Analysis of Dynamic Response of RC Flat Plate Frame’s Performance under Dynamic Loads

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Abstract. The progressive collapse of structures under accidental actions is a serious threat to the public safety. Numerical analysis of a 2x2-bay and single-story reinforced concrete flat plate frame model is done in this paper, the time of failure and the position of failure column are taken into account. It can be found that the Dynamic Amplification Factor (DAF) increases with the decrease of failure time, the DAF under compressive membrane action is less than the stage of the tensile membrane action and the compressive membrane action is more important to avoid progressive collapse. When the time of failure is not changed, the DAF is negatively correlated with the load under compressive membrane action and the DAF is positively correlated with the load under tensile membrane action.

1. Introduction
A progressive collapse initiates as a result of local structural damage and develops, in a chain reaction mechanism, into a failure that is disproportionate to the initiating local damage [1]. Flat plate frame which is widely used because of its advantages is at the risk of progressive collapse. In 1995, Alfred P. Murrah Federal Building in Ohio was hit by a truck bomb, causing progressive collapse of the structure [2]. In 1997, the whole plate of a British parking lot fell off due to punching failure of one of the slab-column connections [3]. In 2000, progressive collapse of a shopping centre in Switzerland caused by punching failure of slab-column connection [4]. The progressive collapse of the flat plate frame which is a serious threat to the public safety attracts the attention of the engineering ambitions. In recent years, a lot of researches have been done on the resistance of progressive collapse of slab flat plate frame. Slab-column connections under vertical and lateral reversed load were analyzed by Ma Yunchang and LvXilin in 2001, the plastic limit state method was used and a set of equations was derived and simplified to practical formulas [5]. In 2012, the experiment of a 2x2-bay and single-story reinforced concrete flat plate frame model was carried out by ZHANG Fanzhen, the compressive-tensile membrane action was revealed [6]. Since 2013, Yi Weijian carried out a lot of experiments on slab-column connections, the effects of concrete strength, ratio and yield strength of longitudinal reinforcement on the failure modes and punching shear capacity were analyzed [7, 8, 9, 10]. The experiment of flat plate frame under dynamic loads is complex and difficult, so the researches focus on the static loads. ANSYS/LS-DYNA is used in this paper to analyze the model in reference [6]; the
effects of failure time and position of failure column are studied. These research results possess a
certain reference value to the design of flat plate frame to resist progressive collapse.

2. Model Establishment
Discrete model is established using ANSYS/LS-DYNA. Element SOLID164 and
MAT_CSCM_CONCRETE are used for the concrete; BEAM161 and MAT_PLASTIC_ KINEMATIC are used for the steel. Strain rate effect is considered by the parameters given by the
materials model. The finite element model is established according to the frame model under large
load in the reference [11]. The loading time is 9.6ms and the load size is 12.5kN.

A 1/4 finite element model is established which is shown in Fig.1. The material parameters used in
this study is shown in table 1. Compare the results of numerical simulation with the experimental
results. The horizontal displacement of middle column, the vertical displacement of frame and the
strain of steel is shown in Fig.3.
Figure 3. The results of numerical simulation and the experimental.

Table 1. The material parameters.

| Members  | Concrete $\sigma_c$/MPa | Longitudinal steel $\sigma_y$/MPa, $\sigma_u$/MPa, d/mm | Stirrup $\sigma_y$/MPa, $\sigma_u$/MPa, d/mm |
|----------|-------------------------|----------------------------------------------------|------------------------------------------|
| Beam     | 37.2                    | 563, 635, 8/12                                     | 300, 420, 6                              |
| Column   | 12                      |                                                    |                                          |

It can be seen from the results of comparison that the results of numerical simulation is basically consistent with the experiment. Reasonable prediction of the response of RC structure under dynamic load can be given by the model.

3. Dynamic Response of Flat Plate Frame
The performance of resistance to progressive collapse of flat plate frame under static load is studied in the reference [6]. The numerical simulation method is adopt in this paper to analyse the performance of resistance to progressive collapse of the flat plate frame under dynamic load.

A 1/4 finite element model is established which is shown in Fig.2 in order to improve the calculative efficiency. The material parameters which are selected according to the experiment are shown in Table2.

