An analysis research of the stiffness characteristics of hospital building materials

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ABSTRACT. This paper primarily aims to introduce different stiffness ratio requirements for hospital buildings of various structural styles, to achieve a new standard. The requirements of each stiffness ratio are analyzed, according to the specification formulas and illustrations. And whether the structural deformation situation complies with the code requirement or dissatisfies the specification requests can be intuitively reflected through the application of the chart form, respectively. The corresponding measures complying with the code requirement and the matters needing attention in the schematic design phase are proposed. The comparison analysis for the lateral rigidity and lateral stiffness ratios is performed by applying different methods for the project cases of shear wall, frame tube and partial frame shear wall structures. The proposed computing method may better reflect the stiffness characteristics of the component's cross-section, with regard to vertical layer, storey height and materials, as well as the actual situation of the turning constraint on both ends. The result thus determined can better reflect the real lateral rigidity of the construction, which is available as a benchmark for engineers designing hospital building structures.

KEYWORDS. Hospital building; Stiffness properties; Material.

INTRODUCTION

Stiffness and strength are two basic concepts in structural design work. Strength reflects the load resistance ability of a structural component, while stiffness reflects its ability to resist transformation. Previously, when designing ordinary and non-seismic multilayer reinforced concrete and brick structures, the component strength requirement was generally emphasized, while the rigidity requirement was ignored. But in the case of hospital building the horizontal load has become the control factor, due to its high altitude and to the fact that it has to bear a relatively high horizontal load (wind load and earthquake action), thus the horizontal load has become the control factor, and its ability to resist deformation under a horizontal load, namely, overall lateral stiffness, has become an important indicator of design control. Rigidity not only influences structural deformation, but also exerts great effect on the load-carrying capacity of structural components [1]. Structures with high stiffness feature limited deformation and a large load-carrying capacity, while structures with low stiffness feature significant deformation and a small load-carrying capacity. Thus, the ability to better control the stiffness of the whole structure and the relative rigidity of its components is a prerequisite for determining whether the building's structural system is safe, economic and reasonable [2].

MATERIALS AND METHODS

At present, the rigidity of the later layers of hospital building structures is usually measured with the following formula:

$$K_i = V_i / \Delta_i \tag{1}$$

where:

K_i is the lateral rigidity in the i^{th} layer;

V_i is the shearing force of the i^{th} layer influenced by a horizontal earthquake (lateral force);

Δ_i is the inter-story displacement of the i^{th} layer relative to the $i-1^{th}$ layer influenced by a lateral force[3].

For theoretical analysis purposes, the following problems arise among the computing methods for calculating the lateral layer stiffness of hospital building structures:

(1) the rigidity of the structural component or lateral layer is the only parameter related to the physical and geometric characteristics of the component and its composing structure, namely once the structure takes shape it becomes the inherent characteristic of the structure itself, which is only related to its own physical geometric characteristics and has nothing to do with the external load, but both V_i and Δ_i in type (1) are the calculation results determined by the lateral force, and they are inevitably related with the external load, which changes along with lateral layer rigidity [4].

(2) In type (1), inter-story displacement Δ_i is caused by a lateral force (horizontal earthquake action), when calculating the inter-story displacement Δ_i in the i^{th} layer. Its value inevitably contains the mechanical deformation influence of many vertical components in the other storeys and, therefore, cannot reflect the contribution of the vertical component's mechanical deformation in the i^{th} layer, while it is the integration of both mechanical and non-mechanical deformation. As a result, lateral rigidity K_i in the i^{th} layer, calculated by applying Δ_i, will inevitably be on the low side [5].

