The Influence of Material Hysteretic Property on Seismic Collapse-Resistant Capacity of RC Frame Structure

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Abstract. To study the influence of hysteretic behavior of material on the seismic collapse-resistant capacity of reinforced concrete frame structure, a 5-story plane frame was selected as the research object, the incremental dynamic analysis method was used to analyze the collapse vulnerability of the structure. According to the collapse probability curve, the seismic collapse-resistant capacity of the RC frame structure with different hysteresis parameters was quantitatively evaluated. The research shows that the concrete strength grade has the most significant influence on the seismic collapse-resistant capacity. Reducing the concrete strength degradation or increasing the strain hardening rate of the steel can slightly improve the seismic collapse-resistant capacity ability; The concrete hysteretic pinch and the steel hysteretic energy consumption has no effect on the seismic collapse-resistant capacity of the structure. The seismic collapse-resistant capacity of the structure is negatively correlated with the strength grade of the steel bar, but its impact is not obvious.

1. Introduction
Accurately predicting the elasto-plastic response of structures under strong earthquakes is the main work to achieve performance-based seismic design and one of the key problems of the current research [1]. When a material-based model is used to analyze the RC frame structure's collapse resistance, the constitutive relationship of the material determines the reliability of the numerical simulation results and plays a key role in the accuracy of the nonlinear dynamic analysis results [2]. However, current research mainly focuses on the influence of structural parameters on the elasto-plastic response of the structure. The study on the influence of the hysteretic properties of the material on the collapse resistance of the structure is not performed.

Some scholars at home and abroad have shown that the material hysteretic model plays an important role in the analysis of structural collapse resistance. Heo[3] studied the effect of different steel bar constitutive model on the inelastic seismic performance of RC frame structures. Hao Zhou[4] used three different concrete constitutive models to analyze the whole process of seismic collapse of reinforced concrete frame-shear wall structures, and found that improper selection of the constitutive model will give a wrong collapse mode or analysis result. Xiaobin Hu[5] showed that the concrete constitutive structure with different hysteretic characteristics has a large difference in the story displacement angle during dynamic analysis. Research by Jianping Han[6] showed that neglecting the strength degradation of the steel bars would overestimate the seismic performance of the structure. Although existing studies showed that the use of material constitutive models proposed by different scholars have certain effect
on the collapse resistance of the structures, few studies have quantitatively evaluated the influence of the material hysteresis on the structure's resistance to earthquake collapse.

In this paper, by analyzing the vulnerability of a reinforced concrete regular frame, the hysteretic characteristics of concrete (including the property of strength degradation, hysteretic pinch, concrete strength) and the hysteretic characteristics of steel bars (including the property of strain hardening rate, hysteretic energy consumption, reinforcement strength level) on the collapse-resistant capacity of RC frame structure. Some useful advice for the realization of performance-based seismic design is proposed.

2. RC frame model

According to Chinese Code for Design of Concrete Structures, a common 5-story RC frame structure is designed by PKPM. The seismic fortification intensity of the building is 7 degree(0.1g), the site category is class II with seismological grouping of second group. The concrete strength of structure is C30, the longitudinal reinforcement is HRB400, and the stirrup is HRB335. The weight of floors concrete is automatically calculated by PKPM. The additional dead loads are 1.4 kN/m² and the 3.5 kN/m² for the floors and roof respectively. The additional dead load of the beam is 4.0 kN/m². And the live loads for all stories and roof are 2.0 kN/m². The elevation of the structure is shown in Figure 1. The dimensions and reinforcement of beams and columns are shown in Table 1.

![Figure 1. Structural elevation](image)

The analytical model was established through the finite element software OpenSees. The modified Kent-Park hysteresis model was adopted as the concrete constitutive model, and the Pinto reinforcing steel constitutive model was selected as the reinforced constitutive model. The constraint effect of the stirrup was simulated by modifying the strength and ductility of the concrete in the core area.

| Member                  | Section size | Longitudinal tendon | Stirrup     |
|-------------------------|--------------|---------------------|-------------|
| 1-4 layer side beam     | 250*500      | top 3@20 bottom 2@22 | Φ8@100/200  |
| 1-4 layer middle beam   | 250*500      | top 3@20 bottom 2@18 | Φ8@100      |
| 5 layer side beam       | 250*500      | top 3@18 bottom 3@22 | Φ8@100/200  |
| 5 layer middle beam     | 250*500      | top 3@18 bottom 2@18 | Φ8@100      |
| 1 layer column          | 500*500      | 10@18               | Φ8@100/150  |
| 2-4 layer column        | 400*400      | 8@18                | Φ8@100/150  |
| 5 layer column          | 350*350      | 8@18                | Φ8@100/150  |
3. Effect of concrete hysteretic characteristics on the collapse-resistant capacity of structures

