Nonlinear Analysis of the New Composite Frame Structure

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Abstract: In this paper, we have made nonlinear finite element analysis of extension-story concrete composite frame on the basis of the experimental study of the new extension-story concrete composite frame. We obtain bearing capacity under drab loading and hysteresis curve, bearing capacity, ductility coefficient, etc in low cyclic loading. Research shows that the composite structure framework has excellent performance of earthquake resistance, which can satisfy 7 degrees seismic fortification demand.

Keywords: clad steel and concrete composite beam; composite frame; seismic performance; nonlinear; finite element

1 Introduction
In the early eighties of last century, the United States and Japan take the lead in developing a new type of composite frame structure system[1,2], which can fully utilize and play steel components and reinforced concrete members of their respective bending or compressive strength, stiffness, ductility and architectural function applicability aspect advantages, namely the composite frame structure (referred to RCS) which is composed of reinforced concrete columns and steel beams and has been successfully applied in middle-rise and high-rise buildings, achieving good economic results. However, with the further study of composite frame structure computational theory, people find the shortcomings in structure of composite frame structures under the action of fire resistance and negative moment. In order to improve the shortcomings, the authors propose a new composite frame structure and carry out the experimental study. On the basis of previous research, this paper further analyzes the nonlinear properties of the composite frame in low cyclic loading and reveals the failure form, failure mechanism, anti-earthquake ductility and energy dissipation capacity, deformation restoring capacity, loading capacity of the composite frame structure through the finite element simulation.

2 Material constitutive relationship
2.1 Concrete
Concrete stress - strain relationship under uniaxial compression with a combination formula of Hongnestad[3] and our country concrete code[4]:

\[
\sigma = \begin{cases} 
\sigma_0 \left[ 2 \left( \frac{\varepsilon}{\varepsilon_0} \right) - \left( \frac{\varepsilon}{\varepsilon_0} \right)^2 \right], & \varepsilon \leq \varepsilon_0 \\
\sigma_0 \left[ 1 - 0.15 \left( \frac{\varepsilon - \varepsilon_0}{\varepsilon_u - \varepsilon_0} \right) \right], & \varepsilon_0 < \varepsilon < \varepsilon_u 
\end{cases} 
\]

(1)

where, \( \sigma_0 = f_c, \varepsilon_0 = 0.002, \varepsilon_u = 0.0033 \). \( f_c \) is the compressive strength design value of concrete prism body. When \( \varepsilon = \varepsilon_u \), take \( \sigma_u = 0.85f_c \). Concrete stress-strain relationship is shown in Figure 1. Concrete failure criterion with the Willam-Warnker five parameter model[5,6], the formula is as follows.

\[
\frac{F}{f_c} - s \geq 0 
\]

(2)

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where, $F = F(\sigma_1, \sigma_2, \sigma_3)$ is the stress combination, $f_c$ is the function of main stress. $S$ for the failure surface function, $S = S(f_t, f_c, f_{cb}, f_1, f_2)$

The default value in the program: $f_{cb} = 1.2f_c$, $f_1 = 1.45f_c$, $f_2 = 1.725f_c$. Close concrete crushed criteria, considering only tensile softening effect, set the limit strength under uniaxial compression for -1.

![Figure 1: Concrete stress-strain relationship under uniaxial compression](image1)

![Figure 2: Von-Mises yield surface](image2)

![Figure 3: Strengthening model](image3)

![Figure 4: Steel stress-strain relations](image4)

### 2.2 Steel

Steel yield criterion with the Von Mises yield criterion, when the equivalent stress exceeds the material yield stress, plastic deformation will occur. Von Mises yield surface shown in Figure 2. In the 3-D, the yield surface of Von Mises yield criterion is a cylindrical surface with $\sigma_1 = \sigma_2 = \sigma_3$ for shaft, in the 2-D, the yield surface is an ellipse, any stress state in the interior of yield surface, any stress state in the exterior of the yield surface will cause yield. Servo strengthening model assumes that the size and shape of the subsequent yield surface are the same as the initial yield surface. In the strengthening process, the subsequent yield surface is only the whole initial yield surface translation in stress space, strengthening model shown in Figure 3. Steel (including steel, steel plate) constitutive relation with bilinear servo strengthening model, which strengthening modulus $E_t = 0.01E_u$. Steel stress-strain relationship is shown in Figure 4.

