CRACK DAMAGE DISTRIBUTION OF CONCRETE FILLED STEEL TUBE FRAME UNDER EXTREMELY STRONG GROUND MOTION

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ABSTRACT:
Seismic response and crack damage of concrete filled steel tube frame (CFT-frame) under strong ground motion are numerically analyzed and the damage ratio and damage distribution in the frame are investigated. In order to prevent the damage concentration, the design condition of CFT-frame expressed by the strength ratio of concrete to steel tube is derived from the numerical results of seismic response and damage ratio distribution. CFT-frames are designed on the basis of the proposed design condition and the calculations of the seismic response and damage of them have been carried out. From the calculated results, it is ascertained that the proposed design condition of CFT-frame is useful to prevent the damage concentration in CFT-frame under strong ground motion.

KEYWORDS: concrete filled steel tube, seismic response analysis, accumulated plastic deformation, steel tube crack, damage ratio.

1. INTRODUCTION
Seismic response collapse of concrete filled steel tube frame (CFT-frame), which is composed of CFT-column and H-section beam, is closely related to the fracture of CFT-column caused by the steel tube crack1)-3). Especially the first crack fracture of CFT-column among all CFT-column fractures in the frame is directly related to the seismic response collapse of CFT-frame. From this reason it is required in the ultimate earthquake resistant design of CFT-frame to prevent the damage concentration of CFT-column.

The main conditions of ultimate earthquake resistant design of multi-story CFT-frame are the story shear strength and the distribution condition of it. The crack fracture of CFT-column under seismic load can not be prevented only by making the story shear strength of frame large enough because the crack fracture of CFT-column is effected by the strength ratio of filled concrete to steel tube of it4). To prevent the fracture damage concentration of CFT-frame, the design condition expressed by the strength ratio of filled concrete to steel tube of CFT-column is required.

On the basis of numerical analysis of seismic response damage of multi-story CFT-frame, the fracture damage ratio of CFT-column and the damage distribution of CFT-frame are investigated and the optimum design condition to prevent the fracture damage concentration of CFT-column are derived from the numerical results.

2. NUMERICAL ANALYSIS METHOD OF SEISMIC RESPONSE AND DAMAGE DISTRIBUTION
2.1 Multi-story CFT-frame model
In the dynamic collapse analysis of CFT-frame1)-3), the multi-story plane frame is assumed to be composed of the rigid panel zones of beam-column connection and the axially elastic members with elastic-plastic hinges at the both ends as explained in Fig.1. The mass of frame is concentrated in every panel zone of beam-column connection and the rotational inertia of it is determined by assuming the mass in the panel zone distributes uniformly.

The deformation of frame is expressed by the rotation (\(\theta_i\); I: number of beam-column connection), the horizontal displacement (\(u_i\)) and the vertical displacement (\(w_i\)) of every rigid beam-column connection. The viscous damping of frame is expressed by the Rayleigh Damping in which the damping factors of the first mode (\(h_1\)) and the second mode (\(h_2\)) are assumed to be \(h_1=0.02\) and \(h_2=0.02\).

2.2 Restoring force characteristics and model of CFT-column
The restoring force model of elastic-plastic hinge was determined on the basis of the dynamic loading test of CFT-column5)-6). Fig.2 shows how to define the restoring force (M) and the deformation (\(\phi(=\delta_c/L_c)\)) by the horizontal load (H), the axial load (N) and the column-end deflection (\(\delta_c\)) of test.

According to the test results the restoring force divided by \(M_a\) (\(M/M_a\)) of CFT-column until the local buckling of steel tube is approximated by the Bi-linear model whose skeleton curve is explained in Fig.3(A) and after the local buckling of steel tube it is expressed by the Clough model7) as shown in Fig.3(B). The stiffness ratios in the plastic...
range in Fig.3(A) and Fig.3(B) are given as \( K_1/K_0 = 0.2 \), \( K_2/K_0 = 0.001 \) which are approximated on the basis of the test result.

The restoring force model mentioned above is defined by the restoring force divided by \( M/M_u \) which the ultimate bending strength \( M_u \) changes at every moment according to the varying axial force of CFT-column. From this reason the restoring force model presented here can simulate the effect of varying axial force of CFT-column.

