WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2020.134398

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVI ISSUE 3 2020

RESISTANCE TO PROGRESSIVE COLLAPSE PERFORMANCE ANALYSIS OF STEEL OPEN-WEB SANDWICH PLATE STRUCTURE

W.Y. ZENG[1], J. LUO[2], J.C. XIAO[3]

In order to investigate the progressive collapse performance of steel open-web sandwich plate structure, the sensitivity index and the importance coefficient of the bars are analyzed by the alternate path method. The condition that the model has perimeter supports with different parameters shows the result that: the redundancy index of structure increases at the structural edge, and the redundancy index will be reduced to changing degrees at the middle structure, when the stiffness of higher ribs increases. The redundancy index has little change, when the stiffness of lower ribs or shear keys increases. The sensitivity index of the shear keys dropped significantly, but the sensitivity index of the higher ribs and lower ribs increase, when the span to depth ratio increases. The sensitivity index of the higher ribs in L1 line increases significantly, when the span to depth ratio declines. So it is advisable to strengthen the higher ribs to avoid excessive sensitivity of ribs, when the span to depth ratio declines.

Keywords: sensitivity analysis, rod failure, steel open-web sandwich plate structure, progressive collapse, redundancy index.

[1] MSc., Guizhou University, Spatial Structure Research Center, Guiyang, 55009, China, e-mail: 630084497@qq.com
[2] PhD., Eng., China Construction 4th Engineering Bureau 6th Co., Ltd, Hefei, 230000, China, e-mail: 1027561901@qq.com
[3] Prof., PhD., Guizhou University, Spatial Structure Research Center, Guiyang, 55009, China, e-mail: jcxiao@gzu.edu.cn

1. INTRODUCTION

The progressive collapse of large-span spatial structures in normal or emergency use would cause considerably physical damages and lead to social disasters, such as the truss roof failure in Hartford City and the roof failure of Kemper Arena Gym in Kansas City. Industrial standards [1-4] in each of the countries mentioned in this article emphasize the importance of designing with resistance to progressive collapse.

ASCE7-02 [4] standards provide the following three design methods to deal with the progressive collapse: indirect method, transform load path method (AP method), and specific local resistance direct design method.

The AP method has three primary benefits: (1) exclusion of the rod failure cause, (2) consistency with seismic design methods in design standards used by many countries, and (3) utilization in studying structural progressive collapse [5-8].

With the increasing number of large-span and multi-tall buildings, traditional forms of reinforced concrete structures are occasionally appropriate for numerous projects due to excessive self-weight, long construction period, and poor space performance. Open-web sandwich plate structures, which have emerged over time, appear in many new constructions. Some engineering examples are shown in Fig. 1.

Most current studies on progressive collapse focus on truss and frame structures, while investigations on the open-web sandwich plate structure are limited. Therefore, studying the progressive collapse of the open-web sandwich plate structure is of considerable importance.

(a) Multi-purpose Gymnasium in Heilongjiang University of Chinese Medicine

(b) Bottom and middle floor of Flower Building in Guiyang

(c) Type II steel open-web sandwich plate of Public Security Building in Zhuhai

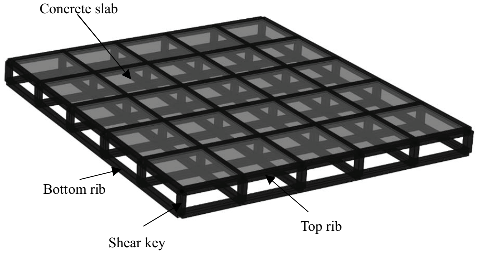
(d) Type I steel open-web sandwich plate of Footbridge in Guiyang Normal College

Fig. 1. Open-web sandwich plate structure projects.

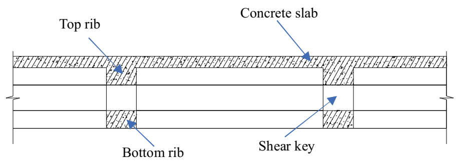
2. STEEL OPEN-WEB SANDWICH PLATE STRUCTURE

The open-web sandwich plate structure was proposed by academician K.J. MA of Guizhou University in 1995. Subsequently, the research group conducted systematic and comprehensive research and application of this type of structure. The structural form is constantly enriched, and its engineering practice is spread all over the country. The structure can be divided into a concrete open-web sandwich plate, open-web sandwich plate of U-shaped steel–concrete composite, and steel open-web sandwich plate structure by material type. The third type can be divided into ortho-laid open-web sandwich plate structure and ortho-laid open-web sandwich plate structure considering grid form.

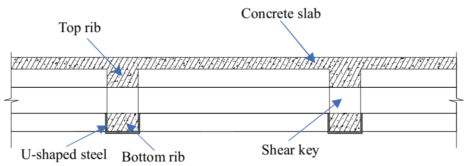
Concrete open-web sandwich plate comprises two layers of ribbed reinforced concrete slab and reinforced concrete shear key. The structures of open-web sandwich plate of U-shaped steel-concrete and concrete open-web sandwich plate are similar. However, open-web sandwich plate of U-shaped steel–concrete has more U-shaped steel for covering the bottom ribs than that of concrete open-web sandwich plate. U-shaped steel can be used as a tensile member and bottom rib formwork. The steel open-web sandwich plate structure comprises top and bottom T-shaped steel ribs, steel pipe shear keys, and reinforced concrete slabs [9]. The specific structure of the three forms of open-web sandwich plate is shown in Fig. 2.