3.1. Concrete hysteretic model

The modified Kent-Park model is a commonly used constitutive model of concrete. Its skeleton curve is divided into rising section, falling section and platform section. This model reflects the hysteretic energy consumption and strength degradation characteristics under reversed loads. In this paper, the effects of concrete strength degradation, hysteresis pinching, and strength grade on the collapse-resistant capacity of the structure are studied by changing the ultimate compressive strain of the concrete, subsequent unloading stiffness, and peak compressive stress. The model parameters of different structures are shown in Table 2.

![Figure 2. Correction Kent-Park hysteresis model](image)

**Table 2. Model parameters of different structures**

| Model number | Ultimate compressive strain | Subsequent unloading stiffness | Concrete strength |
|--------------|-----------------------------|-------------------------------|-------------------|
| Model-1      | 0.004                       | 0.5E_r                       | C30               |
| Model-2      | 0.005                       | 0.5E_r                       | C30               |
| Model-3      | 0.006                       | 0.5E_r                       | C30               |
| Model-4      | 0.004                       | 0.25E_r                      | C30               |
| Model-5      | 0.004                       | 0.75E_r                      | C30               |
| Model-6      | 0.004                       | 0.5E_r                       | C40               |
| Model-7      | 0.004                       | 0.5E_r                       | C50               |

3.2. Strength degradation

When the concrete compressive strain larger than the strain of peak stress, it is in the falling section of the concrete skeleton curve, in which section the compressive strain increases as the compressive stress of the concrete decreases gradually. There is the strength degradation in this section. In the Kent-Park model, the strength degradation of concrete is controlled by the negative stiffness of the falling section. By changing the value of the ultimate compressive strain, concrete hysteresis models Model1 ~ Model3 with different strength degradation can be constructed.

In this paper, the spectral acceleration $S_a(T1, 5\%)$, which is suitable for short-to-medium-period structures, is used as the IM index in IDA, the maximum inter-story displacement angle $\theta_{\text{max}}$ is used as the DM index. According to FEMA350 report [7], the structure collapses is defined when the slope of the IDA curve drops to 20% of the elastic stage, or the maximum inter-story displacement angle reaches 10%. The 22 far-field seismic waves recommended by ATC-63[8] are used to analyze the structure's vulnerability[9]. The vulnerability curves and collapse resistance indexes of different concrete strength degradation models are shown in Figure 3 and Table 3.

If the collapse probability is constant, the earthquake intensity increases as the ultimate compressive strain of the concrete increases. It’s shown that the gentler degradation of concrete strength improves of the collapse-resistant capacity of the structure. And the Collapse Resistance Ratio (CMR)[10] increases with the increase of the concrete's ultimate compressive strain, which decreasing the concrete strength...
degradation. The CMR increases 7.34% as the ultimate compressive strain increases from 0.004 to 0.005. When the ultimate compressive strain increases from 0.005 to 0.006, the CMR increased 10.4% and the logarithmic standard deviation decreased, which indicates that the dispersion of the structure's ground motion responses have gradually decreased. The main reason is that the ductility of the beam-column section increases as the strength degradation of the concrete decreases, which improves the deformability of the structure. Therefore, reducing the strength degradation of concrete can improve the seismic collapse resistance of the structure.

![Figure 3. Vulnerability curve of different concrete strength degradation models](image1)

**Figure 3.** Vulnerability curve of different concrete strength degradation models

| Ultimate compressive strain of concrete | 0.004 | 0.005 | 0.006 |
|----------------------------------------|-------|-------|-------|
| $S_a(T,5\%)$/g | 1.19   | 1.28   | 1.41   |
| $S_a(T)_{\text{great earthquake}}$ | 0.46   | 0.46   | 0.46   |
| CMR | 2.59   | 2.78   | 3.07   |
| Logarithmic standard deviation | 0.6953 | 0.6813 | 0.6633 |

### 3.3. Hysteretic energy consumption

During earthquakes, the concrete dissipates energy under cyclic load. The pinching of the hysteresis curve represents the energy dissipating capacity of the concrete. By changing the subsequent unloading stiffness of the concrete material, concrete hysteresis models with different energy dissipating capacity are obtained. As the subsequent unloading stiffness decreases, the "pinching" degree of the concrete hysteresis curves decreases, and the energy consumption capacity increases. 3 Concrete models Model1, Model4 ~ Model5 with different hysteretic energy consumption were constructed. Figure 4 is the vulnerability curve of each model. Table 4 gives the CMR of each model. It can be seen that the CMR of each model is equal, and the logarithmic standard deviation does not change much. Therefore the concrete hysteresis has no significant effect on the seismic collapse resistance of the structure.