Table 2. The material parameters.

| Members  | Concrete $\sigma_c$/MPa $\rho$/kg·m$^{-3}$ | Longitudinal steel $\sigma_y$/MPa, $\sigma_u$/MPa, d/mm | Stirrup $\sigma_y$/MPa, $\sigma_u$/MPa, d/mm |
|----------|------------------------------------------|----------------------------------------------------|------------------------------------------|
| Plate    | 39.5                                     | 452, 589, 6.5/14                                   | 300, 420, 6                              |
| Column   |                                          |                                                    |                                          |
Assume that the axial force of the column is $G$ before failure, the failure time of column is $t$ and the axial force of column is $G(t)$ during the column failing. It can be found that the load carried by plates because of the failure of column is $F(t) = G - G(t)$ which is shown in Fig.4. Distributed load is applied on the plates as the curve shown in Fig.4. The loads which are respectively $10.25 \text{kN/m}^2$, $12.65 \text{kN/m}^2$, $15.05 \text{kN/m}^2$, $17.37 \text{kN/m}^2$ and $19.35 \text{kN/m}^2$ are chosen according to the experiment. The times of failure are respectively 10ms, 20ms, 40ms, 60ms, 80ms and 100ms. There are totally 30 kinds of working conditions. The peak and stable value of the vertical displacement of column under different working conditions are shown in table 3.

![Figure 4. Load curve.](image)

![Figure 5. DAF of different working conditions.](image)

The cracks of the top and bottom when the failure time is 20ms and the load is $17.37 \text{kN/m}^2$ are shown in Fig.6. It can be seen that the cracks under dynamic load are basically the same as that under static load.

![Figure 6. Cracks.](image)
The DAF is calculated according to the peak value of the column vertical displacement which is shown in Fig.5. It can be found that the DAF decreases with the increase of the time of column failing when the loads are the same.

It is given in the reference [6] that the vertical displacement of column when the compressive membrane change to tensile membrane is 42mm. Draw a dashed line corresponding to the displacement of 42mm in Fig.5 according to the different points’ peak value of displacement. It can be seen that the DAF under tensile-compressive membrane action is on both sides of the dashed line and the DAF under compressive membrane action is less than the stage of the tensile membrane action. It shows that the compressive membrane action is more beneficial to the resistance to progressive collapse than the tensile membrane action. The compressive membrane action should be taken a full consideration and the threshold value should be improved when the flat plate frames are designed.

Table 3. The peak and stable value of the vertical displacement of column.

| Loads/kN·m⁻² | Failure time/ms | Static | 10 | 20 | 40 | 60 | 80 | 100 |
|-------------|-----------------|--------|----|----|----|----|----|-----|
| 10.25       | 14.88           | Peak   | 33.51 | 31.93 | 27.96 | 24.02 | 21.81 | 23.19 |
|             |                 | Stable | 30.62 | 29.43 | 26.54 | 23.56 | 22.62 | 22.91 |
| 12.65       | 27.71           | Peak   | 52.59 | 51.08 | 47.12 | 43.93 | 42.46 | 42.45 |
|             |                 | Stable | 47.65 | 46.46 | 43.70 | 41.47 | 40.45 | 40.33 |
| 15.05       | 41.20           | Peak   | 93.63 | 90.04 | 89.36 | 87.19 | 83.96 | 79.29 |
|             |                 | Stable | 87.11 | 82.42 | 84.04 | 82.87 | 80.07 | 75.55 |
| 17.37       | 54.70           | Peak   | 123.46 | 113.11 | 113.70 | 117.53 | 107.12 | 107.95 |
| 19.35       | 73.00           | Stable | collapse | 117.53 | 107.12 | 107.95 | collapse | collapse |

The DAF curve when the load is 12.65kN/m² below the DAF curve when the load is 10.25kN/m². Divide the plate into many beams, the compressive membrane action of plate can be seen the superposition of the arch action of beams. The cracks at the middle of the beams’ lower surface and at the ends of beams’ upper surface develop as the loads increasing. The rise of arch increases so that the arch action enhance. So the DAF under the compressive membrane action decreases. It can be judged that the DAF under the compressive membrane action is negatively correlated with the load when the failure time of column is equal.

The DAF curve when the load is 17.37kN/m² above the DAF curve when the load is 15.05kN/m². Divide the plate into many beams, the tensile membrane action of plate can be seen the superposition of the catenary action of beams. The stiffness of beams degenerates because of the steel yield and concrete cracking as the loads increasing. The catenary action is weakened so that the DAF under the tensile membrane action increases. It can be judged that the DAF under the tensile membrane action is positively related to the load when the failure time of column is equal.

4. Conclusion
Numerical analysis of the flat plate frames under different dynamic loads has been made in this paper. The dynamic response of flat plate frames when the failure times of middle column are different has been studied. It can be found that the Dynamic Amplification Factor (DAF) increases with the decrease of failure time, the DAF under compressive membrane action is less than the stage of the tensile membrane action and the compressive membrane action is more important to avoid progressive collapse. When the time of failure is not changed, the DAF is negatively correlated with the load under compressive membrane action and the DAF is positively correlated with the load under tensile membrane action.

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