Analysis on the Evaluation Method of In-Plane Rigidity Performance of Floor System

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Abstract. Structural analysis usually divides the rigidity performance of floor system into three types: rigid, stiff and flexible. For specific engineering buildings, how to evaluate their rigid performance, there is no uniform regulation in national regulations. Based on the general analysis of the relative specifications and research contents of the rigid performance of the floor, two types of analysis and evaluation methods of the rigid performance of floor system are summarized, type I and type II method. The type I method is more convenient to use. The type II method can directly reflect the essence of the rigid performance of the floor, but it is more complicated to use.

1. Introduction
In structural analysis, we usually use the floor rigidity assumption. This assumption can meet the accuracy requirements of structural analysis in many cases, and it also greatly reduces the freedom of structural analysis, which brings great convenience to structural analysis and design. However, the true performance of the horizontal loaded floor is not the rigid body. It has only limited bending and shear stiffness, and will produce corresponding in-plane deformation. Such a performance has great impact on the seismic performance of the overall structure[1-3]. Article 3.6.4 of China's seismic design code (GB50011-2010)[4] provides: for seismic analysis of structures, transverse partitions of rigidity, block stiffness, semi-rigidity, local elasticity and flexibility shall be determined according to the plane shape of the building and the roof, and the deformation in the plane, then the resistance shall be determined according to the arrangement of the anti-lateral force system. Co-work between lateral force members and analysis of seismic internal forces between components. The above provisions clearly put forward the requirements for the analysis and evaluation of the in-plane stiffness performance of the floor during the seismic analysis of the structure, but it does not give a specific analysis and evaluation method, so the operability is not strong in the actual application. Based on the comprehensive analysis of relevant research at home and abroad, this paper systematically summarizes and compares the analysis and evaluation methods of the rigid performance of the building, and provides reference for the analysis and evaluation of the rigid performance of the concrete building.

2. Relationship between the in-plane stiffness and rigidity of the floor system
The rigidity performance and the stiffness of floor system in the plane are two different concepts, but there is a certain correlation between the two. The in-plane stiffness of the floor system generally includes the bending stiffness and the shear stiffness, and both of them are generally defined by the expressions (1) and (2) respectively.
\[ B_f = \frac{EI_f}{11.5EI_f + GA_fL^2} \]  

(1)

\[ K_l = \gamma l \left[ 1 + \frac{1}{3} \left( \frac{L}{B} \right)^2 \right] \]  

(2)

Where: \( L \), \( B \) is the length and width of the floor respectively, \( A_f \) is the sectional area of the floor, \( LB^{-1} \) is the aspect ratio of the floor, \( I_f \) is the cross sectional moment of inertia of the floor, \( E \), \( G \) is the elastic modulus and shear modulus of the floor material, \( \gamma \) is the correction factor of the rectangular section of the floor considering the shear deformation, and \( l \) is the opening size of the floor. For fabricated floor systems, horizontal equivalent shear stiffness is also generally defined as follows.

\[ k = \frac{V}{\Delta} \]  

(3)

Where: \( L \) is the length of the floor slab, \( V \) is the horizontal shear force, and \( \Delta = y_{ss} - y_s \) (see Fig 1)

According to the discussion of the concept of mechanics in [5], it is pointed out that for the stiffness in the plane of the floor, the expression of shear stiffness is more reasonable than the bending stiffness. Generally speaking, the stiffness in the plane of the floor is the shear stiffness of the floor. Or horizontal equivalent shear stiffness.

Rigidity performance of the floor system refers to the ability of the floor to distribute and transmit the horizontal force and coordinate the deformation of the surrounding lateral resistance components under the horizontal load. Generally, it can be classified as three types: rigid, flexible and semi-rigid floor. It has been pointed out in the literature [6] that the rigidity of the floor is not only related to the in-plane stiffness of the floor itself, but also to the stiffness and distribution of the lateral resistance components. That is to say, the rigidity of the floor is a relative concept, and its analysis and evaluation should not only be based on the stiffness of the floor, but also be based on the stiffness of the corresponding lateral resistance structure. In the process of structural analysis, the rigid performance of the floor should be first analyzed and evaluated. Only after the rigidity of the floor is clarified can the corresponding to structural modeling and analysis methods be applied.

