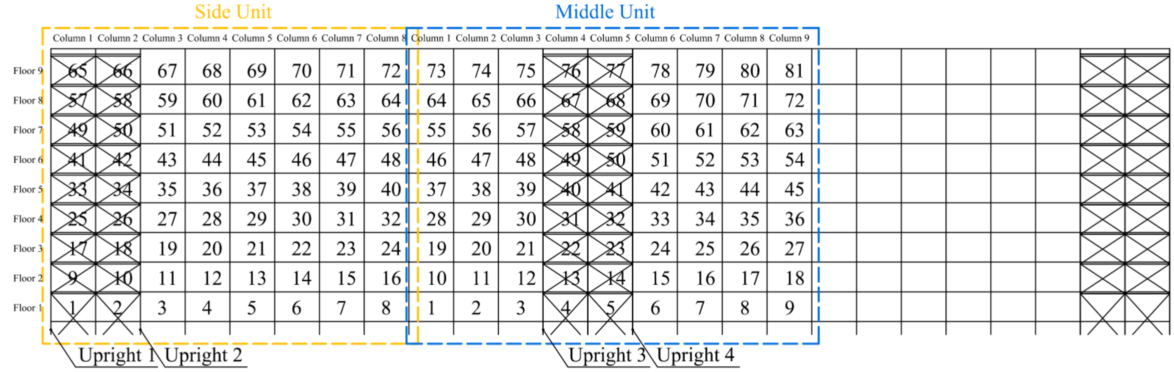

Figure 7: Number of load position in side unit and middle unit

4.3.1 Adjustment process of side unit

The over-limit load adjustment process of side unit in double entry rack is as follows (see Figure 8), with a maximum of two adjustments required.

1) Adjust the goods from the top floor of the bracing area to the two side columns or other units in order from top to bottom. Since the goods in columns 4~8 have little effect on the seismic performance of the rack, the goods in column 1, floor 3 and above are adjusted from top to bottom to columns 4~8 or the nearest vacant load position in other units (no extra vacant load position in the calculation unit).

2) Calculate the stress ratio after each adjustment.

3) Determine whether the stress ratio exceeds the limit. If the limit is not exceeded, then the adjustment is finished; if the limit is exceeded, then go to process 1) to continue the adjustment until the stress ratio is reduced to below the limit.

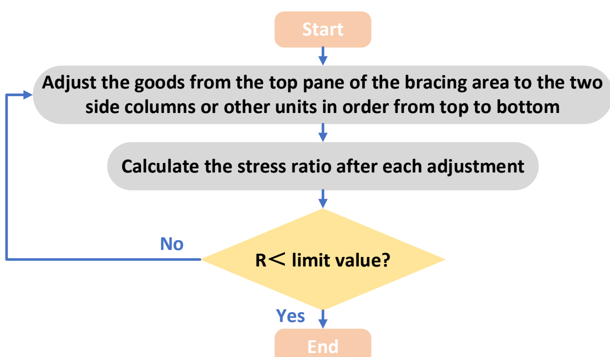

Figure 8: Load adjustment process of side unit

4.3.2 Adjustment process of middle unit

The adjustment process of middle unit in the double entry racks is as follows (see Figure 9). It takes at most 5 times to adjust from red to yellow light and at most 9 times to adjust from red to green light.

1) Determine whether positions 2, 4 and 6 in the calculation unit are vacant. If positions 2, 4, 6 are vacant, the rack will be under the most unfavorable seismic condition. Therefore, it is necessary to judge the three positions first. If there are vacant positions, then these vacant positions need to be filled in turn; if not, the other positions will be adjusted.

2） From floor 3 of the bracing area, adjust the goods to the vacant positions of 2, 4 and 6 in order from bottom to top. The stress ratio contribution value of goods located above the 3rd floor of the bracing area is about the same. Considering the efficiency of the stacker, the load is adjusted in this order.

3) Calculate the stress ratio after each adjustment.

4) Determine whether the adjusted stress ratio exceeds the limit. If the limit is not exceeded, the adjustment will be ended; if the limit is exceeded, the following process will be continued.

5） Judge whether positions 2, 4 and 6 are full or not. If positions 2, 4 and 6 are not full, continue the adjustment in process 2); if positions 2, 4 and 6 are full, adjust the other positions.

6) Adjust goods from the top floor of bracing area to the two side columns or other units in order from top to bottom. If the adjustment of positions 2, 4 and 6 did not reduce the stress ratio to below the limit, the goods above the third floor of bracing column need to be adjusted outward, as side columns have little effect on the seismic performance of the rack.

7) Calculate the stress ratio after each adjustment.

8) Determine whether the stress ratio exceeds the limit. After the adjustment of process 2) and process 6), judge whether the adjusted load distribution exceeds the limit. If the limit is not exceeded, the adjustment will be ended; if the limit is exceeded, the adjustment will be transferred to process 6) and continue until the stress ratio is reduced to below the limit.

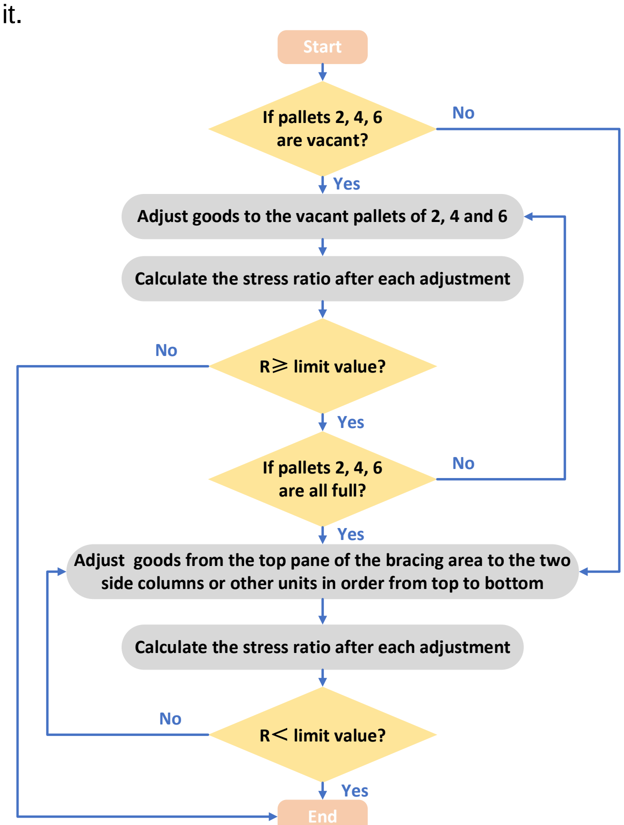

Figure 9: Load adjustment process of middle unit

4.4 Implementation of the early warning system program

The program implementation flow of safety evaluation and load distribution warning system is described in the previous section. This program is written using MATLAB including four parts: input data, safety evaluation, over-limit load redistribution and output data. The code is not described in detail in this paper.

5. Conclusions

This paper describes in detail the safety evaluation of racks with spine bracings, early warning of over-limit load distribution and process of program implementation. Besides, the reliability of the formula for safety evaluation are analyzed. The conclusions obtained are as follows:

(1) The safety evaluation formula of the rack with spine bracing has been derived. The error range of the maximum stress ratio of the upright calculated according to the formula is within ±0.005. The reliability meets the requirements.

(2) The safety evaluation process and the over-limit distribution load warning process of the rack with spine bracing have been given. The program can be written according to the process so as to realize the automatic safety judgment.

(3) An automated warehouse in Nanjing is analyzed according to the developed system to show that the safety evaluation formula of the rack with spine bracing is reliable and universal.

6. Acknowledgments

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