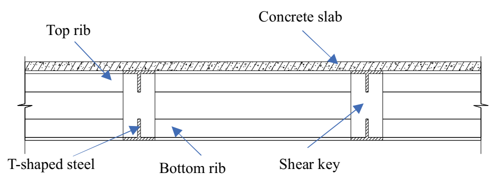
(a) Schematic diagram of open-web sandwich plate



(b) Cross sections of concrete open-web sandwich plate



(c) Cross sections of open-web sandwich plate of U-shaped steel-concrete composite



(d) Cross sections of steel open-web sandwich plate

Fig. 2. Structural diagram of open-web sandwich plate.

The empty abdomen height should be 1/25–1/35 of the span, and the empty part can host pipelines and offset the floor height. The structure has a good overall mechanical performance. The two-way steel ribs on the floor are arranged neatly and beautifully. The decorative ceiling can be made in the lower part, which can save late renovation costs.

The open-web sandwich plate structure has the same function as slab–column structure–big pillar net, big bay, and flexible room division. In addition, this structure offsets the disadvantage of the frame beam–slab structure, in which beams are found on the walls. The open-web sandwich plate structure is a kind of steel grid structure system that integrates the functions of load-bearing, enclosure, decoration, and pipeline support.

3. NUMERICAL SIMULATION

3.1. SENSITIVITY ANALYSIS METHOD [13, 14]

The simulation of structural local damage often uses the AP method to remove the key element and make the element out of work and determines whether the new load transfer path can be formed after the redistribution of internal force. The formation of a new transmission path indicates that the remaining structure has the capability to "bridge," and the original structure has good resistance to progressive collapse; otherwise, the resistance to progressive collapse is poor. The sensitivity and the importance coefficients in the AP method are generally used to describe the performance of progressive collapse.

In the sensitivity analysis, the response of the structure (stress, strain, supporting capacity, and displacement) under conventional load is used as the research object. The rod, as a damage parameter, is removed. Let S_{ij} be the sensitivity index of the i element to the jth damage parameter. Let γ be the response of element i with structural integrity; let γ' be the response of element i that has failed. Therefore, the value of S_{ij} is calculated as follows:

$$S_{ij} = (\gamma - \gamma') / \gamma , \tag{3.1}$$

where S_{ij} is the sensitivity index of the i element to the jth damage parameter, γ is the response of element i when the structure is intact, and γ' is the response of element i after structural damage.

The importance coefficient has different calculation methods. In this paper, the sensitivity analysis of a single member response is conducted, and the importance coefficient is the mean value of the remaining member sensitivity coefficient. Let n be the total number of members. The value of α_j is shown in equation (3.2).

$$\alpha_j = \sum_{i=1, i\neq j}^{n} S_{ij} / (n-1), \tag{3.2}$$

where α_j is the importance coefficient of element j, and n is the number of elements.

The internal force of the rod will be reduced, and the structure will not be destroyed when S_{ij} is less than zero. Only the S_{ij} non-negative case is considered to improve the applicability of the equation. The stress of the i rod increases when S_{ij} is between 0 and 1. Moreover, the rod i yields or buckles when S_{ij} is equal to 1. The sensitivity index reflects the influence of rod failure on the stress response of the surrounding members. The importance coefficient reflects the average effect of the stress response of all the members after failure of the member. The structure possibly fails after the i-rod is removed and the i-rod sensitivity index S_{ij} is the largest. A sensitive rod possibly causes considerably internal force redistribution or progressive collapse after the initial damage.

3.2. MODEL INTRODUCTION

The design of the steel open-web sandwich plate structure model is based on the "Design and Construction Regulations for the Reinforced Concrete Open-Web Sandwich Plate Slab" [12] and the previous paper [15]. The span of the model is 36 m, and the grid size is 3 m × 3 m. The 1/8 model is used as the calculation model (dashed part) because the model is square symmetrical as shown in Fig. 3(a). The height between the top and bottom ribs is 1 m, and the thickness of the concrete slab is 0.08 m. The model also uses the perimeter support (each span has a form of column support) as shown in Fig. 4. The model is analyzed by large-scale finite element software sap2000. Moreover, the model considers the p-Δ effect, divides the grid length by 0.1 m, and ignores the effects of studs. The structural dimensions, maximum stress ratios, and load values are shown in Table 1. An ideal model is used for analysis to simplify the calculation. The dynamic effect of removing the failed member is ignored.

Nodes 1–5 in Fig. 3(a) are the displacement change collection points. Fig. 3 (b) shows the line number and the number of shear keys that must be removed. L1–L13 are the line numbers; L1, L3, L5, L7, L9, L11, and L13 are transverse bars of the corresponding row (including top ribs, bottom ribs, and shear keys); L2, L4, L6, L8, L10, and L12 are the longitudinal bars of the corresponding row (including top ribs, bottom ribs, and shearing bonds). Figs. 3(c) and 3(d) are numbered drawings showing the removal of the top and bottom ribs, respectively. Nos. 1–28 are the removal of the shear keys, Nos. 29–70 are the removal of the top ribs, and Nos. 70–112 are the removal of the bottom ribs.

