A study on energy distribution law of frame structure across ground fissure

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Abstract. In order to study the frame structure energy dissipation mechanism on the ground, a 3×3 span 5-story frame structure was used as the research background, and a shaking table test with a scale ratio of 1:15 was designed. Based on the prototype structure, a finite element model based on ABAQUS is established. The correctness of the finite element model is verified by experimental comparison. On this basis, the plastic energy dissipation and damping energy consumption of the structural beam and the plastic energy dissipation law of the column are analyzed. The weak part of the structure of the trans-ground fissure structure under energy conversion is found. This study provides a reference for the arrangement of energy-consuming devices in seismic design and disaster prevention and mitigation design for similar structural engineering.

1. Introduction
Xi'an is located in the ground fissure zone of the Weihe Basin. The existence of ground fissures has seriously affected the urban planning of Xi'an[1]. With the improvement of urbanization and the impact of talent introduction plans and household registration policies, the contradiction of urban land shortage is more prominent. Therefore, making full use of the land resources in the ground fissure area has become an important subject that urgently needs to be studied in urban construction. There are many studies on the dynamic response of engineering structures under ground fissure environment[2]. Huang Qiangbing et al.[3]used large-scale shaking table tests to show that the acceleration response of the ground fissure site showed a significant amplification effect; Xiong Zhongming et al.[4]used finite element software to establish the interaction between the ground fissure site and the structure with no difference between the upper and lower walls. Calculation model, quantitative analysis of frame structure acceleration, displacement and displacement angle change law:. For the research on structural energy distribution, Ye Lieping[5]summarized the relevant research results of building structures based on energy seismic design methods, and pointed out that structural damage energy dissipation mechanism control is the key to determining the cumulative energy consumption distribution of structures and realizing energy-based seismic design. From the energy point of view, based on the shaking table test of a ground fissure frame structure with a scale ratio of 1:15, a finite element model of the ground fissure structure is established, and the accuracy of the established finite element model is verified. The distribution law of plastic energy dissipation of the structure spanning ground fissures under earthquake action is analyzed. The research results provide basic data for guiding the design of shock absorption and energy dissipation for ground fissures affected areas or cross-ground fissure structures.
2. Shaking table test design

2.1. Model parameter determination

This experiment was completed by the research team at the Key Laboratory of Structure and Seismic Resistance of the Ministry of Education, Xi'an University of Architecture and Technology [6]. The experiment selected a 3×3 five-story span that crossed Xi'an ground fissure f4 (Northwest University-Northwestern Polytechnical University ground fissure). The frame structure is designed for shaking table test as a research background. The type of construction site where the frame structure is located is Class II, the designed seismic group is the first group, and the seismic class of the frame structure is Class II. Refer to the shaking table test research of Xu Weizhi et al. [7]. This test uses an artificial mass model to scale the original structure and the soil at a scale of 1:15. The specific dimensions of the original structure before scaling and the model structure after scaling are shown in Table 1. Shown.

| Tab 1. Model size before and after the scale |
|---------------------------------------------|
| **Original structure**                      |
| total measurement                           |
| Side span column                            |
| Mid-span column                             |
| Board thickness                             |
| Height of each floor                        |
| Soil                                        |
| **Model structure**                         |
| 18mx15.6mx21m                                |
| 400mmx500mm                                 |
| 500mmx500mm                                 |
| 120mm                                       |
| 3.6m                                        |
| 45mx22.5mx22.5m                              |
| 1220mmx1060mmx1200mm                        |
| 27mmx33mm                                   |
| 33mmx33mm                                   |
| 8mm                                         |
| 240mm                                       |
| 3mx1.5mx1.5m                                 |

2.2 Making the upper frame structure and model earth box

The upper frame structure is a 3×3 five-story scaled frame structure, and the model structure plan is shown in Figure 1. This model uses M6 particulate concrete to simulate the C30 concrete in the prototype structure, and uses galvanized iron wire to simulate the steel skeleton of the original structure.