3. Analysis of the evaluation method of the rigid performance of the floor

As mentioned above, floor system can be divided into rigid floor, flexible floor and semi-rigid floor based on the different rigid properties, but how to assess whether a given building system is rigid, flexible or semi-rigid, there is still no unified standard. Comprehensive analysis of domestic and international correlative standards and research work, the analysis and evaluation of the rigid
performance of floor system can basically be summarized as the following two kinds of evaluation methods.

3.1. Type I evaluation method
This type of evaluation method is mainly based on the comparison between the relative deformation of the floor itself and the average lateral deformation of the adjacent anti-later resistance structure. The analysis and evaluation of the rigid performance of the floor system in the United States and Iran are basically based on this kind of evaluation method.

3.1.1. American code. FEMA273 [7], ASCE7-16 [8], and ASCE/SEI-41-17 [9] in the United States have clearly defined the classification of the rigid performance of the floor system based on a evaluation index \( \lambda \). Such the index is defined as the ratio of maximum in-plane relative deformation of the floor and the average story drift of the vertical lateral force-resisting elements of the associated story (As shown in equation 4). When \( 0.5 < \lambda < 2 \), the floor was assessed as a rigid floor, when \( \lambda > 0.5 \), the floor was assessed as a flexible floor, and when \( 0.5 \leq \lambda < 0.5 \), the floor was assessed as an elastic floor.

\[
\lambda = \frac{\Delta_{MDD}}{\Delta_{ADVE}}
\]  

(4)

Figure 2. Schematic diagram of rigid performance evaluation of floor system.

In addition to the above displacement ratio determination, ASCE 7-16 [8] also stipulates that for the lightweight floor system and the wooden floor system of the profiled steel plate, when the structural anti-side system is a supporting steel frame, a concrete shear wall or a steel-concrete When the shear wall is combined, the floor cover is directly judged as a flexible floor; and for a concrete floor or a profiled steel plate, when the span/width of the floor is not more than 3 and the floor plan is regular, the floor can be judged as Rigid floor; the latest ASCE/SEI-41-17 [9] further stipulates that the profiled steel floor combination cover is such that when the span/width of the floor is not more than 5 and the floor plan is regular, the floor meets the rigid floor assumption.

3.1.2. Iran code. The structural seismic design code of Iran [10] has the same parameters (\( \lambda \)) as the US regulations for the evaluation of rigid performance of floor system. Both of the two codes adopt the ratio of the maximum displacement in the plane of the floor to the average lateral displacement of the floor as the evaluation index, but the value of the index for design code of Iran is not in line with that of the United States. According to Iranian regulations, a floor system can be regarded as rigid floor if the evaluation index \( \lambda < 0.5 \), once the index \( \lambda \geq 0.5 \), the floor system will be regarded as stiff floor and the in-plane deformation of the floor should be considered during the structural analysis.

3.2. Type II evaluation method
This type of evaluation system is mainly based on the deviation comparison of force and deformation performance of floor between the two situation of considering the actual stiffness in floor plan and adopting the assumption of rigid floor. The evaluation system is mainly based on the summary of relevant
test and analysis results of the cast-in-place concrete floor system. It usually includes the following three methods of analysis and evaluation:

3.2.1 Method based on deformation deviation comparison At present, the European Code (EC8, 2004)[11] uses a method based on the comparison of deformation deviations for the analysis of the rigidity performance of the floor. The evaluation method considers that when the deformation deviation in the plane of the floor is not more than 10% between the two case of considering the in-plane actual stiffness of the floor and adopting the assumption of rigid floor, the floor system can be regarded as a rigid floor, otherwise the building floor system should be regarded as an elastic floor, and the in-plane deformation performance of the floor structure should be considered during structural analysis.

