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NUMERICAL SIMULATION ON SHEAR FAILURE OF RC BEAMS

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Abstract
This paper presents finite element analysis on size effect in shear strength of reinforced concrete beams. It is shown that the tensile stress transfer through bond mechanism and the strain-softening in tension and shear associated with fracture energy law of concrete are the main points which cause the size effect in RC members. A spatially averaged continuum constitutive model which covers the reinforcement-confined concrete and plain concrete is proposed for simulating the unstable propagation of diagonal shear cracking. The model was verified by using the FEM program applied to RC beams comparing with JSCE code on shear strength, and the size effect experiments including RC beams of huge size was also simulated by the proposed model.
Key words: Size effect, Shear Failure, RC beam

1 Introduction

In recent years, the scale of concrete structures is becoming larger and larger owing to the advances made in materials, and improvement in design and construction techniques. One of the problems of increases in size is the evaluation of nominal shear strength. The nominal shear strength of a reinforcement concrete beam has been found in experiments to be gradually reduced as the beam depth increases, this is generally regarded as the size effect in shear. In order to estimate the accurate shear strength of large reinforced concrete structures, the experiment for large reinforced concrete beams without shear reinforcement was conducted, Iguro et al. (1985), and the effective depth ranges from 10cm to 300cm. On the other hand, the progress of numerical procedures based on the finite element method for reinforced concrete structures in the past twenty years is remarkable, and shear behaviors of reinforced concrete structures has been studied. Because concrete not only exhibits nonlinear deformational behavior but also fracture is a major feature of interest to engineers, the cracked concrete model and associated size effect on shear will be a major topic addressed in this study.

2 FEM program WCOMD-SJ

In this paper, FEM program WCOMD-SJ, Okamura et al. (1991), is used for analyzing reinforced concrete structures, to predict the experimental shear strength for RC beams of large scale. In this program, the smeared crack model is employed by combining the constitutive laws of concrete and reinforcing bars. The concrete model is composed of tension stiffening model, compression model and shear transfer model. These models are given as the relationship between average stress and average strain in reinforced concrete control volume. The crack spacing, or density, and diameter of reinforcing bars have negligible effect on spatially average stress-strain relation defined on RC control volume, Okamura et al. (1993). Therefore, the continuum damage model of concrete encompasses the reduction of compressive capacity of cracked concrete in relation to the mean strain normal to the crack.

In some cases, such as large reinforced concrete beams without shear reinforcement which will be hereafter analyzed, as the reinforcement ratio is very small and reinforcing bars are located at the bottom of the beam, some volume of concrete is outside the RC control volume in which

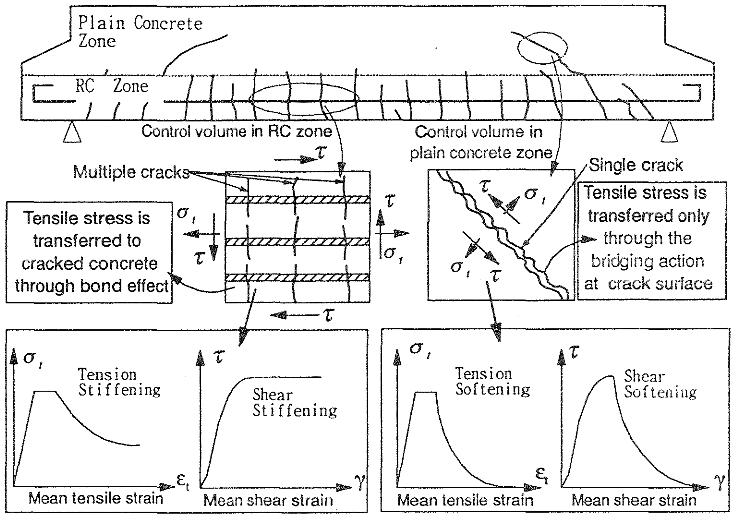


Fig. 1. The different models of cracked concrete in RC structure

tensile stress is not transferred through the bond mechanism with reinforcement. The specially averaged behavior of concrete far away from reinforcing bars is different than the concrete surrounding reinforcing bars because the bond effect decreases as the distance from the steel bar increases. This means the cracked concrete model for reinforced concrete shown in Fig. 1 can only be applied to concrete near the reinforcement. In order to predict the behavior of lightly reinforced beams, it is needed to propose a modified cracked concrete model for plain concrete zone which is the component of reinforced concrete but far from the RC control volume (Fig. 1).

3 Proposed model for concrete in RC zone and plain concrete zone

In dealing with RC beam without shear reinforcement as shown in Fig.1, the spatially averaged mechanical property of concrete near or far away from the reinforcement is supposed totally different as the concrete confined by steel bars will show stable stress release owing to the bond effect either tension or shear. The concrete outside the bond effect zone is supposed the same as plain concrete, showing sharp strain-softening character as the tensile stress is transferred only through the bridging action at the crack surface. These different properties should be simulated in the concrete cracking model for FEM computation as these characters decide the unstable propagation of diagonal shear cracks, which causes the sudden shear failure.