![Fig 1. Layout plan of model structure](image)

The soil used in the model is in-situ fissure site soil [8], and the model soil is configured after sieving and controlling the moisture content and density of each layer of soil. The specific control parameters are shown in Table 2.

| Tab 2. Parameters of soil layers in ground fissure site |
|-----------------------------------------------------|
| **Soil layer name**                                 |
| **Moisture content %**                              |
| **Density (g/cm³)**                                 |
| **Shear modulus (MPa)**                             |
| **Cohesion (Pa)**                                   |
| **Internal friction angle (°)**                     |
| **Expansion angle (°)**                             |
| loess                                              |
| 23.5                                               |
| 1.68                                               |
| 110.49                                             |
| 48000                                              |
| 27.6                                               |
| 9.2                                                |
| Ancient soil                                       |
| 22.9                                               |
| 1.78                                               |
| 139.45                                             |
| 49000                                              |
| 27.3                                               |
| 9.1                                                |
| Silty clay                                         |
| 25.2                                               |
| 1.90                                               |
| 163.34                                             |
| 45000                                              |
| 26.6                                               |
| 8.866667                                           |

2.3 Test loading plan and data collection

This shaking table test selects two surface waves El-Centro wave, Jiangyou wave and one bedrock wave.
Cape Mendocino wave as the test seismic waves, which are loaded in seven steps along the direction perpendicular to the ground fissure, with peaks of 0.1g, 0.2g, 0.3g, 0.4 g, 0.6g, 0.8g, 1.2g. The frequency is swept with 0.05g white noise before each stage is loaded.

3. Numerical analysis based on ABAQUS software
The finite element analysis of the superstructure and the size of the soil is the size before the scale. The specific size is shown in Table 1. The upper frame structure beams and columns adopt B31 beam elements, and the floor slab adopts shell elements; the steel bars in the beams and columns are defined in keywords using the rebar command stream, and the rebar layer in the floor is inputted. The concrete constitutive of beam and column adopts the concrete UConrete02 model considering the tensile strength in the PQ-Fiber subroutine model, the slab concrete constitutive adopts the damage accumulation model in ABAQUS, and the steel adopts the ideal elastic-plastic type. The soil model uses C3D8R three-dimensional solid element simulation. The constitutive model adopts the Mohr Coulomb model, and the established finite element model of the ground fissure site and the upper frame structure is shown in Figure 2. The simulation of soil ground fissures is set as hard contact in this model, and the tangential action is simulated by the Coulomb friction model with a penalty friction coefficient, and the friction coefficient is 0.3. In order to compare the acceleration response of the finite element model and the test model, and verify the accuracy of the finite element model, the ground motion table response of three kinds of seismic waves under 0.1g and 0.4g excitation respectively is used as the seismic input, and the acceleration measurement points according to the test model The placement position of the finite element model is to monitor the acceleration of the corresponding position.

![Fig 2. The whole model of the superstructure above the ground fissure](image)

4. Comparative analysis of numerical simulation and test results

4.1 Comparative analysis of acceleration
The table response under the action of 0.1g and 0.4g El-Centro waves is used as the seismic input, and the acceleration measurement points of the test superstructure are arranged according to the acceleration measurement points of the test superstructure. The comparison is shown in Figure 3.

![Fig 3. Comparison of acceleration experimental value and simulated value under the action of El-Centro wave](imagea)
4.2 Comparison error analysis
Comparing the acceleration results obtained from the test and the numerical simulation, it is found that
the simulated acceleration of each layer is consistent with the experimental acceleration. The
experimental value is slightly larger than the calculated value, and the acceleration is the smallest at the
bottom and the highest at the top. Because the finite element soil viscoelastic artificial boundary setting
is different from the experimental soil boundary (soil box); the test model production error, and the size
effect of the test plan according to the 1:15 scale ratio design causes the finite element simulation results
The numerical value is slightly different from the test results, but the finite element software simulation
of the dynamic response of the cross-ground fissure structure has obvious regularity, which is consistent
with the change trend of the shaking table test results. It can approximate the simulation test situation
and verify the correctness of the modeling calculation method in this paper. Therefore, the finite element
model can be used for energy analysis of shaking table test to determine the energy distribution law of
frame structures spanning ground fissures.

