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FINITE ELEMENT ANALYSIS OF PULLING-OUT BEHAVIOR FOR RC FOOTING SUPPORTED BY FOUR PILES

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Abstract

In this research, the pulling-out behavior of the RC footing of power transmission towers is simulated by 3-D FEM computation. In the FEM program, nonlinear constitutive models are used for reinforced concrete and also for plain concrete, as a large volume of the footing is plain concrete. The results of computation show a similar capacity to those of the experimental data. Also, the shear cracks and yield of shear reinforcement in the computational results indicate the shear failure mode. As one full-scale experiment had been conducted for investigating the effect of size on the bearing capacity of RC footing, the FEM simulation was also carried out for this experiment. It was concluded that this FEM code can predict the 3-D behavior of RC footing of different sizes.

Key word: Finite element analysis, RC footing, size effect

1 Introduction

The RC footing supported by four piles is the most commonly used type for power transmission towers. The leg of the tower is fixed in the footing as an anchor. Some experiments had been carried out by pulling out the anchor and analyzing the failure mode and ultimate capacity. It was found in these experiments that diagonal cracks occurred from the end of the steel-fix- plates and finally failure happened in shear mode. From a series of tests including full-scale models, the existence of size effect has been confirmed (Sonobe et al., 1994). As the scale of a model becomes larger, the nominal shear strength decreases.

On the other hand, the development of FEM techniques makes it possible to simulate the behavior of RC structures, including the nonlinear behavior of RC, the fracture of concrete and the size effect on shear strength (An et al., 1997). It would be very useful for the design work on the footing of power transmission towers, if an FEM code could successfully predict the 3-D pulling-out behavior of the RC footings. In this paper, a 3-D FEM program for nonlinear analysis of RC structures is used to simulate the pulling-out test of footings of different size.

2 Pulling-out shear failure of RC footing

Pile-supported footing is one of the commonly used types of foundation for power transmission towers. Figure 1 shows an RC footing of this kind. Loads from the tower are transmitted through a cross-shaped anchor to the footing. As wind load is dominant for the tower, the footing is assumed to receive not only compressive load but also tensile load. A typical pattern of cracking is also shown in Fig. 1, which is observed on the surface of the specimen after pulling-out testing.

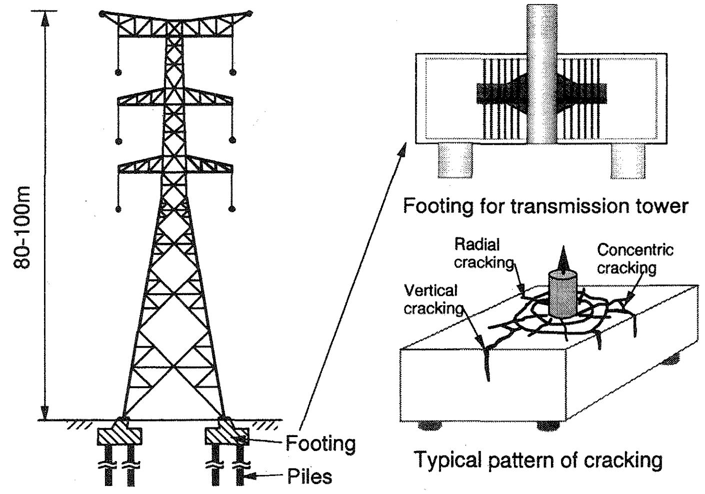


Fig. 1. Footing for transmission tower and typical cracking pattern

It was found in pulling-out tests that, first, radial cracks caused by bending occurred, and then, when diagonal cracks originating from the anchor extended to the surface, concentric cracks were observed. Ultimately, the diagonal cracks dominated, causing shear failure accompanied by pull-out of the leg.

The measured strain data for steel bars can be used to confirm the shear failure mode. As the diagonal cracks developed, strain increased and shear reinforcement gradually yielded. All of the remaining shear reinforcement yielded when the ultimate capacity was reached. Strain in positive moment reinforcement increased with the growth of radial cracks. However, the main reinforcement did not yield through out the tests.

For simulating these pulling-out experiments, the total behavior should be reproduced in FEM computational results, so at least the following points need to be compared with the experiments:

- Ultimate capacity;
- Strain of shear reinforcement;
- Strain of main reinforcement; and
- Cracking pattern.

