Finite Element Analysis of Dynamic Time History of Steel Frame Structure Filled with Rubber Brick

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Abstract. Studying the influence of rubber brick infilled wall on the seismic performance of steel frame has theoretical and practical significance for the use of materials in civil engineering industry. The modal analysis of SF, RSF, LSF, R1SF and R2SF, and the nonlinear dynamic time history analysis under the action of two actual seismic waves and one artificial seismic wave are carried out by using the large finite element analysis software ABAQUS. Based on the comparison of the infilled wall materials and the layout of the infilled wall, the influence of the structural frequency and the maximum horizontal displacement is analysed. The structure of the study indicates that: under the action of seismic waves, the natural vibration frequency of the whole structure is reduced by adding the rubber brick infilled wall, and the increasing speed of the natural vibration frequency of the whole structure is slowed down. Under monotonic and low-cycle reciprocating loads, rubber brick filled walls can effectively improve the bearing capacity and lateral stiffness of the whole structure, improve the stress concentration of frame columns, but weaken the energy dissipation capacity of the whole structure.

Keywords. rubber brick, finite element analysis, dynamic time history analysis, filled wall steel frame, low cycle reciprocating load.

1. Introduction
With the rapid development of the automobile industry, the production of waste rubber tires is increasing, which has become one of the main industrial wastes[1]. In recent years, many scholars carried out a lot of research on the recycling methods of waste rubber, the most common treatment method is to crush or grind them into rubber particles with different particle sizes, which are applied in industries, agriculture, public construction and other fields[2]. Based on this, a kind of autoclave free brick is put forward, which is made of rubber powder instead of coarse and fine aggregate in concrete. Rubber brick has low cost, which can effectively reuse resources and relieve environmental pressure. As a new type of industrial system, steel structure house has the advantages of high integration, good structural stability and convenient construction. The residential structure system, which is listed as the main promotion by the construction department, has been recognized and supported by the construction industry[3]. At the same time, many cities in our country are in the seismic zone, so it is necessary to study the methods to improve the seismic performance of building structures. Steel structure has good ductility, energy absorption and energy dissipation capacity, but the anti lateral
displacement capacity is poor, so it needs to add lateral support to improve the anti lateral displacement capacity of the structure. The rubber brick with small density, light self weight and good damping characteristics is very suitable to be used as the lateral support of the infilled wall in the steel structure residence. At the same time, it can effectively improve the seismic performance of the whole structure.

At present, scholars at home and abroad mainly focus on the improvement and application of rubber concrete materials, not too much research on the application of rubber powder in masonry materials. Based on the investigation and analysis of the research status and development trend of waste rubber tire recycling and infilled wall steel frame structure at home and abroad, the main research content and path of this paper are formulated: the pure steel frame structure and infilled wall steel frame structure are modeled by the finite element analysis software ABAQUS, and the dynamic time history of each model is analysed. The influence of infilled wall material and infilled wall arrangement on the seismic performance of the structure is discussed.

2. Material constitutive model
In this simulation, Q235 welded I-beam was used. The steel column is HW 300×300×10×15, and the steel beam is HN 400×200×8×13. The infill wall is 200mm thick, the wall material is rubber brick and lime sand brick, and the strength is MU10. The infill wall is modeled as a whole, and the masonry materials are all modeled as plastic-plastic damage.

2.1. Constitutive model of steel
In this simulation, a double-fold line model was used for the steel[4]. The constitutive relationship curve of steel is shown in Figure 1. To ensure the convergence of the model, this simulation takes Er = 1 / 50Es.

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\frac{\sigma}{\sigma_{\text{max}}} = 1.2 - 0.2 \left(\frac{\varepsilon}{\varepsilon_0}\right) \quad \varepsilon > \varepsilon_0 \quad (1.1)
\]

Figure 1. Constitutive relation curve of steel

2.2. Constitutive model of rubber brick and lime sand brick masonry
In this simulation, the constitutive relationship curve of rubber brick masonry measured by Lu Shan[5] in 2011 was selected. The constitutive relationship curve of autoclaved lime sand brick masonry measured by Zhang Zhongji[6] and other studies. The decreasing part of the curve uses the constitutive model proposed by Zhu Bolong[7] of Tongji University, as shown in equation 1.1 and Figure 2.

Figure 2. Constitutive relation curve of steel
2.3. Modulus of elasticity and Poisson's ratio
The elastic modulus and Poisson's ratio of the two masonry and steel are shown in Table 1.