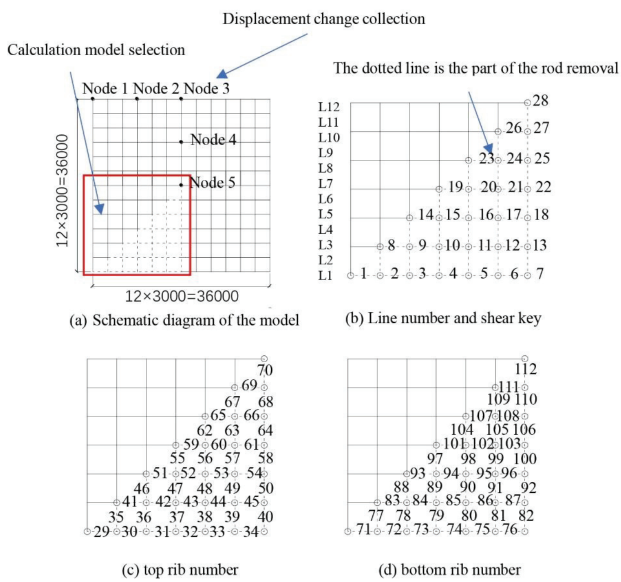


Fig. 3. Calculation model of steel open-web sandwich plate structure.

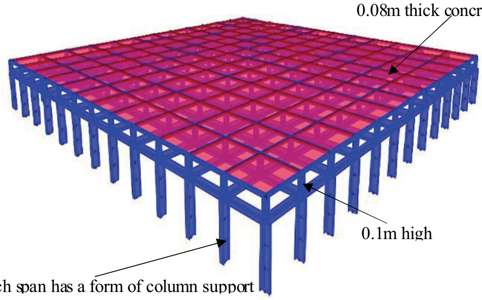


Fig. 4. Model diagram.

Table 1. The basic parameters of bars.

	The parameters of bars /mm	**Design maximum stress ratio**	**Load value kN/m²**
Top rib size	T180×180×12×12		
Bottom rib size	T400×450×30×30	0.867	1.20
Shear key size	Rectangular tube 280×15		

Table 2. Structural parameters with different top ribs stiffness.

Top rib size	**Design load kN/m**	**Design maximum stress ratio**
T180x180x12x12	1.20	0.867
T220x220x14x14	1.20	0.870
T260x260x16x16	1.31	0.881

4. DIFFERENT PARAMETER ANALYSIS

This model analyzes the parameters of stiffness, structure height–thickness ratios, and structural spans with different rods. The basic parameters of the structural rod are shown in Table 1.

4.1. ANALYSIS OF TOP RIBS STIFFNESS PARAMETERS

This redundancy of the rod is analyzed by changing the top rib stiffness of the structure. The basic parameters of the structural rod are shown in Table 2.

4.1.1. SENSITIVITY ANALYSIS OF TOP RIBS STIFFNESS

The progressive collapse performance of different top rib stiffness models is analyzed by the AP method, and the sensitivity index of each rod is calculated by Equation (3.1). The maximum value is obtained, and the result is shown in Fig. 5(a). The sensitivity indexes of the shear keys, top ribs, and bottom ribs are respectively shown in Figs. 5(b), 5(c), and 5(d).

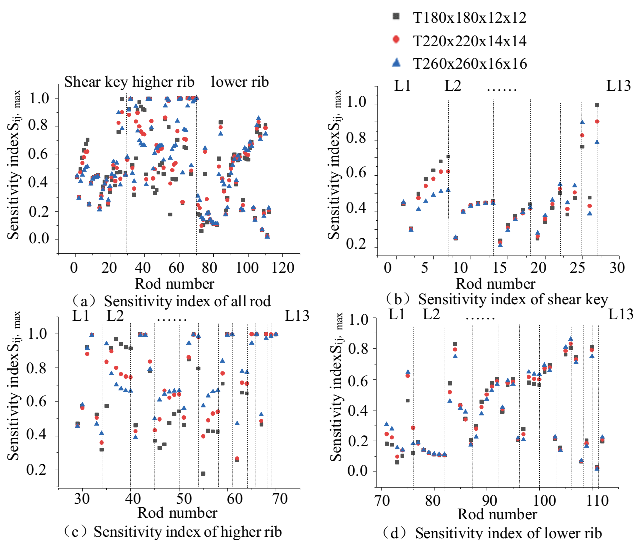


Fig. 5. The sensitivity index of structure with different stiffness of top ribs.

Fig. 5(a) shows that the change in stiffness also results in considerable changes in the sensitivity index at the center of the structure (as shown in L9, L11, and L13 rows). The stiffness and the sensitivity index both increase at the L9 and L11 lines, whereas the increase in stiffness is inversely proportional to the sensitivity index at the L13 line.

Fig. 5(b) shows that the sensitivity index of Nos. 1–18 shear keys on the L1–L5 lines decreases with the increase in the stiffness of the top ribs, and its value respectively decreases by 0.1 and 0.01 at the side span and the middle. The sensitivity index of Nos.19–25 shear keys on the L7–L9 lines increases with the stiffness of the top ribs, and its value is mostly increased by 0.05. The sensitivity index of Nos. 26 and 27 shear keys on the L11–L13 lines decreases with the increase in the stiffness of the upper ribs, and the values are 0.09 and 0.21, respectively. The sensitivity index of the shear keys in the middle of the structure is 1.0, indicating a sensitive rod. Increasing the stiffness of the top ribs can reduce the sensitivity index of the shear keys at the side span and the middle of the structure, except for shear keys in the middle.