### 2.3 Local buckling and crack fracture of CFT-column

From the cyclic loading test of CFT-column it is shown that the steel tube of CFT-column cracks and fractures when the accumulated plastic strain of steel tube becomes to be equal to the critical value \( (\alpha \varepsilon_f) \). From this result the crack and fracture condition of CFT-column is expressed by Eq.(1)\(^5\)\(^-\)\(^6\).

\[
\Sigma \varepsilon_{TC} + \Sigma \varepsilon_T = \alpha \varepsilon_f \tag{1}
\]

in which \( \varepsilon_T \) is the plastic tension strain of steel tube in the tension stress side and \( \varepsilon_{TC} \) is the plastic strain due to the local buckling deformation of steel tube in the compression stress side as explained in Fig.5. In Eq.(1), \( \alpha (-0.3 \rho + 5.0) \): constant expressed by the strength ratio of concrete to steel tube \( \rho \), \( \varepsilon_f \): fracture strain, \( \Sigma \) summation of plastic strain under cyclic load. From Eq.(1) the damage ratio of steel tube \( (\xi_{cr}) \) is expressed by Eq.(2).

\[
\xi_{cr} = (\Sigma \varepsilon_{TC} + \Sigma \varepsilon_T) / \alpha \varepsilon_f \tag{2}
\]

The local buckling of steel tube in the calculation of \( \varepsilon_{TC} \) is obtained by the upper bound theorem of the limit analysis\(^7\). By the use of Eq.(1) and Eq.(2), the local buckling and the crack of steel tube in the restoring force of CFT-column are decided and it is assumed that the restoring force and the stiffness of CFT-column are fully lost after the steel tube crack.

### 2.4 Restoring force model and crack fracture of H-section beam

The H-section beam of multi-story CFT-frame is also expressed by the elastic member with the elastic-plastic hinges at both ends as shown in Fig.1. The restoring force of the elastic-plastic hinge is decided by the Bi-linear model shown in Fig.4 in which the restoring force characteristics are given by the full plastic moment \( (M_p) \) and the ultimate bending strength \( (M_u) \) of H-section beam. The strain hardening of behavior H-section beam is approximated by Eq.(3) which is obtained by assuming the H-section beam is expressed by the two-flange section member.

\[
\frac{K_1}{K_0} = \frac{1/y - 1}{1.5y(1 - y)(1 + u) - 1}
\]  \( \tag{3} \)

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**Fig.1** Frame model of numerical analysis

**Fig.2** Loads of CFT-column \((H, N)\) and restoring force \((M)\) of fixed-end

**Fig.3** Restoring force model and skeleton curve of CFT-column

**Fig.4** Bi-linear model and skeleton curve of H-section steel beam

\( (K_1/K_0: \text{Eq.}(3), K_2/K_0=0.001, \phi_p=M_p/K_0) \)
in which \( y(=\sigma_y/\sigma_u) \) and \( u(=\varepsilon_u/\varepsilon_f) \) mean the yield stress ratio and the ultimate tensile strain ratio respectively. The crack fracture of H-section beam\(^3\) is assumed to be the very low-cycle fatigue behavior and to be approximated by the Palmgren-Miner rule\(^9\). From the Palmgren-Miner rule that the damage ratio of H-section beam is given by the accumulation of the damage in each cycle, the damage ratio at any moment under cyclic load can be expressed by Eq.(4) in which \( N_f \) means the number of cycle to fracture under the j-th cycle load.

\[
\frac{b_{cr}^0}{\sigma_{cr}} = \sum \frac{1}{N_{fj}}
\]

(4)

The number of cycle to fracture \( N_f \) in Eq.(4) is approximated by the Coffin-Manson expression\(^9\) in Eq.(5).

\[
\epsilon_{p_a} = \epsilon_f(2N_f)^c
\]

(5)

in which \( \epsilon_f \): fracture strain and \( \epsilon_{p_a} \): plastic strain amplitude of H-section beam.

2.5 Strong ground motion

To calculate the seismic response and damage of CFT-frame, JMA-KOBE NS & UD (1995) recorded in Kobe and the artificial ground motion ART NS & UD are used as input ground motion. The acceleration response spectra \( (S_a) \) of them are shown in Fig.6 comparing with each others. In order to investigate the effect of the characteristics of ground motion, the ground motions satisfy the conditions that the spectrum intensities \( (SI) \) of them are the same and the response spectra are quite different between them as shown in Fig.6.

