Comparison of Practical Calculation Methods for Overall Frame Structures with Filler Walls

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Abstract: At present, the calculation of filler wall in building structure industry is usually implemented by the method of cycle reduction. However, the empirical coefficient proposed by the cycle reduction in view of standard is not accurate. The factors such as the number of filler walls and the rate of opening holes in the structure have different effects on the stress of the structure. Because the stiffness degradation of filler wall is different at different floors and under different stress conditions, the determination of equivalent diagonal bracing width is more complicated. It has been a controversial issue that how the new damping filler wall in the industry to establish an effective formula for calculating the cross-section width of equivalent diagonal brace to be applied to the elastic calculation of the first stage of the seismic and the elastic-plastic calculation of the second stage of the seismic in the case of large earthquakes.

1. Introduction

In the 2008 Wenchuan earthquake with magnitude 8.0, the infilled wall in the frame structure was destroyed in a large area, resulting in incalculable losses. In view of this, it is of great significance to study its seismic performance[1]. The stiffness effect and intensity effect of the filler wall have great influence on the stress state, period and seismic response of frame structure and so on. The periodic reduction model is adopted in the design of infilled wall structure according to the Chinese design code. The horizontal seismic action calculated by the model is not distributed by the filler wall, but by the frame structure. From the case of repeated earthquake damage, we could know that simply consider the effect of infilled wall by pure frame period reduction method can't reflect the real structural response, especially in the case of large openings in the structure.

Therefore, at present, the sophisticated finite element model is more accurate for the calculation of the frame structure with filler wall. However, the sophisticated finite element model has large amount of calculation, which takes up more computing resources, consumes time and not easy to converge. Moreover, the more refined the model will introduce more assumptions and may cause more errors. In order to solve the limitations of refined models, scholars have proposed various equivalent diagonal bracing model, which is widely used in the research field of frame structure with filler wall. And It is difficult to determine its width accurately because of many influencing factors. Therefore, through comparing, a more convenient analytical method suitable for structural design is gained by analysis.
2. Comparison of Various Calculation Methods
The stiffness of frame structures with filler walls is constantly changing under the action of horizontal force such as earthquake. Especially for filler walls, the failure stage of them generally has four stages. From the four stages of failure, in the first stage, the filler wall and the frame are bonded together to form a whole, the contribution of the filler wall stiffness is the largest at this time, but its duration is very short, so filler wall obviously can’t be used for design; in the second stage, from peripheral cracks to wall cracks, reinforced concrete frame generally does not appear cracks, and the entire structure is basically in elastic state. In the third stage, cracks appear on the wall and continue to expand until it runs through continuously along the whole wall width, and the stiffness of the filler wall decreases continuously and degenerates obviously; in the fourth stage, the stiffness of the filler wall can be neglected, and almost all the horizontal forces are borne by the frame, so in the case of frequent earthquakes, the failure mode of infilled wall second stage is mainly discussed by this paper. In this paper, three models are established on the basis of the proposed example model. The first model is a pure frame model considering the dead load of filler wall and the reduction cycle coefficient is 0.7. The second one is an infilled frame structure considering the dead load and stiffness of filler wall. The third one is to use the theory of equivalent diagonal bracing formwork to establish an infilled frame wall structure considering the dead load and stiffness of the filler wall in order to study the influence of filler walls on the seismic behaviour of frame structures.

3. An Analytical Example of Filler Wall with Openings

3.1. Engineering Situation
A building is a 7 floors infilled frame structure with a height of 3.6m, and the planar of column net is shown in Figure 1. The column cross section is 700mm * 700mm and the beam section is 200mm * 600mm. Concrete strength grade is C30, elastic modulus is 3*10^4MPa, filler wall thickness is 200mm, brick strength grade is MU10, mortar strength is M5, masonry elastic modulus 2.4*10^3MPa, mass density 19 KN/m^3. The main reinforcement of all beam and column of all beam and column is HRB400, and the stirrup is HRB400, the thickness of the plate is 100mm, the live load of the floor is 2KN/m^2, and the transverse load of the floor is 1.5 KN/m^2. The fortification intensity is 8 degree and class III site. The design earthquake is grouped into the first group.