Fig. 5(c) shows that the sensitivity index of Nos. 29–40 top ribs on the L1–L2 lines decreases with the increase in the stiffness of the top ribs, and its value is below 0.02 and 0.23–0.26 in the L1 and the L2 rows, respectively. Nos. 41–70 top ribs of the L3–L13 lines remarkably increase with the stiffness of the top ribs, and the value is mostly between 0.19 and 0.25. The redundancy of the top ribs at the middle of the structure is sufficient, and the additional stiffness increases the value of the structural sensitivity index.

Fig. 5(d) shows that the sensitivity index of the bottom ribs of Nos. 71–76 at the L1 line slightly increases with the stiffness of the top ribs, and its value is between 0.12 and 0.18. The stress of the bottom ribs at the L1 row is mainly borne by the support point. Increasing the weight of the top ribs will also increase the sensitivity index. When the stiffness increases, the sensitivity index of the bottom ribs rises to 5.61% in the L2 row, and the change reaches 44.42% in the L13 line. When the number of rows increases, the influence of the stiffness change on the sensitivity index of the bottom ribs increases in the L2–L13 rows.

4.1.2. IMPORTANCE COEFFICIENT ANALYSIS OF TOP RIBS STIFFNESS

The importance coefficient of the model is analyzed and calculated using Equation (3.2). The importance coefficients of the shear keys, top ribs, and bottom ribs are shown in Figs. 6(a)–6(d).

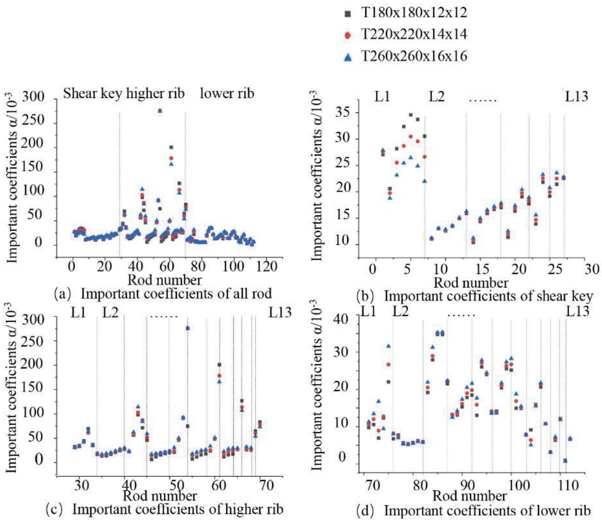


Fig. 6. The importance coefficient of structure with different stiffness of top ribs.

Fig. 6(a) shows that the distribution of the structural importance coefficients is consistent with the changes in stiffness of the top ribs.

Figs. 6(b)–6(d) show that the effect of stiffness change on the importance coefficient is primarily at the shear keys and bottom ribs in the L1 row. The importance coefficient of the bottom ribs decreases as the stiffness of the shear keys increases. The increase in bottom rib stiffness also raises the importance coefficient of the bottom ribs.

4.2. ANALYSIS OF SHEAR KEYS STIFFNESS PARAMETERS

The redundancy of the rod is analyzed by changing the shear key stiffness of the structure. The basic parameters of the structural rod are shown in Table 3.

4.2.1. SENSITIVITY ANALYSIS OF SHEAR KEYS STIFFNESS

The sensitivity index of different shear key stiffness models is analyzed, and the sensitivity index of each rod is calculated using Equation (3.1). The maximum value is obtained, and the result is shown in Fig. 7(a). The sensitivity indexes of the shear keys, top ribs, and bottom ribs are shown in Figs. 7(b), 7(c), and 7(d), respectively.

Table 3. Structural parameters with different shear keys stiffness.

Shear key size	Design load kN/m	Design maximum stress ratio
Rectangular tube 280x15	1.20	0.867
Rectangular tube 290x16	1.30	0.869
Rectangular tube 300x17	1.40	0.87

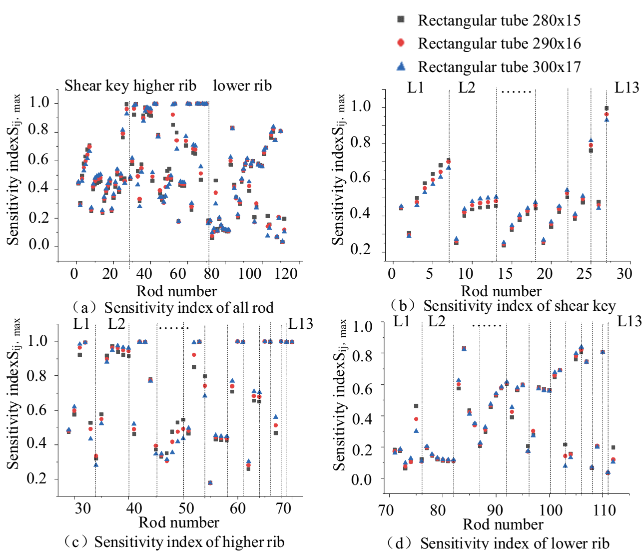


Fig. 7. The sensitivity index of structure with different stiffness of shear keys.