3. DESIGN OF MULTI-STORY CFT-FRAME

3.1 Design conditions of CFT-frame

The CFT-frames to be calculated in this study are composed of CFT-columns and H-section beams and designed under the following conditions\(^3\).

i) According to the Japanese design code, the ultimate base shear strength ratios \( (C_B) \) of the 15-story 3-bay frames and the 7-story 3-bay frames are \( C_B=0.25 \) and \( C_B=0.40 \) respectively. The ultimate strength of frame is calculated by the limit analysis assuming the collapse mechanism of frame with plastic hinge at every beam-end and the upper and lower column-ends in the top story and the first story.

ii) The column-over-design factors \( (r_c) \) of all stories except the highest story are the same in each frame. There are three kinds of factors and they are \( r_c=1.2, r_c=1.5 \) and \( r_c=2.0 \).

iii) The stress ratios of filled concrete to steel tube \( \rho (=\sigma_cA_c/\sigma_uA_s, A_c, A_s: sectional areas of concrete and steel tube respectively) \) of all CFT-columns are assumed to be the same in each frame. In considering with the range of test data \( (\rho<3.4) \) the strength ratio of CFT-column is \( \rho<5.0 \).

iv) Every H-section beam of multi-story frame assumes the critical conditions of the width-to-thickness ratio of flange \( (b/t_f) \) and web \( (h/t_w) \) and the lateral buckling length \( (L_bh/A_f) \). They are \( b/t_f=20, h/t_w=71 \) and \( L_bh/A_f=375 \).

3.2 Designed CFT-frames

Multi-story CFT-frames analyzed in this study are 15-story 3-span frame and 7-story 3-span frame. Assuming that any section of steel tube are available, they are designed under the conditions mentioned above.

The story-height of every CFT-frame is 4.0 m and the span lengths of outer span and inner span are 8.0 m and 6.0 m respectively. The weight of each story is 2000KN. The yield stress \( (\sigma_y) \) and tensile strength \( (\sigma_u) \) of steel tube and H-section beam are \( \sigma_y=340N/mm^2, \sigma_u=440N/mm^2 \). The fracture strains \( (\varepsilon_f) \) of steel tube and H-section beam are the same and it is \( \varepsilon_f=0.2 \). The compression strength of concrete \( (\sigma_c) \) filled in steel tube are \( \sigma_c=30N/mm^2, 60N/mm^2 \) and \( 120N/mm^2 \).

The designed all CFT-frames are shown with white circles in Fig.7 in which there are the diameter \( (D) \) of CFT-column in the first story and the natural period \( (T) \) of CFT-frame. In account that the design conditions of CFT-frame are quite different among them, every diameter of CFT-column \( (D) \) is in practical range and the natural peri-
ods (T) of 15-story frame and 7-story frame are nearly constant respectively. From these designed frames it is ascer-
tained that the design method of multi-story CFT-frame shown in the former section is useful.

4. DAMAGE CONCENTRATION OF CFT-FRAME

The damage distributions of CFT-frame under JMA-KOBE NS&UD and ART NS&UD are shown in Fig.8(A) and Fig.9. The damages of CFT-frame shown in these figures are the crack fracture ratio of CFT-column (cDcr) and H-section beam (bDcr) explained in section 2.3 and section 2.4. In Fig.8 the damage ratios are expressed by the thick lines perpendicular to the axis of column and beam. The thick lines are also explained by the numerals in the fig- ures. Fig.9 shows the seismic response damages of all CFT-frames shown in Fig.7. In Fig.8(A) and Fig.9 we can see the remarkable differences of damage concentration among the CFT-frames and the remarkable concentration of damage ratio in some CFT-frames in spite that all CFT-frames shown in these figures are designed under the same design condition of ultimate story shear strength and strength distribution along the story. From these results it is also ascertained that the damage concentration can not be prevented only by the design conditions of story shear strength or distribution of it.

5. DESIGN CONDITION TO PREVENT DAMAGE CONCENTRATION

5.1 Accumulated plastic deformation of CFT-column

According to cyclic loading test of CFT-column, the crack fracture of CFT-column is closely related to the accumulated plastic deformation of it\(^3\)-\(^6\). From this reason, the distributions of the accumulated plastic deformation in numerically analyzed CFT-frames under strong seismic load are examined and some of the results are shown in Fig.10. The thin real lines are numerically analyzed seismic responses and the thick real lines show the approximations expressed by the sum of the natural deformations \(P_i\) given by Eq.(6).

\[
P_i = \sum \frac{\phi}{\phi_{u}}
\]

in which \(\phi_{u}=M_{u}/K_{o}\), \(M_{u}\): ultimate bending moment, \(K_{o}\): initial bending stiffness, \(\phi\): CFT-column deformation