![Figure 1. Structural standard floor planar graph.](image)

3.2. Finite Element Modeling Parameters
In this paper, the concept of equivalent diagonal brace is used to analyze and model. Solid element is adopted in the whole frame structure, and the diagonal brace element is defined according to the relationship between force and deformation. The dead weight of filler wall is equivalent to dead load applied to the frame beam. The equivalent diagonal bracing width is determined by the formula of member width (See Equation (1) and Equation (2)) proposed by R. J. Mainstone in 1974 in the basic
of Polykao Equivalent bracing model. The stiffness of diagonal bracing is determined by Equation (3) and Equation (4)[3]. The concrete examples are divided into three cases. The first case is to consider the dead load of filler wall and adopt the pure frame model of frame cycle reduction factor which is 0.7 provided by Technical Specification for Concrete Structures of High-rise Buildings[2]; the second case is to consider the dead load and stiffness of filler wall; the third case is an infilled wall structure considering the dead load and stiffness of the filler wall is established by using the theory of equivalent diagonal brace; the fourth case is to simulate the damping infilled wall by using the theory of equivalent diagonal brace, and the concrete model is shown in Figure 2.

Filler wall width:

\[ \lambda = \sqrt{\frac{E' \sin 2\theta}{4EI_hh}} \]  

(1)

“E”, “E’” are the elastic modulus of masonry and concrete, “t” is the thickness of wall, “I_{h}” is the moment of inertia of column section, “h” is the height of wall, and “\theta” is the angle between diagonal line and beam.

\[ W = 0.175(\lambda h)^{-0.4}d \]  

(2)

“h” is the column height of periphery frame.

Filler wall stiffness:

\[ K_w = \sum \frac{1}{\delta_s + \delta_s} = \frac{E_w \cdot t}{h/b[(h/b)^2 + 3]} \]  

(3)

Equivalent diagonal bracing stiffness:

\[ K_0 = \sum \frac{\beta K_w \cos^2 \theta}{\cos^2 \theta \cdot h/b[(h/b)^2 + 3]} \]  

(4)

Figure 2. Diagrams of each analysis model.

3.3. Analysis of Calculation Results

Table 1. Multiple cycle comparisons of different models.
3.3.1. Modal Analysis
Model analysis was carried out on the four models, respectively, the model with cycle reduction coefficient of 0.7, the model of filler wall with opening holes, the model with equivalent diagonal brace and the model of filler wall with damping. The first three cases of self-vibration period were obtained, and the theory of equivalent diagonal brace was verified and analyzed. See Table 1 for details. According to the comparison of the first 7 natural vibration periods of model 2 and model 3, it is found that the natural vibration period of the two models is basically same. In view of the above results, the equivalent bracing theory is applied to the simulation analysis of filler walls. According to the comparison of the first seven natural periods between model 1 and model 3, it is found that there is a big gap between the two models. In view of this result, it is concluded that the cycle reduction coefficient given in the code is affected by the number of infilled walls, the area of openings and other factors, so the empirical values provided in the code can’t be used blindly.

3.3.2. Interlaminar Displacement Angle and Interlaminar Maximum Shear Force
Analysis of interlayer displacement angle and interlaminar shear force of the four models under seismic force, it is found that there are some defects in the periodic reduction coefficient proposed in the current domestic codes. In this example, if the method of cycle reduction is adopted, the interlaminar maximum shear force is smaller and interlaminar displacement angle is larger than that obtained by the model of filler wall and the equivalent diagonal bracing. The floor location of the interlaminar displacement angle changes. In view of this, there is a phenomenon of force breaking away from structure. See Figure 3 for details.