3 Computation tool and verification

The 3-D FEM code **COM3** (Maekawa et al., 1997) used here can simulate the behavior of reinforced concrete structures, such as 3-D RC footings (Maki et al., 1996), by installing the constitutive models of RC, including all the effects of stress transfer through cracks, the stress transmitted from the reinforcing bars and the behavior of reinforcement. The inputs needed are the shape of structure, reinforcement arrangement and material strength. The outputs of nonlinear responses include the details of damage, stress and strain of both concrete and reinforcement, and deformation induced in the structures. By using this program, the ultimate state can be examined for design purposes.

The RC constitutive models include the smeared model for cracked concrete and discrete model, for the local displacement to overall displacement differs according to the size and the shape of members. The important points to consider are: the local behavior of reinforcing bars at the cracking section, the bonding effect of reinforcing bars and the deformation and failure of concrete between cracks. These problems have been solved during the last ten years (Okamura et al., 1991). Figure 2 outlines the models used in the nonlinear constitutive relationship of average strain and stress in reinforced concrete material.

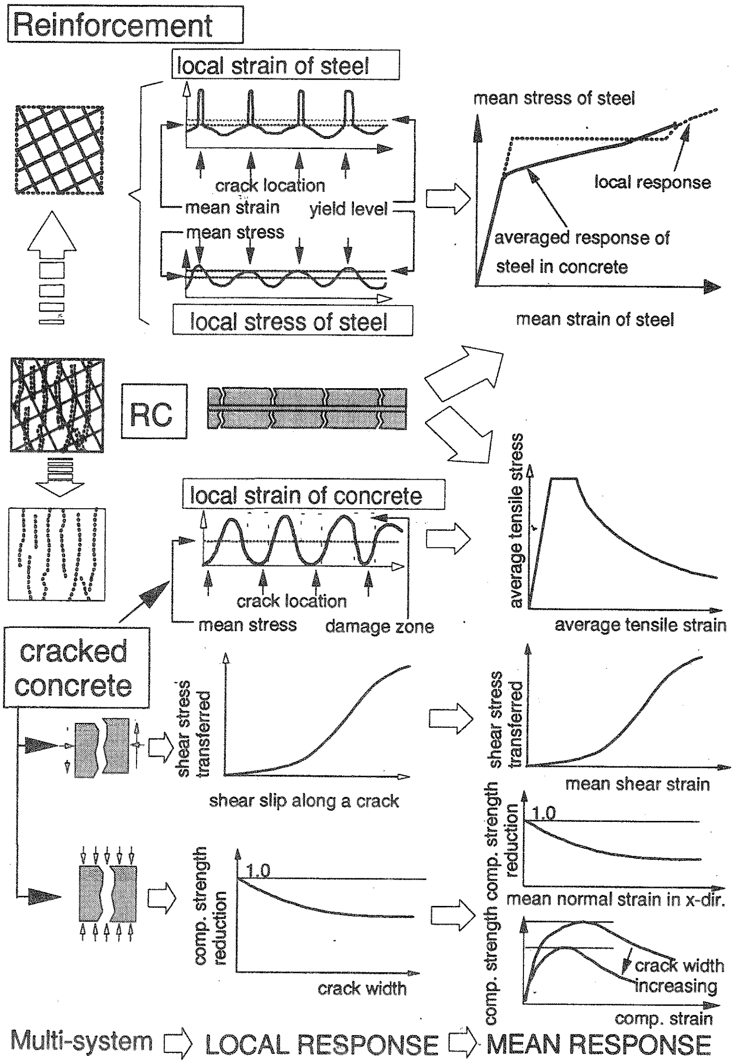


Fig. 2. Nonlinear constitutive model for RC

Owing to bond of concrete to the reinforcing bars, the concrete continues to support a part of the tensile force even after cracking has taken place in the reinforced concrete. In order to consider the influence of bond effects, the relation between the average stress and average strain of concrete is given as a tension model for cracked concrete. This tension model shows tension stiffening because the stress transferred from the steel bars by the bond effect is taken into account.

The tensile model of cracked concrete with tension stiffening is shown in Fig. 3.