5. Energy analysis of ground fissure site frame structure

5.1 Energy balance expression in ABAQUS
Energy output is an important part of ABAQUS/Explicit analysis. The energy components in ABAQUS
are richer, mainly including internal energy, kinetic energy, strain energy, energy input to the soil-
structure system by ground motion, damping energy consumption, plastic damage energy consumption,
Time-dependent energy consumption, surrounding media energy consumption, etc., these energies obey
the law of conservation of energy, combined with the energy integral formula of the above formula, the
simplified relationship between the energy components can be obtained as follows:

\[ E_u + E_k + E_f + E_{qb} = E_w + \text{constant} \]

Where: \( E_u \) is the internal energy; \( E_k \) is the kinetic energy; \( E_f \) is the energy consumption of the
model contact friction contact; \( E_w \) is the energy input to the soil-structure system by the ground motion; \( E_{qb} \) is the damping energy consumption of the surrounding medium;

5.2 Energy distribution of beam and column in ground fissure structure
In order to study the energy distribution law of the upper structural beams and columns across the ground
fissure, since the ground fissure passes through the mid-span of the structure (see Figure 1), the
longitudinal one-thickness frame analysis is selected, which can reflect the upper and lower beams, The
difference in column energy distribution. Figure 4 shows the numbering of each layer of beams and
columns in a cross frame.

![Serial beam number of each layer](image1)
![Column number](image2)

Fig 4. The number of structural beam and column members

In order to facilitate the analysis of the difference in the distribution of plastic energy consumption
along the height and longitudinal direction of the structure, define the energy distribution coefficient
along the height \( \lambda_h \) and the longitudinal energy distribution coefficient \( \lambda_j \) as follows:
In the formula, $E_{ji}$ is the plastic energy dissipation of columns (beams) in column $j$ (span) of the structure, and $i$ represents the plastic energy consumption of columns (beams) in column $j$ (span) of the structure, and $i$ represents the 1~5 layers of the structure; $\sum E_j$ is the total plastic energy dissipation of columns (beams) in column $j$ (span) of the structure, $j$ represents 1~4 columns or 1~3 span beams; $E_{ij}$ is the plastic energy dissipation of columns (beams) in the $j$ column (span) of the $i$-layer structure; $\sum E_i$ is the total plastic energy dissipation of all the columns (beams) in the $i$-layer structure.

5.3 Distribution of plastic energy dissipation in the superstructure

| Number of layers | Distribution of plastic energy dissipation of each layer of beams (Jiangyou wave/El-Centro wave/bedrock wave) |
|------------------|--------------------------------------------------------------------------------------------------|
|                  | SL                                               | ZL                                               | XL                                               |
| First floor      | 446.5/67.9/643.0                                  | 15.2/8.4/38                                     | 426.6/71.4/588.7                                 |
| Second floor     | 182.8/40.8/34.4                                  | 9.5/7.1/8.4                                     | 231.4/35.6/29.8                                 |
| Third floor      | 509.8/201.8/40.7                                 | 11.2/7.0/8.2                                    | 433.5/69.2/35.8                                 |
| Forth floor      | 637.1/373.2/51.8                                 | 11.7/9.4/8.2                                    | 571.9/211.1/42.8                                |
| Fifth floor      | 481.1/193.9/52.5                                 | 15.3/9.7/9.3                                    | 486.3/96.3/40.6                                 |

Analyzing Figures 5, 6 can be obtained: along the longitudinal direction of the structure, the longitudinal distribution ratio of the plastic energy consumption of the beams at the mid-span (crossing the ground fissure) of the structure under the action of the earthquake is the smallest, and the plastic energy consumption is the least; at the same time, the beams located at the hanging wall The proportion of...
plastic energy consumption distribution is slightly larger than that of the bottom wall, which is in line with the top and bottom effect of the ground fissure site studied by previous researchers[9].