### 3 Finite element model establishing

Concrete unit use integral SOLID65 unit provided by ANSYS and steel use SOLID45 unit to build the model. Parameters such as material properties, model size and load see the experimental design parameters of reference[7]. Use mapping grid to divide the unit, to the places where stress concentration are easy to appear such as the bearing and loading points nearby use add up steel plate to reduce stress concentration. Loading system in analysis is consistent with loading system in test. In addition, when establishing the model, it is assumed that the ground beam give a full constrain to the frame column, so
we built two frame columns directly instead of establish the model of the ground beam part. We exert fully constraint on the frame column bottom directly instead of the action of the ground beam. We select displacement load for the horizontal load here, exerting a larger displacement to the structure, setting up adequate sub-steps, activating the automatic time step and applying predictor options. Specific model is shown in Figs 5 and 6.

We usually adopt incremental method and iterative method[8] to solve the nonlinear problems. Incremental method requires each step to re-form stiffness matrix, relatively taking too much time, and because the use of piecewise linear, error accumulation of each class load will cause large deviation. Iterative method is simple to use and is applicable to reaction of structure under full load. The drawback is that it can not guarantee convergence and can not describe the behavior in the loading process. ANSYS use Newton - Rapson iterative method, it forces the end solution of each load increment to achieve a balance convergence within a tolerance range.
4 Nonlinear analysis of extension-story concrete composite frame under monotonic loading

4.1 Ultimate bearing capacity

The frame column is the main resist lateral force component for structure. In ANSYS analysis, we think that the component damage when the concrete average compressive strain in the root of the frame column achieve concrete ultimate strain. After calculation, the top ultimate horizontal load of framework model is 425kN, which is close to the test results 412.5 kN. The uniaxial loading calculated value is higher than the reciprocating loading experiment value. Figure 8 is the relation curves of top-level lateral displacement and load of the composite frame. The column cracks develop more than the beam under ultimate load, and the cracks of columns are mainly concentrated in joint zone. Crack first appears at the bottom of the outside of the right column when loaded to 46kN; the left upper and bottom of composite beams simultaneously appear transverse crack, but the quantity at the bottom is much less than the crack of the negative moment region flange plate when loaded to 200kN; With the increase of load, transverse cracks of the beam end gradually develop to midspan direction.

4.2 Distribution of framework equivalent stress under ultimate load

Figure 9 is the equivalent stress distribution of combination frame steel members under the ultimate load. It can be seen from Figure 9, in the positive moment zone of framework top-level composite beam, the tensile stress of steel slab close...
to yield, equivalent stress value reached 300MPa and the stress of tensile direction for 330MPa, while in the negative moment zone equivalent stress value of the steel beam floor is 244MPa, the stress of compression direction for 280MPa, the maximum equivalent stress of web steel beams appear at one end of the negative moment zone for 288MPa, minimum appears in the midspan position. Through the stress diagram we can also see that the stress on the flange plate is larger, if the flange in the negative moment zone is very harmful, so welding braces on flange plate is necessary structural measures, otherwise the flange plate may instability failure result of partial pressure.

4.3 Nonlinear analysis of extension-story concrete composite frame under low reversed cyclic loading

Use ANSYS software to analyze the seismic performance of extension-story concrete composite frame under low cyclic loading need to analyze the restoring force model of the overall structure. We can get the hysteresis curve of the structure through ANSYS software calculation, use horizontal force loading before the structure yielding, the top level load is 20kN for a lever, 10kN for a bottom level, cycle one time. After the structure yielding, use displacement loading, loading level is the multiply of yielding top-level lateral displacement, each level cycle three times.

4.4 Hysteresis curve of frame

Frame structure $P - \Delta$ hysteresis curve get through the analysis and calculation of ANSYS software (Figs 10 and 11). From the simulation results, the maximum bearing capacity of frame under repeated load slightly lower than the maximum under one-way load. Under repeated load bearing capacity of the maximum slightly lower than the maximum under one-way load. The cracking load of frame under under low reversed cyclic loading is for 43.5kN, yield load for 253kN, the maximum load for 410.8kN. Component hysteresis curve are basically symmetrical. Before the specimen cracking, hysteresis curve surrounding area is very small, force and displacement basically present linear relationship, hysteresis curve are long and narrow, in load reciprocating action process, stiffness degradation is not obvious, the residual deformation is also extremely small, component basically stay in a flexible working state. After component cracking, hysteresis curve start to present inverse S curve, with the load increasing gradually, hysteresis curve gradually began to tilt to displacement axial obviously, hysteresis curve surrounding area increased gradually. With the load increasing, the rigidity of frame degenerate obviously, this show the structure enter the nonlinear working stages. In the same displacement magnitude, hysteresis curve surrounding area slightly reduced, this suggests that the energy-dissipating capacity of frame degenerate, this also reflects the effect of frame cumulative damage. Under the ultimate load, the vertex ultimate displacement $\Delta u$ of model frame reach -59.78mm, lateral shift rate $u/H$ for 1/50, meet the requirements of large deformation when the earthquake effect. The effective displacement ductility coefficient when frame destroyed is 4.1, meet the ductility coefficient requirements of general ductility frame. This indicates that the model frame has good ductility which meets the seismic requirements of rarely met earthquake. From the frame $P - \Delta$ curve shown in figs 10 and 11, we can see that during the whole process from cracking, yield to damage, under the action of level repeated loading, the overall rigidity of frame gradually declined with the increase of displacement and cycling times, reflect in plastic deformation stage, the stiffness degradation performance of the anti-seismic structure is good. Under low reversed cyclic loading, although frame resilience curve has pinched daiwan phenomenon, it is superior to ordinary reinforced concrete frame structure. In the calculated load - displacement curve, the nonlinear effect is not obvious, especially reinforced concrete drop section cannot be calculated, this is because material where the local stress is higher than the failure stress destroyed leading to calculation does not converge.