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![Fig.7 Diameter of CFT-column (D) and natural period (T) of CFT-frame](image_url)

![Fig.8 Seismic response damages of CFT-frame (cDcr, bDcr)](image_url)
by natural frame deformation, \( m \): order of natural frame deformation, \( C_m \): constant, \( i \): number of story. The dashed lines show the natural deformations included in the thick real line. We can see that Eq.(6) gives the good approximation of the accumulated plastic deformation of CFT-column.
To apply the approximated distribution of accumulated plastic deformation of CFT-column to design condition of CFT-frame, the average values of all CFT-frames are calculated and shown in Fig.11. The obtained values, which are designated by \( P_{oi} \) in Fig.11, express the maximum value among the accumulated plastic deformations of all column-ends in each story.

5.2 Plastic tension strain components of CFT-column
As mentioned in Eq.(2), the fracture damage ratio of CFT-column is given by the two components of \( \Sigma \epsilon_T' / (\alpha \epsilon_f) \) and \( \Sigma \epsilon_T / (\alpha \epsilon_f) \). The time histories of the component in seismic response of CFT-frame are shown in Fig.12. It is shown in this figure that the two components and the time histories of them are similar between them. According
to the design condition and the input ground motion, the differences between the two components changes but the
time histories of them are similar to that in Fig. 12. From this reason it is assumed here that the damage ratio can
be approximated only by the plastic strain in the tension stress side \( \Sigma \varepsilon_T \) as shown in Eq.(7).

\[
D_{cr} = 2 \Sigma \varepsilon_T / (\alpha \varepsilon_f) \quad \quad \quad (7)
\]

5.3 Plastic tension strain and deformation of CFT-column

The relation between the plastic tension strain \( \varepsilon_T \) and CFT-column deformation \( \phi / \phi_u \) is derived by assuming
the following conditions5).

i) The bending moment of CFT-column distributes linearly along the axis and the curvature in the plastic zone
between \( M_p \) and \( M_u \) also distributes linearly as shown in Fig. 13.

ii) The plastic zone does not change according to the column deformation.

The plastic tension strain of steel tube \( \varepsilon_T \) at fixed-end section can be expressed by the curvature of this
section \( \kappa_p \) as shown in Eq.(8).

\[
\varepsilon_T = (1 + \cos \theta_n) \frac{D}{2} \kappa_p
\]

in which \( D \): diameter of steel tube, \( \theta_n \): polar coordinate of neutral axis. From the equilibrium condition of axial
force and the stress distribution of CFT-column under ultimate bending moment as shown in Fig. 14, Eq.(9) is
obtained.

\[
\pi (1 + \rho) \frac{N_u}{N} - \frac{1}{\sqrt{3}} (3 \theta_n - 2 \pi) - \pi (\theta_n - \sin \theta_n \cos \theta_u) = 0 \quad \quad \quad (9)
\]

in which \( N/N_u \) \((N_u = \sigma_c A_c + \sigma_u A_e)\): axial force ratio, \( r \) \((=\sigma_{ce}/\sigma_c, \sigma_{ce} \text{ : strength of confined concrete})\): confine effect. The confine effect of filled concrete \( r \) was given by \( r=0.76/\rho+0.765 \) on the basis of CFT-column test. From the conditions i)-ii) mentioned above, the curvature \( \kappa_p \) of plastic deformation at the fixed-end can be expressed by the plastic deformation ratio \( \mu (=\phi_p / \phi_u) \) in which \( \phi_p (=\delta_p / L_c) \): plastic column deformation, \( L_c \): column length as shown in Eq.(10).

\[
\kappa_p = \frac{6}{(1 - M_p/M_u)(2 + M_p/M_u)} (\frac{\phi_u}{\delta_c}) \mu \quad \quad \quad (10)
\]

Substituting \( \kappa_p \) in Eq.(10) into Eq.(8), \( \varepsilon_T \) is expressed by \( \mu_T \) which is the plastic deformation ratio of CFT-column

\[\text{Fig.11 Approximated distribution of accumulated plastic deformation (P}_{oi})\]

\[\text{Fig.12 Time histories of damage ratio components of CFT-column under strong seismic load}\]

\[\text{Fig.13 Assumed plastic deformation and moment distribution of CFT-column}\]

\[\text{Fig.14 Stress distribution of CFT-column under ultimate bending moment}\]
to give the plastic tension strain of steel tube in the tension stress side.