Along the height of the structure, the energy distribution of each beam at the bottom of the structure perpendicular to the direction of the ground fissure is relatively close; with the increase of floors, the difference in the proportion of plastic energy consumption in the upper and lower walls changes significantly, which is due to the increase in the height of the ground fissure site The effect of the upper and lower plates is obvious, and the nonlinear deformation of the beam at the hanging plate is more than that of the bottom plate.

Tab 4. The plastic energy dissipation of each layer columns

| Number of layers | Distribution of plastic energy dissipation of each layer of column (Jiangyou wave/El-Centro wave/bedrock wave) |
|------------------|----------------------------------------------------------------------------------------------------------|
|                  | SYZ  | SJZ  | XJZ  | XYZ  |
| 1                | 253.5/95.5/75.5 | 246.9/106.2/356 | 252.9/94.5/684 | 222.7/81.0/43.9 |
| 2                | 230.0/81.0/43.9 | 199.1/81.5/45.8 | 214.2/72.5/34.4 | 205.7/71.6/25.9 |
| 3                | 172.9/63.6/17.5 | 166.9/68.1/32.9 | 181.4/61.6/24.5 | 153.8/55.0/18.4 |
| 4                | 120.8/44.4/12.3 | 127.6/50.7/21.0 | 134.6/47.5/17.1 | 637.1/373.2/51.8 |
| 5                | 63.6/21.9/6.4  | 84.2/31.4/11.5  | 91.8/30.6/10.3  | 63.3/20.4/6.1   |

Fig 7. The plastic energy dissipation ratio of columns ($\lambda_1$)

Fig 8. The plastic energy dissipation ratio of columns ($\lambda_h$)

According to the analysis of Figures 7 and 8, it can be seen that along the longitudinal direction of the structure, the energy distribution of the first and third floors of the structure is relatively close under the action of the earthquake. The plastic energy consumption of the column near the ground fissure is slightly larger than that of the column far away from the ground fissure. The distribution changes greatly, and the plastic energy consumption of the column close to the ground fissure is significantly more than that of the column far away from the ground fissure, indicating that the column is still consuming energy in the case of brittle failure of the beam.

Along the structure height direction, as the storey height increases, the plastic energy consumption of each column gradually decreases, except for individual floors, it basically decreases linearly. The
6. Conclusion

Based on the shaking table test, the finite element model of the ground fissure and the upper frame structure is established. Based on the comparison and analysis of the shaking table test and the finite element simulation acceleration response, the energy distribution problem of the upper structure across the ground fissure is studied. The distribution of plastic energy dissipation and damping energy dissipation of beams and columns along the direction of the ground fissure and the height of the structure has been studied. The study shows that:

1) Under different seismic waves, the plastic energy consumption of the upper wall of the upper structural beam is greater than that of the footwall, and the plastic energy consumption of the beam across the ground fissure is the least. In the height direction, the energy distribution of Jiangyoubou and El-Centro is relatively consistent at the heights of each layer, and mutations occur at the second and fourth floors. The second and fourth floors have the least proportion and the fourth floor.

2) Under the action of different seismic waves, the plastic energy consumption of the upper wall of the upper structural column member is greater than that of the foot wall. The closer the column is to the ground fissure, the greater the plastic energy consumption of the column. The energy consumption under the action of bedrock waves accounts for more than the other two waves. In the height direction, the plastic loss of the column increases with the increase of the floor height, which is consistent with the law of the increase of the floor shear force with the increase of the height under the action of the earthquake. The energy consumption of the bottom layer under the action of the bedrock wave accounts for significantly more. This is because the time history curve of the bedrock wave is relatively gentle, which makes the column concrete more plastic hysteretic energy consumption.

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