Table 1. Elastic modulus and Poisson's ratio of masonry and steel

| Material            | Modulus of elasticity (MPa) | Poisson's ratio |
|---------------------|----------------------------|-----------------|
| Rubber brick masonry| 1982                       | 0.19            |
| Lime brick masonry  | 1943                       | 0.15            |
| Steel               | 210000                     | 0.3             |

3. Establishment of finite element model

3.1. Finite Element Solving Module
The universal analysis module ABAQUS/Standard uses an implicit solution method.

3.2. Establishment of steel frame model for infill wall
Application of ABAQUS to create four models of one-story, three-story, single-span frame structure: one-story three-story single-span pure steel frame structure (hereinafter referred to as SF), Rubber brick infilled wall steel frame (hereinafter referred to as RSF), Lime brick infilled wall steel frame (hereinafter referred to as LSF), non-filled bottom rubber brick filled wall steel frame (hereinafter referred to as R1SF), middle-layer unfilled Wall rubber bricks fill the wall steel frame (hereinafter referred to as R2SF). The above four models have a layer height of 3m and a span width of 5.6m. The homogeneity of the structural model uses the solid element C3D8R (octahedral hexahedron linear modeling integrated unit).

3.3. Force form and Boundary constraints
In this simulation, the bottom of the column is fixedly connected, the bottom of the bottom infill wall is hinged to the ground, the steel beam and column nodes are bound and bound, the normal direction between the infill wall and the steel frame is hard contact, and the tangential direction is friction contact. According to GB50003-2011 Code for Design of Masonry Structures, the friction coefficient $\mu$ of masonry sliding along steel members is 0.45.

4. Finite element analysis

4.1. Analysis of the influence of seismic waves
The simulation uses the Standard implicit dynamic algorithm, the seismic fortification intensity is 8 degrees (0.20g), the site category is Class II, and the design earthquake grouping is the first group. According to the requirements of GB50011-2010 (2016 edition) building seismic design code, the ElCentro NS seismic wave and San Fernando NS seismic wave were selected and downloaded from the application of artificial earthquakes named Luxinzheng. The structural characteristic period is 0.35s, the seismic wave lasts for 40s, and the peak acceleration reaches 440cm / s² at 2.14s.

4.2. Adjustment of seismic waves
In the nonlinear dynamic time history analysis of the structure, in order to study the different seismic levels (the seismic dynamic response of the substructure, the peak value of the seismic wave needs to be adjusted according to the specifications. The adjusted seismic wave conditions are shown in Table 2.
Table 2. The first five natural frequencies of the structure

| The name of the seismic wave | Time Step (s) | duration (s) | Peak acceleration (cm/s²) |
|-----------------------------|---------------|--------------|---------------------------|
| El-Centro                   | 0.015         | 10           | 400                       |
| San Fernando                | 0.01          | 15           | -400                      |
| Artificial seismic          | 0.01          | 15           | -400                      |

4.3. Dynamic time history analysis of infill wall material

4.3.1 Elastoplastic time history analysis of El-Centro Wave

Under the action of El-Centro NS seismic waves, elastoplastic time history analysis is performed on SF structure, RSF structure, and LSF structure, respectively, and the top level horizontal displacement time history curves of the three structures are obtained (as shown in Figure 3).

![Figure 3. Horizontal displacement time history curve of structure top floor](image)

Combined with the horizontal displacement time history curve of the top layer of the structure, the vertex values of the curve part within 10 seconds are extracted and compared, as shown in Table 3.

Table 3. Comparison of the peak horizontal displacement of the top floor

| Time (s) | SF Displacement (m) | RSF Displacement (m) | LSF Displacement (m) | Increase compared to SF (%) |
|----------|---------------------|-----------------------|----------------------|----------------------------|
| 0.72     | -0.024              | -0.0211               | -0.0222              | -12.11                     |
| 1.35     | 0.0478              | 0.04080               | 0.04375              | -14.72                     |
| 1.92     | 0.0751              | 0.06780               | 0.07092              | -9.74                      |
| 3.015    | -0.050              | -0.0444               | -0.0475              | -12.63                     |
| 3.75     | 0.0458              | 0.03933               | 0.04065              | -14.17                     |
| 4.29     | -0.046              | -0.0389               | -0.0419              | -15.30                     |
| 6.12     | 0.0259              | 0.02307               | 0.02416              | -10.93                     |
| 7.2      | -0.041              | -0.0360               | -0.0380              | -12.55                     |
| 8.055    | -0.003              | -0.0026               | -0.0031              | -16.60                     |
| 8.85     | -0.052              | -0.0447               | -0.0474              | -14.49                     |

It can be seen from the time-history curve that under the action of the El Centro seismic wave, combined with the data in the table, it can be seen that the top-level horizontal displacement of the two infilled steel frame structures are smaller than the pure steel frame structure, indicating that the addition of the infill wall increases the stiffness of the overall structure and improves the anti-side shift ability of the steel frame. The peak horizontal displacement of the RSF structure at each time is about 10% to 17% different from the SF structure. The peak horizontal displacement at each moment differs from the SF structure by about 2% to 12%. It can be seen from the comparison that the rubber brick-filled wall can absorb more seismic energy due to the better energy absorption capacity of the rubber brick. The effect of improving the lateral resistance of the frame is more significant.