3.2.2 Method based on comparison of load transfer performance deviation The evaluation method is based on the distribution-transfer performance of the horizontal force of the floor system to judge the in-plane rigid performance of the floor. Investigating the horizontal force distribution-transfer performance deviation in the two cases of considering the in-plane actual stiffness of the floor and adopting the assumption of rigid floor, the rigidity performance of floor system can be evaluated. Xi’an Zhao[12] proposed that the floor seismic shearing force can be regarded as a rigid floor when considering the calculation result of the floor stiffness and the deviation of the assumed calculation result of the rigid floor is not more than 8%, otherwise it should be regarded as the elastic floor. In the process of structural analysis, the deformation in the plane of the floor itself is considered. The literature[13] believes that the floor cover can be regarded as a rigid floor when the deviation between the two is less than 10%.

3.2.3 Comprehensive comparison method of deformation deviation and load transfer performance deviation Ju and Lin[14] proposed an in-plane rigid performance analysis and evaluation method for the floor system of frame-shear wall structure, taking into account the floor system in two cases: considering the in-plane actual stiffness of the floor and adopting the assumption of rigid floor. The method gives a rigid performance evaluation index R and the internal force deviation parameter (Error) of the column end as shown in formula (5) and formula (6):

\[ R = \frac{\Delta_{\text{flexible}} - \Delta_{\text{rigid}}}{\Delta_{\text{flexible}}} \]  \hspace{1cm} (5)

\[ \text{Error}\% = 100 \cdot \frac{\sum_{i=1}^{n} \sum_{j=1}^{4} M_{r,ij} - M_{f,ij}}{\sum_{i=1}^{n} \sum_{j=1}^{4} M_{f,ij}} \]  \hspace{1cm} (6)

Where \( \Delta_{\text{flexible}} \) is the average displacement of the floor system considering the deformation of the floor itself; \( \Delta_{\text{rigid}} \) is the average displacement of the floor system when the rigidity assumption is adopted; \( n \) is the number of floor frame columns; \( M_{r,ij} \) is in the assumed case of the rigid floor, the bending moment of the two main axes in the two ends of the i-th column; \( M_{f,ij} \) represents the bending moment of the two main axes in the two ends of the i-th column considering the actual in-plane stiffness of the floor. By regression analysis of R and Error, the regression analysis expression of the stiffness performance index R and the internal force deviation (Error) of the column end is obtained: \( \text{Error}\% = 81.53R + 3.8 \). Through the comprehensive consideration of the deviation of displacement and the performance of the load, the evaluation criteria of the in-plane stiffness of the floor system are determined as follows: when \( R \leq 0.2 \), the deviation of the load performance (Error%) does not exceed 20%, and the floor can be regarded as Rigid floor; otherwise, the floor system should be considered as an elastic floor.

Literature[15] carried out an analysis similar to Ju and Lin[14]. The frame-shear wall structure for the opening of the floor in the rectangular plane is also given a similar evaluation and evaluation method for the rigidity of the floor. Only the regression expression of the evaluation index R and the internal force deviation of the column end obtained by the regression analysis is summarized as the form of the
formula (7). The corresponding floor stiffness performance evaluation criteria are: when $R \leq 0.3$, the load-bearing performance deviation ($\text{Error} \%$) does not exceed 20%, the floor cover can be regarded as a rigid floor; otherwise, the floor system should be regarded as an elastic floor Structural deformation is considered in its own plane.

\[
\text{Error} \% = \begin{cases} 
37.72R + 7.39 & 0 < R \leq 0.85 \\
317.59R - 230.71 & 0.85 < R < 1
\end{cases}
\] (7)

4. Conclusion
Through the general analysis of the relative specifications and research contents of the rigid performance of the floor, two types of analysis and evaluation methods of the rigid performance of floor system are summarized. The analysis shows that, by comparing the force-transfer and deformation performance of the floor system under the two cases of considering the in-plane actual stiffness of the floor and adopting the assumption of rigid floor, the evaluation method of the second type directly reflects the essence of the rigid performance of the floor (the ability of the floor system to form a rigid floor), it should be a widely adaptable evaluation method. However, such a method is more complicated than the Type I evaluation method because of the need to investigate the deformation behavior of the floor under two in-plane stiffness conditions. During the actual operation, the type I evaluation method is more convenient to use.

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