The smeared crack model for concrete confined by reinforcement has been constructed by combining the constitutive law for concrete and that for reinforcing bars. The constitutive law adopted for the RC zone consists of tension stiffening model and the shear transfer model. Either tension or shear models show strain stiffening after cracking (Fig. 2).

For cracked plain concrete outside the RC zone, it shows strain-softening characteristic in tension and shear comparing with the concrete confined by reinforcing bars. The stress-strain curve is decided by adjusting the coefficient c with the element size by getting the constant fracture energy G_f, Bazant et al. (1983). Fig.3 gives two series of tensile and shear stress-strain curves used for simulating one shear experiment including 6 beams with depth varying from 10cm to 300cm, Iguro et al. (1985). The shear model of cracked concrete in RC zone is based on the contact density function, Li et al. (1989).

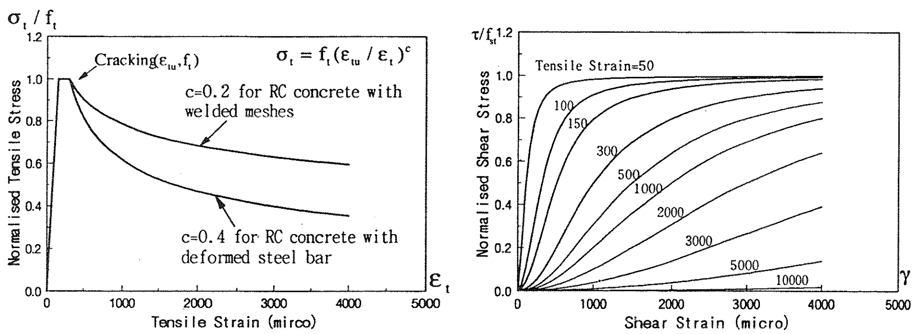
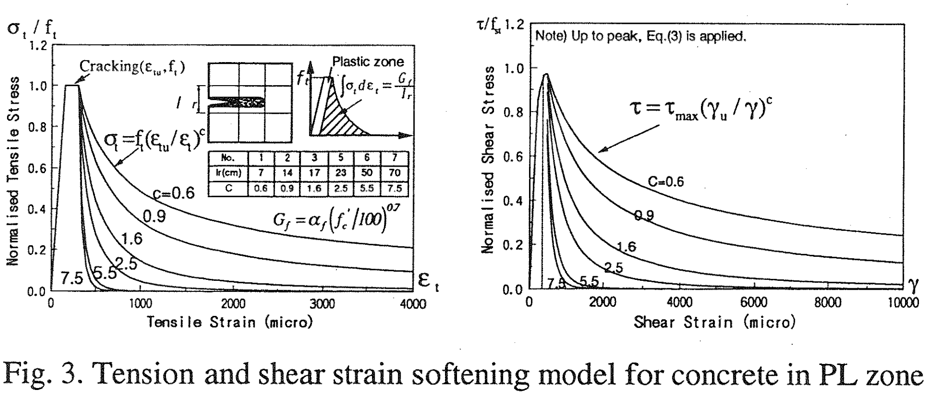


Fig. 2. Tension and shear stiffening model for concrete in RC zone



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. 3. Tension and shear strain softening model for concrete in PL zone

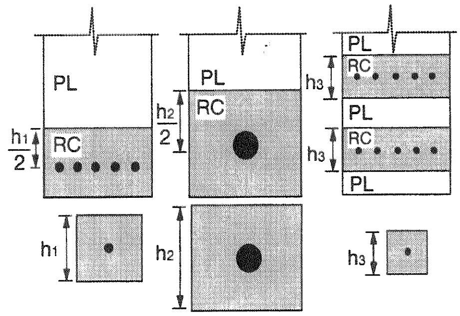


Fig. 4. RC zone definition in computation

There is a further point which needs to be considered when a structure consists of several parts which are of different natures and refer respectively to the reinforced concrete model or the plain concrete model discussed above (Fig. 4). In the case of a beam (Fig. 1), in the area surrounding the main reinforcing bars, reinforced concrete model which considers the tensile stress transfer from steel through bond should be used in FEM computation. For the area far away from the reinforcement bars, the plain concrete model with softening should be used. It is needed to combine the two models in the computation of beam, by dividing the beam into RC control zone and plain concrete zone.

If a reinforcement concrete member that is subjected to tension contains only a very small amount of reinforcement, when first crack forms, the reinforcement crossing the crack may yield and all further deformation will occur at this single crack. This means the reinforcement may be capable of providing crack control in the limited concrete volume, and this volume is related to the RC control zone. Based on this concept, we developed a simple formula (Eq. 1) to decide the height (*H*) of RC Zone (measured from the center of the steel bar). To obtain a real bond effective domain around the steel bars, further effort will be devoted to it. Details can be found in An et al. (1997).

$$H = \frac{1}{2} K \cdot d \sqrt{\frac{f_y}{f_t}} \qquad (1)$$

where: d is the diameter of the steel bar; f_y is the yielding strength of the steel bar; f_t is the tensile strength of the concrete; K is 0.85 in the case of deformed bar and enough covering concrete.