The analyses provided in 4.2–4.5 are all performed analogously to that presented in 4.1. Therefore, the subsequent sensitivity analysis is briefly described in the following table.

The analysis of Fig. 7 is shown in Table 4.

Table 4. Sensitivity analysis of Fig. 7.

Fig	Line number	Rod number	Sensitivity index conclusions	Value	Redundancy conclusions	Cause and effect
7(a)	All	All	Only changed slightly as the stiffness of the shear key changed	\	Only changed slightly	The stiffness of shear keys only slightly contributed to structural redundancy.
7(b)	L1	Nos.1–7	Decreased as the stiffness of the shear key increased	0.4–0.6	Increased	The shear keys are the main force-bearing rod at the support point.
	L2–L13	Nos. 8–27	Increased as the stiffness of the shear key increased	0.01–0.006	Decreased	The shear keys are sufficient at the unsupported point.
7(c) 7(d)	L1–L13	Nos. 20–112	Only changed slightly as the stiffness of the shear key changed	\	Only changed slightly	The change in the stiffness of the shear keys mainly affected the support point, and the rest of the contribution is minimal.

Recommendation: Increasing the stiffness of the shear keys to enhance structural redundancy is not recommended.

4.2.2. IMPORTANCE COEFFICIENT ANALYSIS OF SHEAR KEYS STIFFNESS

The importance coefficient of the model is analyzed and calculated using Equation (3.2). The importance coefficients of the shear key, top ribs, and bottom ribs are shown in Figs. 8(a)–8(d).

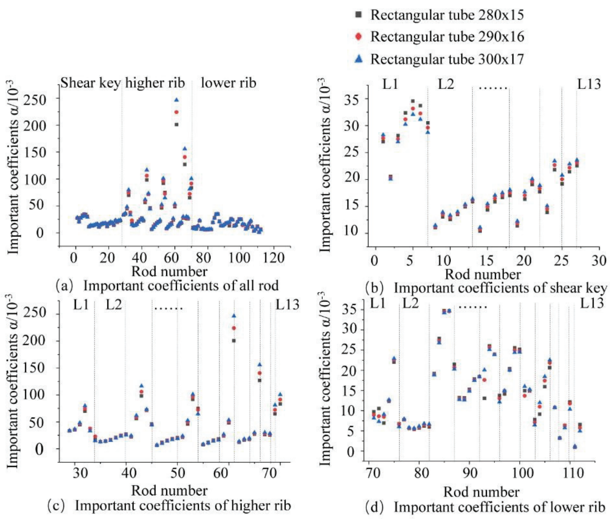


Fig. 8. The importance coefficient of structure with different stiffness of shear keys.

Fig. 8 shows that the change in shear key stiffness has a slight effect on the distribution of importance coefficient. A small change in the importance coefficient is observed at the shear keys in line L1 and at the top ribs at the center of the structure. Moreover, the value slightly varies for the rest of the structure.

4.3. ANALYSIS OF BOTTOM RIBS STIFFNESS PARAMETERS

The redundancy of the rod is analyzed by only changing the bottom rib stiffness of the structure. The structural parameters are shown in Table 5.

Table 5. Structural parameters with different bottom ribs stiffness.

Bottom rib stiffness/mm	Design load kN/m	Design maximum stress ratio
T400x450x30x30	1.20	0.867
T410x460x32x32	1.20	0.856
T420x470x34x34	1.20	0.847

4.3.1. SENSITIVITY ANALYSIS OF BOTTOM RIBS STIFFNESS

The progressive collapse performance of different bottom rib stiffness models is analyzed by the AP method, and the sensitivity index of each rod is calculated using Equation (3.1). The maximum value is obtained, and the result is shown in Fig. 9(a). The sensitivity indexes of the shear keys, top ribs, and bottom ribs are respectively shown in Figs. 9(b), 9(c), and 9(d).

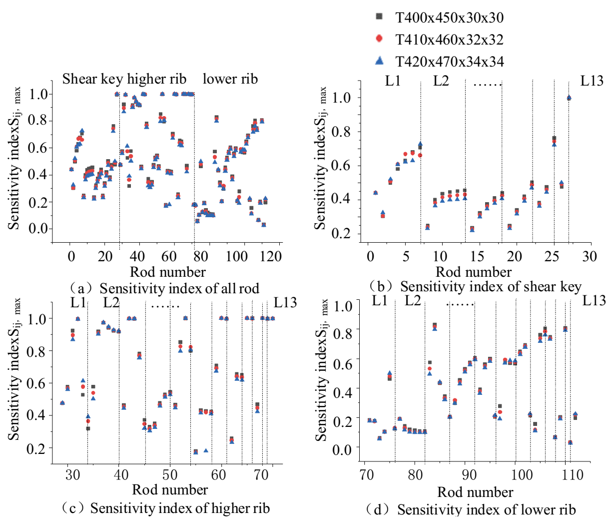


Fig. 9. The sensitivity index of structure with different stiffness of bottom ribs.

The analysis of Fig. 9 is shown in Table 6.

Table 6. Sensitivity analysis of Fig. 9.