(3) The research indicates that the inter-story displacement Δ_i in type (1) is the combined result of the component's mechanical and non-mechanical deformation. The displacement between the upper storeys in hospital building structures is primarily the result of the components' non-mechanical deformation, while mechanical deformation tends to account for a very small proportion of the displacement; thus, as the vertical component's cross-section in this regional floor decreases or storey height increases, the rigidity of the components is significantly weakened. But the lateral layer stiffness calculated according to type (1) is almost the same or changes only slightly, which probably results in what would appear to be a deviation or miscalculation when determining the location of the weak structural layer. And the collapse in the upper floors of many hospital buildings during the Kobe earthquake in Japan is a good representative example of this [6].

(4) Under the effects of a horizontal earthquake, the story shear V_i of the structural top floor would change greatly, when the component rigidity itself of vertical layer in this area does not changes a lot, but the lateral layer rigidity calculated according to type (1) would change a lot, which is also the unreasonable representation of this method .

(5) The seismic safety of the bottom floors of hospital building structures is the concerned question of seismic design, when the storey height at the bottom of the structure has larger demands, due to building function, it tends to form a weak storey at the bottom, the lateral rigidity at the bottom determined by type (1) would be misjudged, as it does not conform to physical truth at this moment, thus it will produce problems in respect of structural seismic safety [7].

THE PRELIMINARY VALIDATION METHOD

Fig. 1 shows the vertical component of different rotational restraints on both the upper and lower ends, although the component itself has the same condition, the lateral rigidity of these components needs to be calculated using different formulas (the influence of shear deformation is excluded).

$$K_1 = 3EI/h^3 \tag{2}$$

$$K_2 = 12EI/h^3 = 4K_1 \tag{3}$$

$$K_3 = \frac{K}{1+(K_1/K_0)h^2} < K_1 \tag{4}$$

where:
E is the elasticity modulus of the component;
I is component's cross sectional moment of inertia;
h is the component height;
K_0 is the bending constraint's stiffness at the bottom, when $K_0 \to \infty$, $K_3 = K_1$.

Any floor in a hospital building structure is composed of many vertical components (walls and columns) and coterminous horizontal components. Lateral layer stiffness must be the summation of the lateral rigidity of the rotational constraints on both ends considered by this group of vertical components. Thus we can infer that when determining the lateral rigidity of the i^{th} layer ,its calculation model is shown as Fig. 2, the i^{th} layer will generate a unit horizontal displacement, while the $i-1^{th}$ has no lateral displacement, the horizontal force needed to impose on the i^{th} layer is the lateral rigidity K_i of the i^{th} layer. The lateral rigidity of the i^{th} layer, determined based on this calculation model (Fig. 2), contains the contribution of all vertical component stiffness values on this floor and considers the influence of rotating constraints on both ends. It is only the shape constant which is related to the geometric physical properties and bending constraint on both ends of the structural component in this layer, but it is unrelated with the external load. This definition could be considered to be the generalization of the single vertical component's lateral stiffness in the hospital building's structure layer.

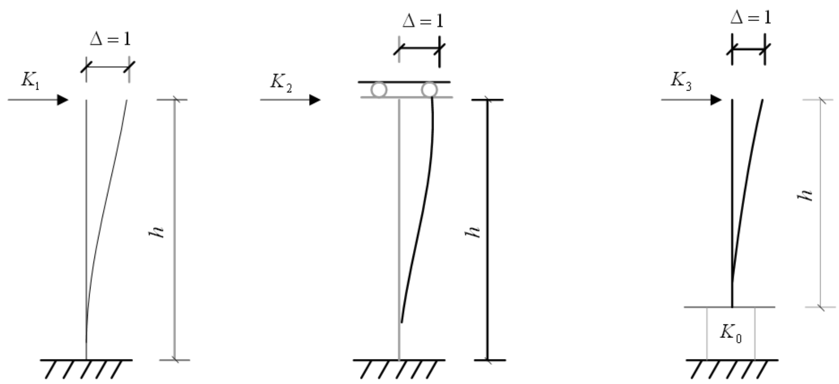

Figure1: The schematic diagram of lateral stiffness meaning for different rotational restraint components on both upper and lower end: (a) The top is free and the bottom is fixed; (b) The top is sliding and the bottom is fixed; (c) The top is sliding and the bottom is spring