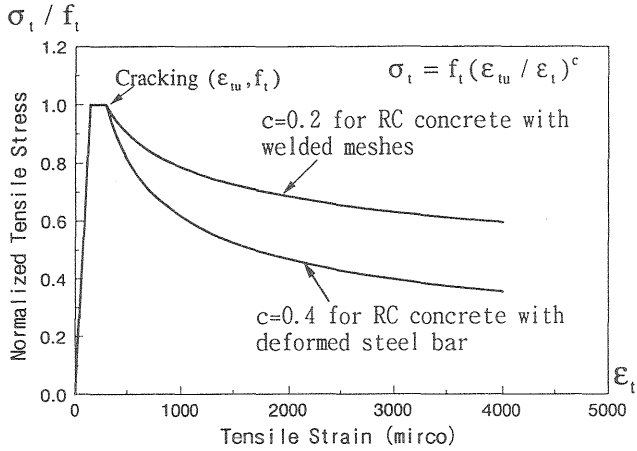
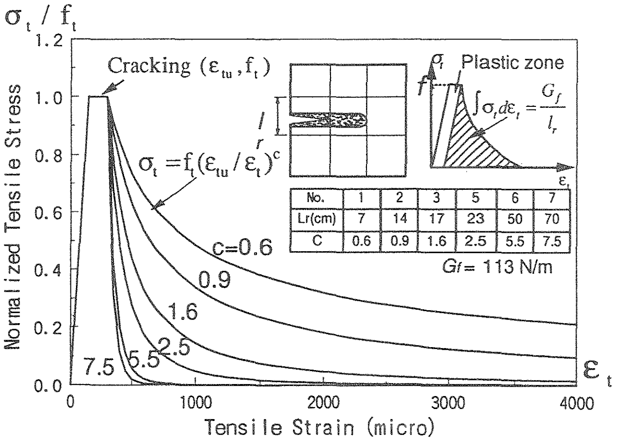


Fig. 3. Tension stiffening model for RC

The concrete outside the bond effective zone is assumed to be the same as plain concrete, showing sharp strain-softening features as the tensile stress is transferred only through the bridging action at the crack surface. The numerical method for FEM computation can be applied by adjusting the strain-softening curve according the element size based on the fracture energy balance (Fig. 4), as in the finite element computation the crack width is replaced by element reference size. In this case, the cracked band is assumed to be localized in an element and adjacent ones are unloaded. Figure 4 shows a typical example of how to adjust the softening curve according the element size. As the element reference length L_r becomes larger, the softening factor c becomes larger to keep the fracture energy G_f constant.



No.	1	2	3	5	6	7
Lr(cm)	7	14	17	23	50	70
C	0.6	0.9	1.6	2.5	5.5	7.5

Fig. 4. Tension stiffening model for plain concrete

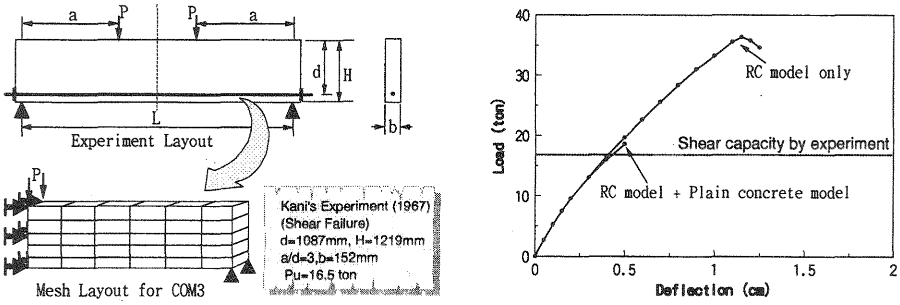


Fig. 5. Verification for 3-D FEM analysis

In the FEM computation, the whole RC member is divided into an RC zone and PL zone. In each zone the suitable strain-stiffening or strain-softening model is adopted. These models are also installed in **COM3** for three-dimensional computation. Here, one experiment on a concrete beam with little main reinforcement is used. The experiment layout, 3-D mesh and the result for simulating this shear beam experiment by Kani are shown in Fig. 5. A difference appears if plain concrete model is not used in the computation.

4 Simulation of pulling out shear failure for RC footing

A mesh for Experiment No.506 (Fig. 6) is developed for simulation of the RC footing's shear failure. 216 isoparametric elements (20 nodes) are used to simulate 1/4 of the footing. The computation is also shown in Fig. 6. According to the anchor and reinforcement arrangement in the footing, different constitutive models are used for different volumes of concrete, such as concrete with two-way arranged reinforcement (main and shear reinforcements), concrete with only shear reinforcements and plain concrete. The steel anchor plate is simulated by elements including reinforcement, and the steel anchor in the center is represented by elastic steel elements.