Fig	Line number	Rod number	Sensitivity index conclusions	Value	Redundancy conclusions	Cause and effect
9	All	All	Only changed slightly as the stiffness of the bottom ribs changes	\	Only changed slightly	\

4.3.2. IMPORTANCE COEFFICIENT ANALYSIS OF BOTTOM RIBS STIFFNESS

The importance coefficient of the model is analyzed and calculated by Equation (3.2). The importance coefficients of the shear keys, top ribs, and bottom ribs are shown in Figs. 10(a)–10(d).

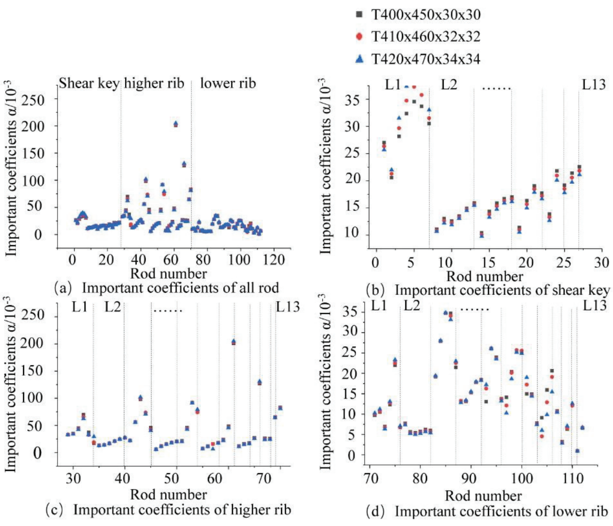


Fig. 10. The importance coefficient of structure with different stiffness of bottom ribs.

Fig. 10 illustrates that the change in the bottom rib stiffness has no effect on the distribution of the importance coefficient of the structure. The importance coefficient of the shear keys in the L1 row and the middle bottom rib member of the structure has a certain degree of influence, whereas the bottom rib stiffness changes. Moreover, the importance coefficient is unchanged for the rest of the structure.

4.4. ANALYSIS OF SPAN TO DEPTH PARAMETERS

The redundancy of the rod is analyzed by only changing the span-to-depth parameters of the structure. The structural parameters are shown in Table 7.

4.4.1. SENSITIVITY ANALYSIS OF SPAN TO DEPTH

The sensitivity of different span-to-depth parameters is analyzed, and the sensitivity index of each rod is calculated using Equation (3.2). The maximum value is obtained, and the result is shown in Fig. 11(a). The sensitivity indexes of the shear keys, top ribs, and bottom ribs are respectively shown in Figs. 11(b), 11(c), and 11(d).

Table 7. Structural parameters with different span to depth.

Span to depth/m	Design load kN/m	Design maximum stress ratio
1.0	1.20	0.867
1.2	1.20	0.960
1.5	0.96	0.868

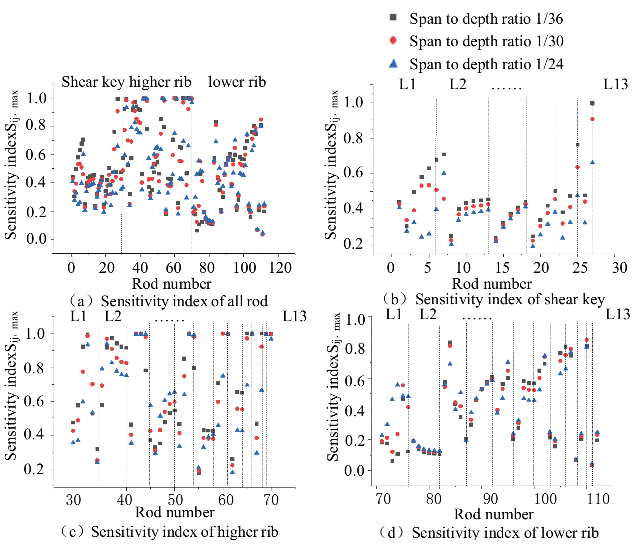


Fig. 11. The sensitivity index of structure with different span to depth.

The analysis of Fig. 11 is shown in Table 8.

Table. 8. Sensitivity analysis of Fig. 11.

Fig	Line number	Rod number	Sensitivity index—conclusions	Value	Redundancy—conclusions	Cause and effect
11(a)	All	All	Decreased as the span to depth increased	\	Increased	\
11(b)	All	Nos. 1–27	Decreased as the span to depth increased	\	Increased	The stiffness of the shear keys is large as the span-to-depth increased.
	L3–L5	Nos. 8–18	Only changed slightly as the span-to-depth changed	0.04–0.06	Only changed slightly	Shear keys have large stresses and bending moments at the periphery and center of the structure, respectively, and strengthening the shear keys at this place will have evident effects.
	L5–L13	Nos. 1–7 and Nos. 19–28	Changed remarkably as the span-to-depth changed	0.2–0.33	Changed remarkably	
11(c) 11(d)	L1	All	Decreased remarkably as the span-to-depth increased	0.08–0.3	Increased	The bottom ribs are directly subjected to the self-heavy load increased by the shear keys.
	L2–L13	All	Decreased slightly as the span-to-depth increased	0.1–0.15	Increased	

Recommendation: The sensitivity index of the bottom ribs should be monitored when the span-to-depth increased.

4.4.2. IMPORTANCE COEFFICIENT ANALYSIS OF SPAN TO DEPTH

The importance coefficient of the model is analyzed and calculated by Equation (3.2). The importance coefficients of the shear keys, top ribs, and bottom ribs are shown in Figs. 12(a)–12 (d).