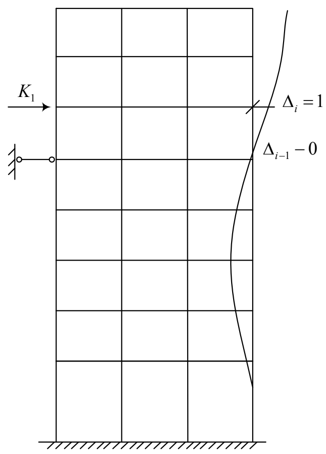

Figure 2: The calculation model of lateral rigidity in the i^{th} layer

The following takes the shear wall structure of a 4-storey hospital as an example (7 degrees, II type site). Its structural typical floor plane is shown in Fig. 3 (the thickness of the shear wall is 100 mm, the main sectional dimensions of the girders are 100×400, 100×350), the lateral layer stiffness and the ratio between them is obtained through the respective calculation by adopting the method in this paper, and type (1) is shown in Fig. 4 and 5. The calculations indicate that the lateral layer stiffness obtained according to type (1) (the new high gauge formula) is generally relatively lower. And on the upper floor, due to that inter-story displacement Δ_i, the value is heavily affected by the non-mechanical deformation of the storey's vertical component, as well as the overall structural bending; the calculation results of the inter-story displacement show a significant increase, as a result of which the calculation results of the lateral layer stiffness will be considerably low, the difference from the bottom to the top being about 2.7~16 times.

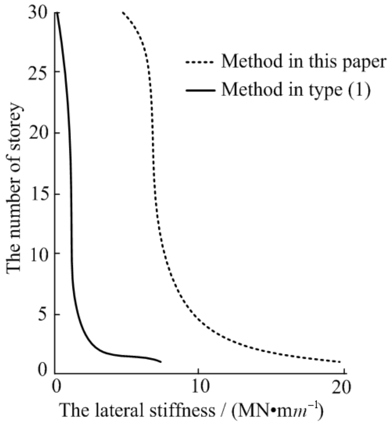

Figure 3: The comparison results of storey's lateral rigidity calculated with two methods.

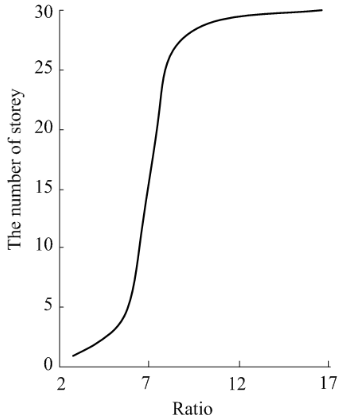

Figure 4: The calculation results of a storey's lateral stiffness ratio.

RESULTS AND DISCUSSION

With regard to the high gauge calculation of the lateral rigidity of a hospital building's structural layer, the following type is applied to obtain the lateral layer stiffness ratio γ_i between the next floor (the i^{th} layer) and the adjacent upper floor (the $i+1^{th}$ layer):

$$\gamma_i = \frac{V_i}{V_{i+1}} \frac{\Delta_{i+1}}{\Delta_i} \tag{5}$$

Through observing the size of lateral layer stiffness ratio γ_i, whether the i^{th} layer will form weak storeys or not, due to relative low rigidity, should be determined according to the limiting value specified by the high gauge, and corresponding seismic strengthening measures should be adopted, thus the calculation results of the stiffness ratio for the lateral layers will directly influence structural design.