4.3.2 Time-history analysis of elastoplasticity of San Fernando seismic waves
Under the action of the San Fernando seismic wave, the elastoplastic time history analysis is performed on the SF structure, RSF structure, and LSF structure, and the top level horizontal displacement time history curves of the three structures are obtained (as shown in Figure 4).

![Figure 4. Horizontal displacement time history curve of structure top floor](image)

Combined with the horizontal displacement time history curve of the top layer of the structure, the vertices of the curve part within 15 seconds are extracted and compared, as shown in Table 4.

| Time (s) | SF     | RSF    | LSF    | RSF Increase (%) | LSF Increase (%) |
|---------|--------|--------|--------|------------------|------------------|
| 2.24    | 0.0122 | 0.0091 | 0.0103 | -25.38           | -15.56           |
| 2.58    | -0.008 | -0.005 | -0.007 | -33.31           | -18.01           |
| 4.52    | -0.019 | -0.017 | -0.017 | -13.17           | -13.46           |
| 6.34    | 0.0107 | 0.0088 | 0.0105 | -17.94           | -2.08            |
| 6.92    | -0.017 | -0.015 | -0.015 | -10.31           | -7.05            |
| 9.29    | 0.0193 | 0.0149 | 0.0161 | -22.60           | -16.58           |
| 11.05   | -0.009 | -0.008 | -0.008 | -13.12           | -10.90           |
| 11.6    | 0.0116 | 0.0090 | 0.0098 | -22.64           | -15.17           |
| 12.3    | -0.013 | -0.0113| -0.012 | -13.03           | -7.18            |
| 14.39   | 0.0145 | 0.0123 | 0.0133 | -15.08           | -8.01            |

Combining the data in Table 6, the peak horizontal displacement of the RSF structure at different times differs from the SF structure by about 10% to 33%. The peak value of the horizontal displacement of the LSF structure at different times differs from the SF structure by about 2% to 18%. The density of the rubber brick is small and the weight is light, which makes the overall structure Because the displacement caused by the seismic inertial force is less than the LSF structure, the rubber brick-filled wall can better improve the lateral displacement resistance of the steel frame.

4.3.3 Elastoplastic time-history analysis of artificial seismic waves

Under the action of artificial seismic waves, elastoplastic time history analysis was performed on SF structure, RSF structure, and LSF structure, respectively, and the top level horizontal displacement time history curves of the three structures were obtained (as shown in Figure 5).

![Figure 5. Horizontal displacement time history curve of structure top floor](image)
Combined with the horizontal displacement time history curve of the top layer of the structure, the vertices of the curve part within 15 seconds are extracted and compared, as shown in Table 5.

| Time (s) | SF | RSF | LSF | SF | RSF | LSF |
|---------|----|-----|-----|----|-----|-----|
| 5.1     | -0.036 | -0.033 | -0.035 | -6.93 | -3.15 |
| 6.8     | -0.046 | -0.043 | -0.044 | -7.13 | -3.24 |
| 10.0    | -0.053 | -0.049 | -0.052 | -7.16 | -3.11 |
| 11.9    | -0.026 | -0.024 | -0.025 | -6.38 | -2.85 |
| 14.8    | -0.038 | -0.035 | -0.037 | -7.09 | -3.28 |

Combining the data in Table 5, it can be seen that in deferent moment, the horizontal displacement of the top layer of the LSF structure and the LSF structure are reduced to varying degrees compared with the SF structure, the peak value of the horizontal displacement of the RSF structure at different times is different from that of the SF structure by about 6% to 8%. The structure difference is about 2% ~ 4%. Rubber powder with good elasticity is added to the brick instead of fine aggregate. When micro cracks occur inside the brick, the rubber powder will release the stored elastic potential energy to fill the cracks and delay the damage of the brick. Therefore, rubber bricks can absorb and consume more seismic energy through their own elastic deformation, thereby better improving the anti-side shifting ability of the overall structure.

5. Conclusion
1. With the increase of the order, the natural frequency of the pure steel frame structure grows faster, and the natural frequency of the filled wall steel frame grows slowly.
2. For different infill wall materials, under the action of three seismic waves, the horizontal displacement of the top layer of the two infill steel frame structures is smaller than that of pure steel frames. The addition of infill walls reduces the horizontal displacement of the overall structure.
3. Different wall layout methods will reduce the horizontal displacement of the overall structure, but when the infill wall is not uniformly distributed, the stiffness distribution of the overall structure along the height is unevenly distributed, thereby making the infill wall The effect of improving the lateral stiffness of the overall structure becomes worse.
4. Under the action of artificial earthquake wave, The horizontal displacement at the top of the structure of the three structure is larger than the other two cases, indicating that the structure responds more severely to artificial seismic waves and the seismic effect is more significant.

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