| mode | (Total mass: 4972.791t) | (Total mass: 5015.660t) | (Total mass: 4972.791t) | (Total mass: 4972.791t) | f | Model 2 |
|------|-----------------|-----------------|-----------------|-----------------|---|--------|
| 1    | 1.2201          | 0.4941          | 0.4520          | 0.4479          | 0.914795 |
| 2    | 1.1218          | 0.4262          | 0.3944          | 0.3929          | 0.925387 |
| 3    | 1.0876          | 0.3961          | 0.3740          | 0.3727          | 0.944206 |
| 4    | 0.3601          | 0.1582          | 0.1473          | 0.1471          | 0.931099 |
| 5    | 0.3335          | 0.1337          | 0.1242          | 0.1240          | 0.928945 |
| 6    | 0.3283          | 0.1199          | 0.1118          | 0.1114          | 0.932444 |
| 7    | 0.1816          | 0.0796          | 0.0741          | 0.0744          | 0.930905 |
3.4. Analysis of Damping Filled Wall

3.4.1. Engineering Situation

At present, more and more research on the filler wall are conducted in the industry. Therefore, it is of great significance to study the calculation of the model of the new damping filled wall[4]. In this paper, the equivalent diagonal bracing model is used to simulate the filler wall and the damping of the damping layer is simulated by setting dampers in the diagonal bracing. In this case, a EI - Centro seismic wave (See figure 4 for details) is used to analyze the rare earthquakes in the 8 degree area. The interlaminar displacement angle and Interlaminar maximum shear force are compared between the model of equivalent diagonal brace and the model of filler wall with damping. Furthermore, the performance analysis of the damped members in the equivalent skew brace model with damping and the performance influence of the most integral structure are carried out.
3.4.2. The Result of Calculation and Analysis
According to the calculation and analysis, the calculation results can be seen in detail (see Figure 5). According to the calculation results, it can be concluded that the interlaminar displacement angle and interlaminar maximum shear force in the X direction of the structure with the model of damping equivalent diagonal braces are reduced compared with the model of only equivalent diagonal braces. The diagonal brace with damping has good energy dissipation under the effect of rare earthquakes.

![Figure 4. EI Centro seismic wave.](image-url)
4. Example of filler Wall with Different Floor Number

4.1. Establishment of Example Model
This example is based on three different calculation methods for frame structures with different number of stories. Case 1 is a pure frame without filler walls; case 2 is an equivalent model based on equivalent diagonal bracing theory; case 3 is a solid filler wall model. The number of floors analyzed is shown in figure 6.

4.2. Comparison and Analysis of Calculating Example Results
According to the calculation results, the number of stories different floors is compared under different algorithms. The quality of specific floor is shown in Table 2, and the detailed results of cycle comparison are shown in Figure 7. According to the results of the chart, the basic period ratio of the tension-compression diagonal bracing model and the model of filler wall as well as the model of pure frame is between 0.670 and 0.699, which is stable and the rule is reliable. The calculated period ratio is between periodic reduction factor 0.6 and 0.7[5], which is consistent with the code. It shows that it
is reasonable to determine the width of the equivalent diagonal brace according to the principle of stiffness equivalence and consider the stiffness of the filler wall.

Table 2. Quality of different floor height (t).

| Stories numbers | No filler wall model | Bracing model | Filled wall model |
|-----------------|----------------------|---------------|------------------|
| 3               | 464.159              | 465.078       | 468.82           |
| 4               | 628.094              | 629.014       | 629.53           |
| 5               | 792.03               | 792.949       | 793.14           |
| 6               | 955.965              | 956.885       | 957.56           |
5. Conclusion

Based on the above analysis, the following conclusions can be drawn:

(1) It is proved that the concept of equivalent diagonal bracing of the infill wall can be used in the structural calculation of infilled walls, which provides a reference for the calculation method of infilled walls in the industry.

(2) At present, the periodic reduction coefficient of frame provided in the Technical Specification for Concrete Structures of High-rise Buildings in China is 0.6-0.7, which is not accurate. The accurate periodic reduction factor needs to consider the influence of various factors such as the number of filled walls, the area of opening holes. However, for full-filled walls, the reduction factor provided in the specification can be adopted.

(3) The damped infill wall can be simulated by the damped equivalent diagonal bracing model. The axial stiffness of diagonal braces is provided by the stiffness of filling walls and diagonal braces respectively, and the damping of diagonal braces is provided by dampers, and it provides a reliable calculation method for this new infilled wall structure.

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