The ratio between interlayer displacements angles should be the basis for determining whether the i^{th} layer will appear as a weak storey, the specifications are shown in the following type:

$$\gamma_i = \frac{\Delta_{i+1}}{\Delta_i} \frac{h_i}{h_{i+1}} \tag{6}$$

The calculation results of type (5) and (6) feature obvious qualitative differences under certain situations. For the structure of box shear, shear wall and frame-tube etc in the high gauge, the original stiffness ratio of the lateral layer is added with the storey height ratio as its amendment, compared with the formula [type (5)], the following formula will be adopted to calculate the lateral layer stiffness ratio:

$$\gamma_i = \frac{V_i}{V_{i+1}} \frac{\Delta_{i+1}}{\Delta_i} \frac{h_i}{h_{i+1}} \tag{7}$$

The type (5) and type (7) in the new high gauge will be compared; it is not difficult to see that their difference only regards the storey's shear ratio V_i / V_{i+1} in type (5), which is amended by the storey height ratio h_i / h_{i+1} in type (7).

The partial framed shear wall with transformation storey is widely applied in hospital building structures, as the shear wall of the partial transformation storey cannot collapse, thus the number of shear walls under the transformation storey decreases and the lateral layer stiffness of the storey is weakened, which requires the calculation of the method of lateral layer stiffness for both upper and lower storeys, in order to accurately determine whether the weak layer will appear on the transformation layer or not and what measures should be adopted to strengthen it, all of which are very important to guarantee the seismic safety of the structures [8].

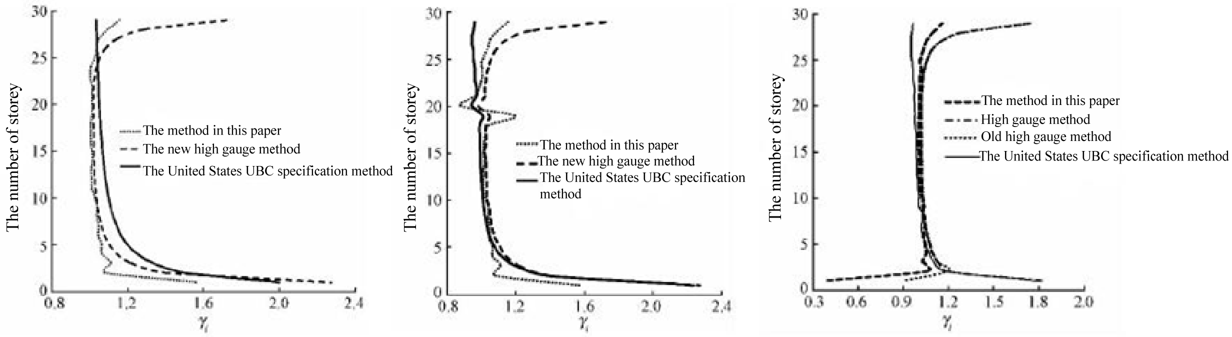

Figure 5: The comparison of the lateral layer stiffness ratio

The lateral layer stiffness comparison of the upper and lower structure layers in the transformation layer generally only considers the shear deformation of the shear wall. If we suppose that both ends of the column undergo no rotation, the calculation formula for the approximate layer's total lateral stiffness k_i of bending deflection will be considered, namely:

$$k_i = \frac{GA_i}{h_i} \tag{8}$$

where:

$A_i = \sum_j A_{wji} = A_{wi}$, A_{wi} is the effective cross-section area of the entire shear wall on the i^{th} storey along the calculation direction (excluding the flange area);

h_i is the storey height of the i^{th} layer;

G is the shearing modulus of elasticity of the shear wall concrete on the i^{th} storey.

When the storey features columns, A_i should still contain the lateral rigidity when assuming that both ends of the pillar have no rotation, which is approximated by the following type:

$$A_i = A_{wi} + \sum_j C_{ij} A_{cij} \tag{9}$$

$$C_{ij} = 2.5\left(\frac{h_{cij}}{h_i}\right)^2 \tag{10}$$

where:

h_{cij} is the cross-section height of the j^{th} pillar on the i^{th} storey along the calculation direction.

