Influence of Torsion Effect on the Mechanical Characteristics of Reinforced Concrete Column

Debin Wang¹, Guoxi Fan*²

¹School of Civil and Safety Engineering, Dalian Jiaotong University, Dalian, Liaoning, 116028, China;
²School of Engineering, Ocean University of China, Qingdao, Shandong, 266100, China

Abstract. The purpose of this paper is to study the effect of torsional effect and loading rate on the flexural capacity of RC members. Based on the fiber model of finite element software ABAQUS, a model has been established with the consideration of the strain rate sensitivity of steel and concrete. The model is used to reflect the influence of the rotational component of ground motion by applying the initial angular displacement. The mechanical properties of RC columns under monotonic loads are simulated. The simulation results show that there has been a decrease in the carrying capacity and initial stiffness of RC columns for high initial torsion angle. With the increase of initial torsion angle, the influence of loading rate on RC columns gradually increases.

1. Introduction

Reinforced concrete (RC) column is the main bearing member in building. So a large number of experimental studies on the mechanical properties of RC columns under bending moment and shear force have been performed. At present, domestic and foreign scholars have carried out a lot of research on the mechanical properties of RC members under dynamic loads. Some conclusions can be summarized as follows: 1) the carrying capacity of RC member increases with the increase of loading rate; 2) the ductility of RC member decreases with the increase of loading rate; 3) the initial stiffness of RC member increases with the increase of loading rate, but the rate of stiffness degradation accelerates [1-3]. The similar conclusions can be draw for other studies reported by Wang [4], Fan [5], Fang [6], and Xiao [7].

However, due to the multi-dimensional and non-static characteristics of ground motion, RC member is often subjected to complex dynamic force, accompanied by torsion effect. Tirasit [8] studied the mechanical properties of RC members under combined bending moment and torsion force. Test results show that the carrying capacity of RC member decreases while the damage area of RC member changes. The bending and torsion tests of RC members were carried out by Belarbi [9, 10], it was found that the failure mode, deformation capacity, and other mechanical behavior of the member changed significantly. Among them, due to the effect of the torsion, the bearing capacity of specimen decreased and the stirrup is yielded in advance. Ray [11] has also carried out tests on RC columns subjected to a combined torsion and bending. Thus, the mechanical properties of RC members are significantly changed after considering the torsion effect.

Based on the above considerations, the load-displacement curves, the carrying capacity and other mechanical behavior of reinforced concrete columns under different loading rate and torsion displacement are studied in this paper.
2. Finite element model and dynamic constitutive model

2.1. Finite element model
The numerical simulation of the RC column is performed by employing finite element software ABAQUS. The 8-node solid reduced integration element (C3D8R) is selected for concrete, while the 2-node truss element (T3D2) is selected for longitudinal reinforcements or stirrup reinforcements. The embedded element is used to represent the interaction between steel reinforcement and concrete. During the process of the simulation, the load at column end was applied with displacement control mode. In order to avoid the stress concentration, the rigid block is built at the loading point corresponding to the bottom and top of RC column, and the rigid connection between the reference point and the rigid block is adopted. Then the displacement and initial torsion angle are applied at the reference point. The influence of loading rate on the mechanical properties of RC column is mainly considered in some cases. Therefore, "Dynamic Explicit solver" is used to calculate the dynamic response of RC column in this paper.

2.2. Dynamic constitutive model of materials
Only compressive skeleton curves and hysteretic rulers are introduced for the dynamic constitutive model of concrete. The CEB model is adopted for concrete, and the detailed introduction of the concrete constitutive model is shown in Reference [12]. Besides, the ideal elastic-plastic model is used as the calculation model for steel reinforcement. The relationship of dynamic strength and quasi-static strength of steel reinforcement is shown as follows [13].

\[
\frac{f_{yd}}{f_{ys}} = 1 + c_f \log \frac{\dot{\varepsilon}}{\varepsilon_0} \quad (1)
\]
\[
\frac{f_{yd}}{f_{us}} = 1 + c_u \log \frac{\dot{\varepsilon}}{\varepsilon_0} \quad (2)
\]
\[
c_f = 0.1709 - 3.289 \times 10^{-4} f_{ys} \quad (3)
\]
\[
c_u = 0.02738 - 2.982 \times 10^{-5} f_{ys} \quad (4)
\]

where \(\dot{\varepsilon}\) is the strain rate of the steel reinforcement under dynamic loading; \(\varepsilon_0\) is the strain rate of the steel reinforcement under quasi-static loading, which is selected as 2.5\times10^{-4}/s.

3. Influence of torsion effect
Due to the multi-dimensional and non-static characteristics of ground motion, RC member is often subjected to complex dynamic force, accompanied by torsion effect. Therefore, based on the finite element model mentioned above, the initial angular displacement is applied at rigid region of the top of the member to reflect the torsion effect. The torsion displacements are given in the form of an initial angular displacement, with the value of 0°, 5°, 10° and 15°, respectively. At the same time, the finite element software ABAQUS can consider the rate-dependent of the material through dynamic constitutive model. Moreover, in order to consider the influence of loading rate on the mechanical properties of the member, a method to calculate the strain rate level of the material under near-field ground motion proposed by Asprone [14] is adopted. The strain rate levels of the material corresponding to the loading rates of 0.1mm/s, 1.0mm/s, 10mm/s and 50mm/s are 10^{-5}/s, 10^{-4}/s, 10^{-3}/s, and 10^{-2}/s, respectively.