![Figure 4. Vulnerability curve of different concrete hysteretic pinch models](image2)

**Figure 4.** Vulnerability curve of different concrete hysteretic pinch models
### Table 4. Index of collapse resistance of different concrete hysteretic pinch models

| Subsequent unloading stiffness | $0.25E_r$ | $0.5E_r$ | $0.75E_r$ |
|-------------------------------|----------|----------|----------|
| $S_a(T_1)_{50\%}/g$          | 1.19     | 1.19     | 1.19     |
| $S_a(T_1)$ great earthquake   | 0.46     | 0.46     | 0.46     |
| CMR                           | 2.59     | 2.59     | 2.59     |
| Logarithmic standard deviation | 0.6884   | 0.6953   | 0.6990   |

### 3.4. Concrete strength grade

The influence of concrete strength grade on collapse-resistant capacity of RC frame is studied in this paper. 3 structural models (Model1, Model6 ~ Model7) with different concrete grades are built. The vulnerability curves of different models are shown in Figure 5. Table 5 shows the CMR of different models.

![Figure 5. Vulnerability curve of different concrete strength grade models](image)

### Table 5. Index of collapse resistance of different concrete strength grade models

| Concrete strength | C30 | C40 | C50 |
|-------------------|-----|-----|-----|
| $S_a(T_1)_{50\%}/g$ | 1.19 | 1.55 | 1.95 |
| $S_a(T_1)$ great earthquake | 0.46 | 0.46 | 0.46 |
| CMR               | 2.59 | 3.37 | 4.24 |
| Logarithmic standard deviation | 0.6953 | 0.6731 | 0.5608 |

When the concrete strength increases from C30 to C40, the CMR of structures increases 30.1%. When the concrete strength increases from C40 to C50, The CMR increases 25.8%, and the logarithmic standard deviation is continuously decreasing which means the dispersion of the structural ground motion response is reduced. It can be seen that increasing the strength level of concrete has a significant effect on improving the seismic collapse resistance of the structure. As the strength of the concrete increases, the ductility of the structural members increases and the compression-strength ratio of columns was reduced. Therefore, the seismic collapse resistance of the structure increases. Moreover, as the strength of the concrete increases, the increment of CMR decreases slightly. The influence of concrete strength is reduced.

### 4. Influence of the hysteretic properties of steel on the collapse-resistant capacity of structures

#### 4.1. Reinforcement constitutive model

The Pinto steel constitutive model is used in this research. The stress-strain relationship is the transition curve between the initial asymptotes of slope $E_0$ and the yielding asymptotes of slope $bE_0$, as shown in Figure 6. This paper studies the effects of the strain hardening rate, hysteretic energy consumption, and strength level of the reinforcement on the collapse resistance of the structure. The model parameters of different structures are shown in Table 6.
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\[ E_1 = bE_0 \]

\[ (\varepsilon_0^0, \sigma_0^0) \rightarrow (\varepsilon_0^1, \sigma_0^1) \]

\[ (\varepsilon_0^2, \sigma_0^2) \rightarrow (\varepsilon_0^1, \sigma_0^1) \]

\[ (\varepsilon_r^2, \sigma_r^2) \rightarrow (\varepsilon_r^1, \sigma_r^1) \]

**Figure 6.** Pinto reinforcement constitutive

**Table 6.** Model parameters of different structures

| Model number | Strain hardening rate \( b \) | Hysteretic energy consumption \( R \) | strength level |
|--------------|-------------------------------|-------------------------------------|---------------|
| Model-1      | 0.01                          | 18                                  | HRB400        |
| Model-8      | 0.02                          | 18                                  | HRB400        |
| Model-9      | 0.03                          | 18                                  | HRB400        |
| Model-10     | 0.01                          | 15                                  | HRB400        |
| Model-11     | 0.01                          | 12                                  | HRB400        |
| Model-12     | 0.01                          | 18                                  | HRB335        |
| Model-13     | 0.01                          | 18                                  | HRB500        |

4.2. **Strain hardening rate**

The strain hardening rate is the ratio of the slope \( E_1 \) in the hardening stage to the slope \( E_0 \) of the initial elastic stage. In Pinto steel bar hysteresis model, \( b \) is the strain hardening rate. Figure 7 shows the vulnerability curves of models with different strain hardening rate (Model1, Model8 to Model9). Table 7 shows the CMR of different models.