It is explicitly stipulated in new high gauge that when the transformation storey is on the 1^{th} and 2^{th} layer, the equivalent shear stiffness ratio between the transfer storey and its adjacent superstructure could be adopted to represent the upper and lower structural change of structural stiffness on the transfer storey.

When the transfer storey is on the 1^{th} storey,

$$\gamma_1 = \frac{G_1 A_1}{G_2 A_2} \frac{h_2}{h_1} \tag{11}$$

where:

h_1, h_2 is the storey height of the 1^{th} and 2^{th} layer.

When the transfer storey is on the 2^{th} layer,

$$\gamma_2 = \frac{G_2 A_2}{G_2 A_3} \frac{h_3}{h_2} \tag{12}$$

where:

h_3 is the storey height of the 3^{th} layer.

Eq. (8) ~ (12) indicate that the lateral layer stiffness of the transfer storey is obtained by supposing that the shear wall's vertical components on this floor only consider the shear deformation. And supposing that there is no relative sideway unit generated from the corner of the pillar's two ends, the shearing force at that moment is its lateral rigidity [9].

The merit of this calculation method is to denote the lateral rigidity of the structural sheaf with the only related shape constant to the geometry and physical properties of the structure layer's vertical component itself, while it has nothing to do with the external load. This is correct, but the essence of this method is to assume the rotation constraint of the vertical component's two ends as infinite rigidity constraints, and that the overall horizontal component is not in a rotational state. When the i^{th} storey generates a sideway unit $\Delta_i = 1$, the horizontal force needed to be exerted is k_i, as it is shown in Fig. 6. It is not in accordance with Fig. 6, especially when it is on the upper and lower floor of the transfer storey (when the transfer storey is on the 2^{th} storey), the flexural rigidity of the horizontal component is generally not large, but quite at odds with the assumed infinite rigidity, even though the flexural rigidity of the beam and slab on the transfer storey is relatively large, it also has a large gap with the infinite rigidity assumption, as a result of which the rationality and accuracy of this calculation methods still needs further research [10].

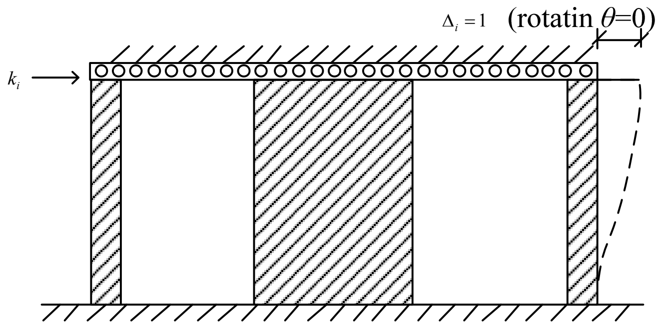

Figure 6: Calculation model of the new and old high guage's lateral rigidity

Based on the above analysis, we can see that the meaning of stiffness ratio is different for different structures, which means that the calculation results may vary widely, which deserves attention in the design phase. Hospital buildings should first consider using uniform stiffness to achieve uniform deformation, meanwhile with the increase in height a more rigid structure should be adopted to reduce the deformation. When the structure of framed shear wall must be adopted, the location of the transfer storey should be reduced as far as possible to decrease the number of weak storeys and overall structural deformation, which is beneficial to structural safety. When there is an annex, the transfer storey should be set up on the annex's surface. If the annex area is large, the pillar and shear wall etc. must have many components to resist lateral force, and rigidity will be greater. The transfer storey should be set up on this layer in favor of resistance to lateral forces, meanwhile it is relatively easy to comply with the specification about the stiffness ratio. In addition, for the structure of the framed shear wall, the storey height of the upper layer on the transfer storey should be enhanced as much as possible. The equipment interlayer with the short storey height must not be built up on the upper layer of the transfer storey. As the equipment interlayer is the shear wall structure, which itself is very rigid, in addition to its short storey height and little deformation, all of which would intensify the stiffness and deformation mutation of the transfer storey, which is not beneficial to the safety of the transfer storey. Meanwhile, in order to make the overall structure comply with the specification about the related requirements of the stiffness ratio between the layers, higher construction costs should be added. According to the above analysis, we can see that structural stiffness and deformation are mainly related to the number of shear walls and storey height. Thus dissatisfaction with the stiffness ratio's requirement should be managed by regulating the number of shear walls and storey height.