As shown in figure 1, the load-displacement curves of the member with the initial angular displacement of 0°, 5°, 10° and 15° are obtained under different loading rates. It can be seen from figure 1 that the carrying capacity of the member decreases with the increase of initial angular displacement. Table 1 shows the carrying capacity of RC members under different loading rates and initial angular displacements. By calculating the data in table 1, it is found that the reduction extent of
the carrying capacity are 33.0%, 28.2%, 29.4% and 30.2% corresponding to the loading rate equalling to 0.1mm/s, 1.0mm/s, 10mm/s, and 50mm/s, respectively, while the initial angular displacement increases from 0° to 15°. It can be seen that the carrying capacity of the member is significantly reduced while the initial angular displacement increases.

![Load-displacement curves under different loading rates and initial torsion angles.](image)

**Figure 1.** Load-displacement curves under different loading rates and initial torsion angles.

**Table 1.** Carrying capacity under different loading rates and initial angular displacements.

| Initial angular displacement | Loading rate | 0.1mm/s | 1mm/s | 10 mm/s | 50 mm/s |
|-----------------------------|--------------|---------|-------|---------|---------|
| 0°                          | 76.6         | 78.3    | 80.5  | 84.5    |
| 5°                          | 59.0         | 62.4    | 63.5  | 65.7    |
| 10°                         | 53.9         | 57.8    | 58.6  | 61.0    |
| 15°                         | 51.3         | 56.2    | 56.8  | 58.9    |

Note: The unit in table 1 is kN.

Besides, variation of the initial stiffness can be estimated by the calculation results. It can be found that the initial stiffness of the member decreases with the increase of initial angular displacement. Take calculation results of the loading rate equalling to 0.1mm/s for an example, the initial stiffness of members with the initial angular displacement equalling to 0°, 5°, 10°, and 15° are 11.8kN/mm, 7.68kN/mm, 6.98kN/mm and 6.76kN/mm, respectively. As the initial angular displacement increases from 0° to 15°, the initial stiffness of the member decreases by as much as 42.7%. It can be found that the influence of torsion effect on the mechanical properties of the member is significant.

4. Dynamic mechanical properties of members under torsion action
Seismic load has random and dynamic characteristics, so it is very important to analyze the mechanical properties of members under fast loading conditions. Based on the consideration of the rotation component of the ground motion, this paper analyzes the changes of the mechanical properties of members under different initial angular displacements and loading rates. In the same way, load-displacement curves of each member are re-adjusted by using the above calculation results. Figure 2 shows load-displacement curves of each member under different initial angular displacements.
By comparing four groups of load-displacement curves, regardless of changes of initial angular displacement, the carrying capacity of the member always increases with the increase of loading rate. The carrying capacity of the member with a loading rate of 0.1mm/s is selected as the reference value, and the carrying capacity growth percentage of members with a loading rate of 1.0mm/s, 10mm/s and 50mm/s are calculated, as shown in table 2. It can be found that as the initial angular displacement increases, the increasing amplitude of carrying capacity of different members is obvious for different loading rates. For example, when the loading rate increases from 0.1 mm/s to 50 mm/s, the carrying capacity of the member is increased by 10.3% for the initial angular displacement equalling to 0°, while that is increased by 14.8% for the initial angular displacement equalling to 15°.

Figure 3 shows the change trend of carrying capacity under different initial angular displacements and loading rates. With the initial angular displacements of 0°, 5°, 10° and 15°, the carrying capacity of the member increases as the loading rate increases, and the overall growth trend is consistent. Based on the above analysis, it can be seen that the increase of initial angular displacement will lead to the increase of strain rate sensitivity of the member. Therefore, it is very important to consider the torsion and dynamic effects of ground motion in seismic design.

### Table 2. Growth rate of carrying capacity under different initial torsion angles.

| Initial angular displacement | Increase percentage of bearing capacity |
|-----------------------------|----------------------------------------|
|                             | 0°         | 5°         | 10°        | 15°        |
| $F_{10} - F_{0.1}$          |            |            |            |            |
| $F_{10} - F_{0.1}$          | 5.1        | 7.6        | 8.7        | 10.7       |
| $F_{50} - F_{0.1}$          |            |            |            |            |
| $F_{50} - F_{0.1}$          | 10.3       | 11.4       | 13.2       | 14.8       |

Note: $F_{0.1}$, $F_{1}$, $F_{10}$, $F_{50}$ are the carrying capacity of members with loading rate of 0.1mm/s, 1.0mm/s, 10mm/s and 50mm/s at different initial angular displacements, respectively.
5. Summary
Based on the above analysis, the following conclusions can be drawn:

1) With the increase of initial angular displacement, the flexural carrying capacity and the initial stiffness of the member decrease.

2) The stiffness degradation amplitude with larger initial angular is more obvious. In addition, as the initial torsion angle changing from 10° to 15°, the initial stiffness degradation is the most significant.

3) The influence of loading rate on reinforced concrete column is more obvious with larger initial angular displacement. Under the condition of higher initial displacement angle, the carrying capacity of the member decreases obviously.

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