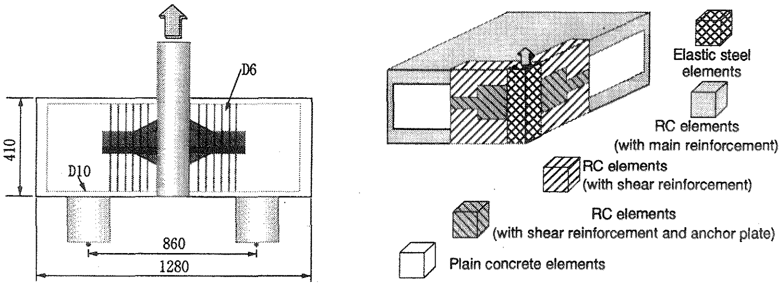


Fig. 6. Simulation object and modeling

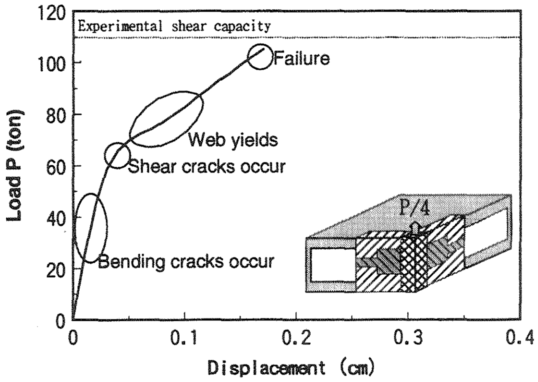


Fig. 7. Load-displacement relationship

The computational result of load-displacement is shown in Fig. 7. It can be seen that the computed capacity is very close to the experimental results. Next, it is necessary to confirm the cracking pattern and strain data to make sure that shear failure occurs in the computation, similar to the experiment.

In Fig. 8 the principal strain at the final computation step on the central section is shown. From the principal strains a drawing of the crack pattern can be derived in the same figure. We can see in the last step that the diagonal cracks extended and reached the surface of the footing, the same as occurred in the experiment (Fig. 1).

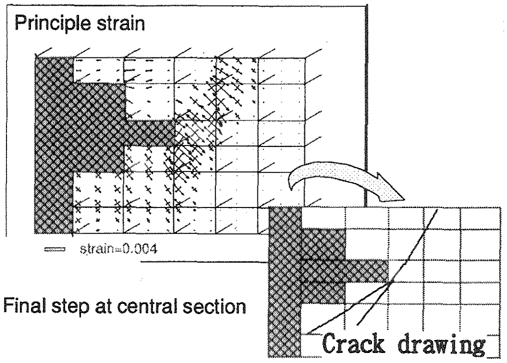
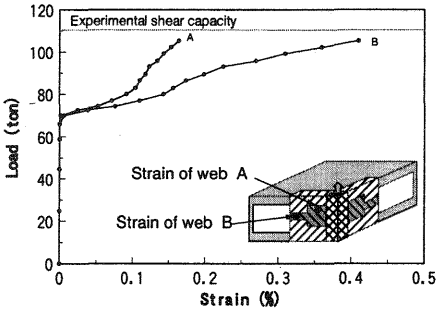


Fig. 8. Principal strain on central section and crack drawing

Next, we need to check the strain in the main reinforcemnet and shear reinforcement. Figure 9 shows the strain records of shear reinforcement from computational results. It is clear that the shear reinforcement yields in the computation. On the other hand, the strain records of main reinforcement (Fig. 10) show that yielding does not happen.



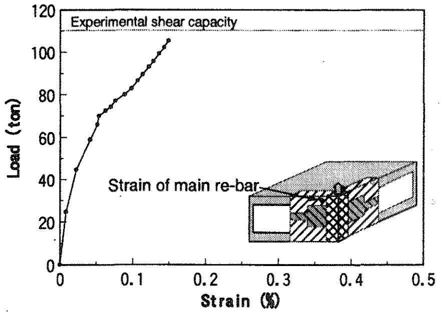
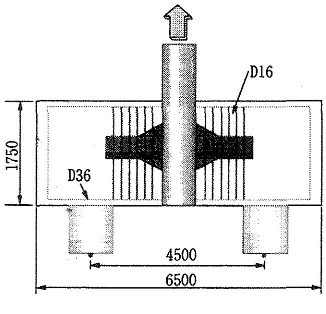


Fig.9. Strain of shear reinforcement   Fig.10. Strain of main reinforcement

From these computational results, it can be concluded that the pulling-out behaviors of RC footing, such as ultimate capacity, behavior of shear and main reinforcement and also cracking pattern are similar to the actual behaviors.