CONCLUSIONS

This paper has discussed the calculation methods of lateral rigidity and its ratio on hospital building's structural layers and pointed out that some problems exist in this respect, as well as suggested methods for their solution [11]. Furthermore, it points out that the calculation method of the structural lateral rigidity on the transfer storey is essentially the calculation method of the layer shear stiffness, assuming that the transfer storey and horizontal component stiffness of its corresponding upper and lower storey is infinitely rigid. Although it reflects the stiffness characteristics of the vertical component's cross-section, storey height and material, the rotation constraints on both ends are supposed to be infinitely stiff, which is not in accordance with reality, and results in too high a lateral layer stiffness, the imbalance range is different in different cases, thus it would result that the calculation results of the lateral layer stiffness ratio is too small or big, so it is difficult to determine beforehand and is disadvantageous for the accuracy and reliability of physical design. Adopting the suggested calculation methods could better reflect the component cross-section of the vertical layer, storey height and stiffness characteristics of material, as well as the actual state of the rotation constraints on both ends, thus the calculation results could better reflect the real lateral stiffness of the transfer storey's structure, which could solve the existing confusion in the engineering field with regard to this problem [12].

REFERENCES

[1] Lian, W., The symposium about the displacement control of hospital building structure, Architectural structure, 30(6) (2000) 27-30.

[2] Xin, W., Hao, Z., Yun, G., Study on the safety assessment system of buildings, Industrial Safety and Environment Protection, 36(9) (2010) 56-57.

[3] Baojun, P., Tao, Z., Shanyi, D., Analysis for the mesoscopic computational mechanics of effective elastic modulus in three-dimensional and multi-directional braided composites, Chinese Journal of Computational Mechanics, 18(2) (2001) 231-234.

[4] Shanyuan, W., Ruguang, Z., et al., Fibre reinforced composite material, China's textile industry university press, (2008) Version 1.

[5] Ko, F. K., Three-dimensional fabrics for composites-an introduction to the Magnaweave Structure, Proc. ICCM-4, Japan Soc. Composite Material, Tokyo, Japan, (2012).

[6] Ko, F. K., Pastore, C. M., Structure and Properties of and Integrated3-D Fabric for Structural Composites, In Recent Advances in Composites in the United States and Japan, ASTMSTP 864, Vinson, J. R. & Taya, M. Editors, Philadelphia: American Society for Testing and Materials, (2005) 428-439.

[7] Ma, C. L., Yang, J. M., Chou, T. W., Elastic Stiffness of Three-Dimensional Braided Textile Structure Composites, In Composite Materials: Testing and Design (seventh Conference), ASTM STP, Philadelphia, 893 (1986), 404-421.

[8] Lian, W., Sen, W., Renfan, S., Computing method research for lateral rigidity of high-rise building structure layer, Architectural structure, 44(6) (2014) 4-9.

[9] Kostar, T. D., Chou, T. W., Design and Automated Fabrication of 3-D Braided Performs for Advanced Structural Composites, Computer Aided Design in Composite Material Technology III, Elsevier Science, (2009) 63-78.

[10] Hongchang, W., Analysis and design for combined action of supporting column transfer beam and upper frame, Hunan University, (2012).

[11] Wang, Y. Q., Sun, X., Determining the Geometry of Textile Performs Using Finite Element Analysis, In: Proceedings of the American Society for Composites, College Station, Texas, September 25-27, (2009) 485-492.