\[ \varepsilon_T = f_T \mu_T \quad \text{in which} \quad f_T = \frac{3(1 + \cos \theta_p)}{(1 - M_p/M_u)(2 + M_p/M_u)} \left( \frac{D}{L_p} \right) \phi_u \]  

\text{(11)}

The accumulated tension plastic strain (\( \Sigma \varepsilon_T \)) is given by Eq.(12) because \( f_T \) in Eq.(11) is not effected by the cyclic load.

\[ \Sigma \varepsilon_T = f_T \Sigma \mu_T \]  

\text{(12)}

in which \( \Sigma \mu_T \) is the accumulated plastic deformation ratio of CFT-column to give the tension plastic strain of steel tube in the tension stress side. \( \Sigma \mu_T \) is nearly equal to the half of the accumulated plastic deformation (\( \Sigma \mu_T = \Sigma (\Delta \phi_p/\phi_u) \)/2). In section 3.3 the accumulated plastic deformation (\( \Sigma (\Delta \phi_p/\phi_u) \)) is shown to be approximated by the value of \( P_i \) (i: number of story) in Eq.(6). By expressing \( \Sigma \mu_T \) by the average value \( P_{oi} \) (Fig.11) of \( P_i \), Eq.(13) is obtained.

\[ \Sigma (\varepsilon_T)_i = (f_T)_i \frac{P_{oi}}{2} \]  

\text{(13)}

By the use of Eq.(13), the fracture damage ratio of CFT-column (\( D_{cr} \)) in Eq.(2) can be expressed by \( P_{oi} \).

\[ (\frac{D_{cr}}{\alpha \varepsilon_T}_i)_i = \left( \frac{f_T}{\alpha \varepsilon_T} \right)_i P_{oi} \]  

\text{(14)}

Under the condition that the fracture damage ratio of every story is equal to \( D_o \) (\( D_o \): constant), the optimum design condition to prevent the damage concentration of CFT-column can be derived and expressed by Eq.(15).

\[ \left( \frac{f_T}{\alpha \varepsilon_T} \right)_i P_{oi} - D_o = 0 \]  

\text{(15)}

5.4 Optimum design condition to prevent damage concentration

Instead of the design condition iii) in section 3.1, the optimum design condition expressed by Eq.(15) is used to design CFT-frames. The strength ratios of concrete to steel tube (\( \rho_i \)) of CFT-columns in these designed CFT-frames are also corresponding to the optimum design conditions to prevent the damage concentration of CFT-frame.

The strength ratios \( \rho_i \) change in the range smaller than about 10% according to the design condition of CFT-frame. From this reason the strength ratios of concrete to steel tube (\( \rho_{oi} \)) as the optimum design condition are given by the average values of \( \rho_i \). The final optimum design condition expressed by the strength ratio of concrete to steel tube (\( \rho_{oi} \)) is shown in Fig.15.

6. DAMAGE OF CFT-FRAME UNDER OPTIMUM DESIGN CONDITION

By the use of the optimum design condition given by \( \rho_{oi} \), CFT-frames are designed under the conditions in section 3.1 except the condition iii). The designed CFT-frames are explained by black circles in Fig.7 and compared with the CFT-frames designed without the optimum design condition and shown with white circle in Fig.7. It is shown in Fig.7 that there is not clear difference of the diameter of CFT-column (\( D \)) and the natural period (\( T \)) among the frames.

In this optimum design of CFT-frame, it is also shown that some CFT-frames can not be designed to satisfy the design condition of \( \rho_{oi} \) because the difference among the values \( \rho_{oi} \) of all stories are too large. From this reason the CFT-frames to which the optimum design condition of \( \rho_{oi} \) is applicable are limited.
The seismic response damage of these CFT-frames under optimum design condition are shown by real lines in Fig.16. The dashed lines in Fig.16 show the seismic response damage of CFT-frame designed under the same conditions in section 3.1 and without the optimum design condition of $\rho_{oi}$. Comparing the real lines with the dashed lines, it is ascertained that the damage concentration and the fracture damage ratio of the real lines are small enough and the derived optimum design condition expressed by $\rho_{oi}$ is useful.

7. CONCLUSIONS
To prevent the fracture damage concentration of CFT-frame, the design condition expressed by the strength ratio of filled concrete to steel tube of CFT-column is derived. On the basis of numerical analysis of seismic response damage of multi-story CFT-frame, it is ascertained that the proposed optimum design condition to prevent the fracture damage concentration of CFT-column is useful.

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