**Figure 7.** Vulnerability curve of different steel strain-hardening ratio models

**Table 7.** Index of collapse resistance of different steel strain-hardening ratio models

| Strain hardening rate \( b \) | \( S_a(T_1, 5\%)/g \) | CMR | logarithmic standard deviation |
|-------------------------------|----------------------|-----|--------------------------------|
| 0.01                          | 1.19                 | 2.59| 0.6953                         |
| 0.02                          | 1.26                 | 2.74| 0.6644                         |
| 0.03                          | 1.29                 | 2.80| 0.6784                         |

As the strain hardening rate increases from 0.01 to 0.02, the CMR increases 5.8%. As the strain hardening rate increases from 0.02 to 0.03, the CMR increases 2.2% and the logarithmic standard deviation increases 0.0464.
deviation is reduced. Therefore, increasing the strain hardening rate of the steel bar improves the seismic collapse resistance of the structure slightly.

4.3. Hysteretic energy consumption
The energy consumption capacity of steel bars under cyclic reversed load is usually measured by the area enclosed by the hysteresis curve. The parameter $R$ is the curvature coefficient of stress-strain relation curve under reversed load. Through this parameter, the hysteretic energy consumption of the steel bar can be modified. The value of parameter $R$ is recommended between 10 and 20 in OpenSees. The hysteretic energy dissipation capacity of the steel bar decreases as the curvature coefficient $R$ decreases. Table 8 shows the CMR of each model (Model1, Model10 ~ Model11). It can be seen that the CMR of the hysteretic energy consumption model of different steel bars is equal, and the logarithmic standard deviation does not change obviously. So the hysteretic energy consumption of steel bars has no effect on the seismic collapse resistance of the structure.

![Figure 8. Vulnerability curve of different steel hysteresis energy consumption models](image)

Table 8. Index of collapse resistance of different steel hysteresis energy consumption models

| Parameter | $R$ | 18 | 15 | 12 |
|-----------|-----|----|----|----|
| $S_d(T_{1,50})/g$ |     | 1.19 | 1.19 | 1.19 |
| $S_d(T_{1})$ great earthquake |     | 0.46 | 0.46 | 0.46 |
| CMR |     | 2.59 | 2.59 | 2.59 |
| Logarithmic standard deviation |     | 0.6953 | 0.6873 | 0.6774 |

4.4. Steel strength
The strength level of steel bars in China is divided according to the standard value of the yield strength of steel bars. To study the influence of steel strength on the seismic collapse resistance of structures, the principle of equal strength substitution is used in this paper. Figure 9 shows the vulnerability curves of models (Model1, Model12 to Model13) with different steel strength. Table 9 shows the CMR of different models. When the strength grade of the steel bar increases from HRB335 to HRB400, CMR is reduced 4.8%. When the strength of the steel bar increases from HRB400 to HRB500, CMR decreases 0.8%. With the increase of the strength level of the reinforcement, the members’ relative height of compression zone increases, which reduces the ductility of the section and results in reduction in the structural deformability. Therefore, the increase of steel strength slightly decreases in the capacity of seismic collapse resistance.
5. Conclusion
In this paper, the influence of material hysteresis on the seismic collapse resistance of RC frame structures is studied. Through the vulnerability analysis, the following conclusions can be obtained:

1. Increasing the strength level of concrete can improve the seismic collapse resistance of the structure, but with the increase of concrete strength, the increase of the earthquake collapse resistance of the structure is slightly reduced.

2. Reducing the strength degradation of concrete and increasing the strain hardening rate of steel bars can improve the earthquake collapse resistance of the structure to a certain extent, but the improvement is limited. The degree of hysteretic pinch of concrete and the energy dissipation capacity of steel bars have no significant effect on the seismic collapse resistance of the structure.

3. Increasing the strength level of the reinforcement will reduce the ductility of the beam-column section. The seismic collapse resistance of the structure has a negative correlation with the strength level of the reinforcement, but the effect is not obvious.

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