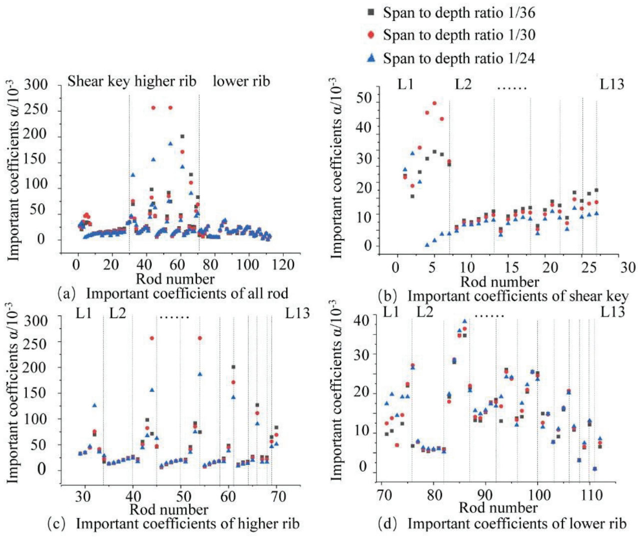


Fig. 12. The importance coefficient of structure with different span to depth.

Fig. 12 shows that the importance coefficient of all rods is unchanged, whereas the span-to-depth parameter changes. The importance coefficient of the shear keys and top ribs significantly increases with span-to-depth parameters, and the value of the bottom ribs is not evident.

4.5. ANALYSIS OF SPAN PARAMETERS

This redundancy of the rod is analyzed by only changing the size of each cell of the structure. The structural parameters are shown in Table 9.

Table 9. Structural parameters with different span.

Span /m	Per mesh size	Design load kN/m	Design maximum stress ratio
36m	3.0mx3.0m	1.20	0.867
30m	2.5mx2.5m	2.88	0.851
24m	2.0mx2.0m	4.56	0.910

4.5.1. SENSITIVITY ANALYSIS OF SPAN

The sensitivity of different span parameters is analyzed, and the sensitivity index of each rod is calculated by Equation (3.1). The maximum value is obtained, and the result is shown in Fig. 13(a). The sensitivity indexes of the shear keys, top ribs, and bottom ribs are respectively shown in Figs. 13(b), 13(c), and 13(d).

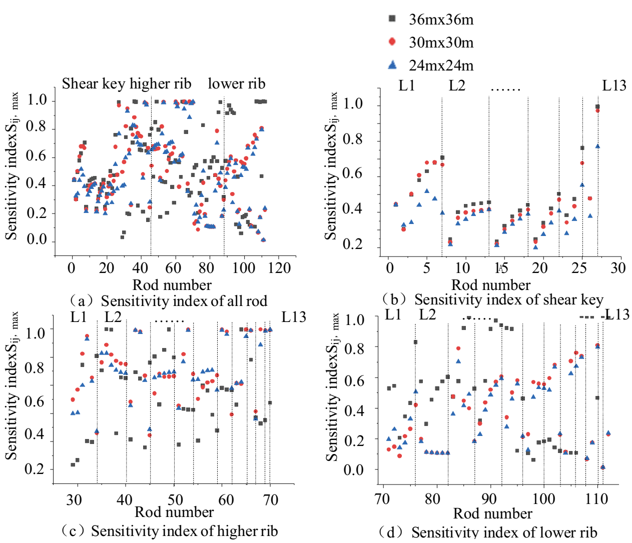


Fig. 13. The sensitivity index of structure with different span.

The analysis of Fig. 13 is shown in Table 10.

Table 10. Sensitivity analysis of Fig. 13.

Fig	Line number	Rod number	Sensitivity index—conclusions	Value	Redundancy—conclusions	Cause and effect
15(a)	All	Almost all	Decreased remarkably as the span decreased	\	Increased remarkably	\
15(b)	L1,9,11,13	No. 1–7 and No. 23–28	Decreased remarkably as the span decreased	Approximately 0.2	Increased remarkably	\
15(c)	L1	No. 29–33	Increased remarkably as the span decreased	Mostly at 0.3, the highest is 0.73	Decreased remarkably	The top ribs in the L1 line may become a sensitive member with span reduction.
	L2–L13	No. 34–70	Decreased remarkably as the span decreased	Approximately 0.2	Increased remarkably	
15(d)	All	No. 79–112	Decreased as the span decreased	Most no less than 0.5	Increased remarkably	Due to the notable decrease in the bending moment bottom ribs caused by the span reduction

Recommendation: The structural redundancy has a significant enhancement with span reduction. The top rib sensitivity index significantly increased in line L1. Therefore, strengthening the top ribs at line L1 is necessary to avoid excessive rib sensitivity caused by span decline.

4.5.2. IMPORTANCE COEFFICIENT ANALYSIS OF SPAN

The importance coefficient of the model is analyzed and calculated by Equation (3.2). The importance coefficients of the shear keys, top ribs, and bottom ribs are shown in Figs. 14(a)–14(d).