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4.5 Frame equivalent stress diagram under failure load

Figure 12 is the composite frame equivalent stress diagram under each stage of load. From the figure we can see that the stress diagram of higher and lower frame beams are basically the same. This suggests that the bending moments are close to each other. Under low reversed cyclic loading, the higher and lower frame beams will appear plastic hinge soon. On the ends of the higher and lower beams, bottom plates have concentrated block stress area respectively, indicates the bottom plate of beam ends will yield first, plastic hinge will also first appear on the beam ends. Through stress diagram we can see stress on flange plate is bigger. If flange in the negative moment region is very harmful, so the welding braces on flange plate are necessary structural measures, otherwise flange plate may instability failure result of partial pressure. We can also see that the bottom of frame column appeared a high stress area, this suggests that the concrete on the bottom of column footing crushed. The development of cracks is: first appear some transverse cracks on the concrete slab of the higher and lower composite beams, then transverse crack propagation, appear vertical cracks at the side of concrete slab.

4.6 Hysteretic restoring force model of frame

From the hysteresis curve got by ANSYS analysis, we can summarize and compute the overall restoring force model of frame, among which skeleton curve summarize and ideal into two frame form by above skeleton curve of hysteresis curve, shown as figure 13, and revise hysteresis rule of Clough’s degradation double linear, get the overall hysteretic restoring force model of frame, shown as figure 14. When the structure is not beyond the yield point, the stiffness maintains the elastic stiffness, the unloading stiffness after yield determined by formulas 3 and 4:

\[ K_{sed} = K_e \left( \frac{d_{yy}}{d_{max}} \right)^{0.5} \]  
\[ K_{cd} = K_e \left( \frac{d_{cy}}{d_{min}} \right)^{0.5} \]

The calculation method of degradation stiffness under reversed loading is according to the furthest point of the latest reverse deformation to calculate. If the furthest point of reverse deformation is not beyond the yield point, the stiffness need not modify. But if it is beyond the yield point, the stiffness need to be modified as formula 5. For example, in order to calculate the stiffness after G point, the calculation by G point and B point coordinate is as follows:

\[ K_{GB} = 0.85 \frac{F_B - F_G}{d_{max} - d_G} \]

5 Conclusions

This article have made finite element analysis of the nonlinear performance of extension-story concrete composite frame under monotonic loading and low reversed cyclic loading through ANSYS software and compiling APDL procedures, drawing the following conclusions:

1) The bearing capacity of the composite frame under the monotonic loading is higher than under low reversed cyclic loading, but the displacement is slightly lower than the latter. This is consistent with actual situation for appearing residual deformation and stiffness degradation in the process of low reversed cyclic loading.

2) Composite slab haven’t yield, but the tensile and compression stress are close to yield value under the ultimate load. This is mainly because of the upper beams without exerting the vertical load, the bending moment of beams mainly generated by the horizontal load.

3) We have simulated the hysteretic performance of composite frame component well through three-dimensional finite element analysis. Under low reversed cyclic loading, although frame resilience curve has pinched daiwan phenomenon, it is superior to ordinary reinforced concrete frame structure.

4) From the generative stress diagram of frame we can see that concrete has concentrated stress area on the top of column and beam-column node area. So in the experiment model these regions are stirrup encryption. This structural measure is necessary, only in this way can we meet the specification requirements of “strong column, weak beam, stronger node”.

5) Summarize and calculate the hysteretic restoring force model of frame by the hysteresis curve get from ANSYS analysis.

6) In the load - displacement curve get from ANSYS simulated analysis, the nonlinear effect is not obvious, especially the drop section, this is because material where the local stress is higher than the failure stress destroyed leading to calculation does not converge.

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References


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