5 Size effect analysis

As mentioned in the introduction, full-scale model tests had been conducted for investigating the size effect in RC footings. Here, one of the full-scale specimens is also computed using the FEM code, to determine whether the size effect can be successfully simulated by this 3-D FEM program. The layout of the specimen is shown in Fig. 11, and the computed load-displacement relationship is shown in Fig. 12. We can see the maximum capacity given by computation is close to the experimental load when all the shear reinforcement yielded.



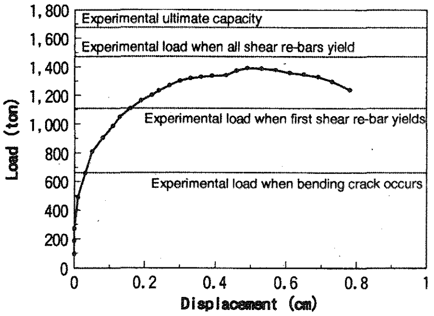


Fig.11. Simulation object (Full-size)   Fig.12. Load-displacement relation

The computational strain output are shown in Fig. 13 and 14. These results show that all the shear reinforcements yield and no obvious yielding happens in the main reinforcements.

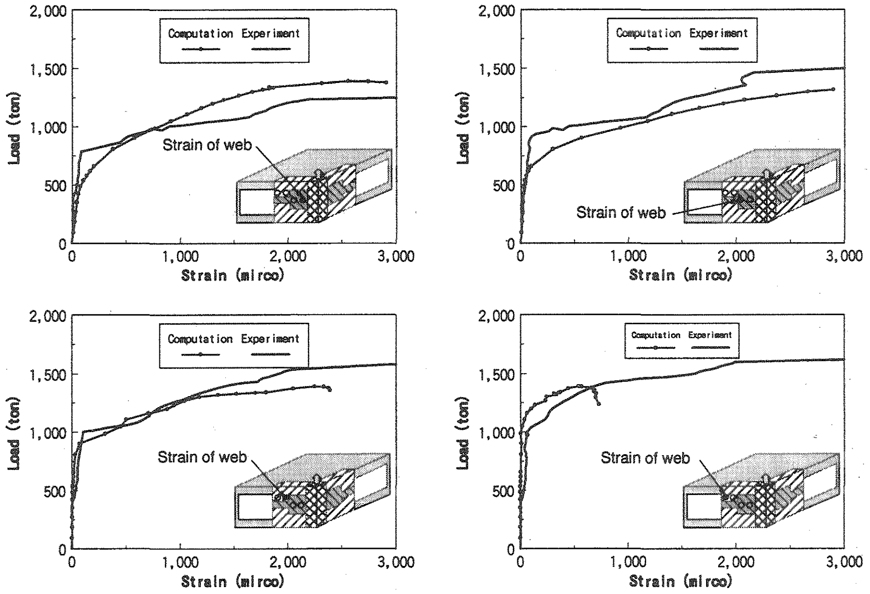


Fig. 13. Strain of shear reinforcement

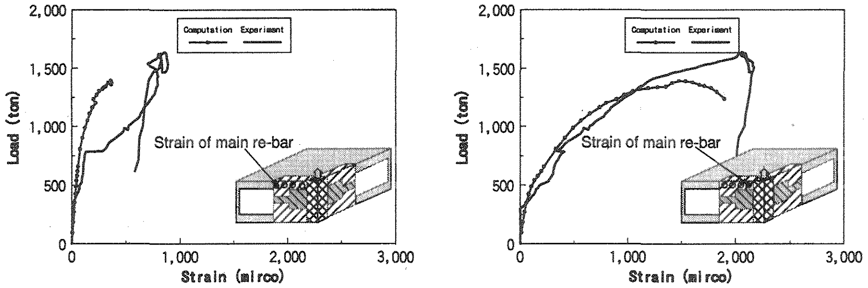


Fig. 14. Strain of main reinforcement

If we compare the results of the full-scale experiment with conventional specimen No.506, the size effect can be recognized by normalizing the shear strength. The norminal shear strength by eliminating other effects such as reinforcement ratio (β_p) and concrete strength (f_c) is calculated as:

$$\frac{Pu \times 1000}{\beta_p \beta_r (f_c)^{1/2} U_p d_t} \qquad (1)$$

where, P_u is ultimate capacity; U_p is a design parameter; β_r is influence of loading area and d_t is the effective depth.

From the experimental results, the size effect of RC footing is evaluated as the dotted line in Fig. 15 (Sonobe et al., 1994). The computational results are also plotted in this figure, demonstrating that the size effect is successfully simulated.