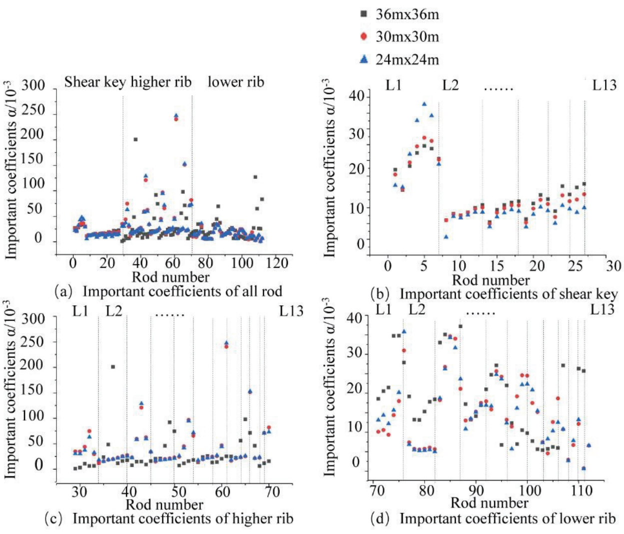


Fig. 14. The importance coefficient of structure with different span.

Fig. 14 shows that the reduction in span parameters has a slight effect on the overall distribution of importance coefficients. With a relatively small increase in the shear keys at the L1 line, the importance coefficient of the bottom ribs is remarkably increased in the L1 and L9–13 rows.

5. CONCLUSION

1. When the stiffness of top ribs increases, the redundancy index of the structure rises at the structural edge, and the redundancy index will be reduced to varying degrees in the middle part of

the structure. Therefore, strengthening of different rods at the middle part separately is suggested when the stiffness of the top ribs is increased.

2. The redundancy index of the structure almost does not benefit from the increase in stiffness of the bottom ribs or shear keys. Therefore, strengthening the two components to enhance structural redundancy is not recommended.

3. When the span-to-depth ratio increases, the sensitivity index of the shear keys significantly decreases, whereas that of the top and bottom ribs increases. The bottom ribs are directly affected by the weight of the shear keys. The sensitivity increases more than the value of the top ribs.

4. The structural sensitivity index of the L2–L13 lines significantly decreased under span reduction. Therefore, reducing the span would significantly increase the structural redundancy.

5. The top rib sensitivity index significantly increased at line L1 due to span reduction. Therefore, strengthening the top ribs at line L1 is suggested to avoid excessive rib sensitivity caused by span decline.

ACKNOWLEDGEMENTS

The authors would like to thank the Guizhou Natural Science Foundation: QKHJC[2017]1036, and the Guizhou Natural Science Foundation: QRF 2017-01, and the Guizhou Province First-class Discipline Construction Project: QYNYL [2017]0013, for financially supporting this research.

REFERENCES

1. Structural use of concrete — Part 1 Code of practice for design and construction, BS 8110-1, 1997.
2. Actions On Structures, Part 1. 7:General Actions-Accidental Actions, Eurocode 1, 1991.
3. Progressive collapse analysis and design guidelines for new federal office buildings and major modernization project, GSA2003, 2003.
4. Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7, 2005.
5. P. Pandey and S. Barai, "Structural Sensitivity as a Measure of Redundancy," Journal of Structural Engineering-asce - J STRUCT ENG-ASCE, vol. 123, 03/01 1997.
6. S. M. Hosseini and G. G. Amiri, "Successive collapse potential of eccentric braced frames in comparison with buckling-restrained braces in eccentric configurations," (in English), Int J Steel Struct, vol. 17, no. 2, pp. 481-489, Jun 2017.
7. A. Salmasi and M. Sheidaii, "Assessment of eccentrically braced frames strength against progressive collapse," Int J Steel Struct, vol. 17, pp. 543-551, 06/01 2017.
8. H. T. Khuyen and E. Iwasaki, "An approximate method of dynamic amplification factor for alternate load path in redundancy and progressive collapse linear static analysis for steel truss bridges," Case Studies in Structural Engineering, vol. 6, pp. 53-62, 2016.
9. Q. Z. Yang, C. J. Ma, H. G. Zhang, L. Hu, and P. Hu, "Structural design of large-span prefabricated integral steel-concrete composite hollow slabs," Building Structure, vol. 44, no. 13, pp. 5-8+57, 2014.
10. Y. Huang, B. Chen, and Y. Kang, "A New Framing System- The Open- Web Sandwich Plate and The Method of Continuous Analysis," Journal of Guizhou University of Technology, no. 04, pp. 69-75, 1997.
11. H. G. Zhang, L. Hu, C. J. Ma, and T. Zheng, "Analysis on Static Behavior of Open-web Sandwich Plate and a Practical Method," Journal of Guizhou University of Technology, no. 03, pp. 82-87, 2006.

12. Technical Specification For Reinforced Concrete Open-Web Sandwich Plate Structures, Di Fang Biao Zhun (Pinyin in China) (DB)22/48, 2005.
13. D. Stevens, B. Crowder, B. Hall, and K. Marchand, Unified Progressive Collapse Design Requirements for The Department of Defense (DoD) and General Service Administration (GSA). 2008, pp. 1-10.
14. Design of structures to resist progressive collapse, Unified Facilities Criteria (UFC) 4-023-03, 2009.
15. B. Yiming and M. Kejian, "Dynamic elasto-plastic analysis of new assembled multi-storey long-span honeycomb steel grid box structure," Paper Asia, pp. 28-33, 01/01 2018.

LIST OF FIGURES AND TABLES:

Received: 15.02.2020 Revised: 03.07