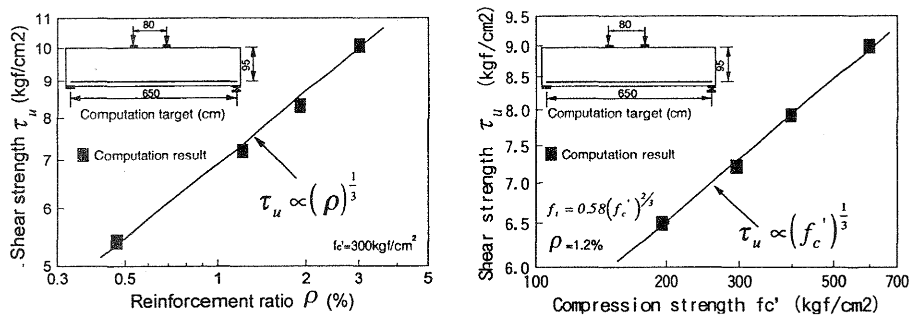


Fig. 5. FEM computational results compared with JSCE code

4 Verification of the proposed model by JSCE code

The JSCE code of shear strength of RC Beams is a summary of huge experimental data and can be used as a verification for the proposed model. In order to verify the proposed model on shear strength prediction, computation was carried out for a beam with depth 95cm (Fig. 5) and the shear strength varying with different reinforcement ratio and concrete strength. The results are also plotted in Fig. 5. The predicted shear strength by JSCE code is proportional to $\rho^{1/3}$ and $f_c'^{\,1/3}$. And the computational results has good agreement with JSCE equation, JSCE (1986).

5 Size effect simulation on shear strength of large RC beams

5.1 Experiment outline

The size effect experiment conducted by Iguro et al. (1985), consists of RC beams without shear reinforcement of different depths "d"; 10cm, 20cm, 60cm, 100cm, 200cm and 300cm, as shown in Fig. 6. The ratio of loading span "l" to "d" is to be l/d=12 in order to give a value close to the lower limit of strength.

The main reinforcement ratio in the vicinity of supporting point where shear failure would occur is defined 0.4%. The beams were loaded by uniformly distributed hydraulic pressure until failure. The observed failure modes were flexural failure for beam No.1 and No.2 and the shear failure for the other beams.

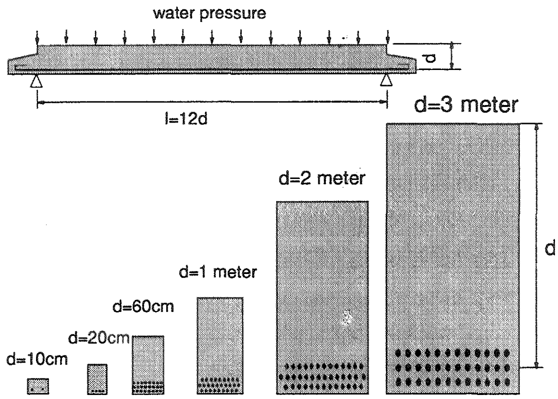


Fig. 6. Details of cross sections and arrangement of reinforcing bars

5.2 Computational results

The reinforced concrete beams without shear reinforcement were analyzed using the program WCOMD-SJ, in which the discussed models are adopted.

5.2.1 Load deflection relation

It can be seen in Fig.7 that, when the proposed plain concrete (PL) model is combined with the RC model in the computation, the analytical results are very close to the experiments. If only the RC model is used, the analytical results are much higher than the experiment data, and if only the plain concrete model is used, the beam will fail with much lower load comparing to the real results. These analysis can also show that the stiffening part of the cracked concrete model can affect the shear capacity, obviously.

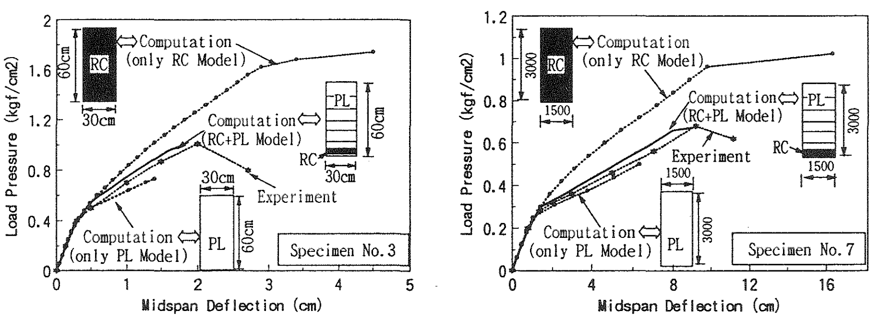


Fig. 7. Load-deflection relation for different specimen at midspan

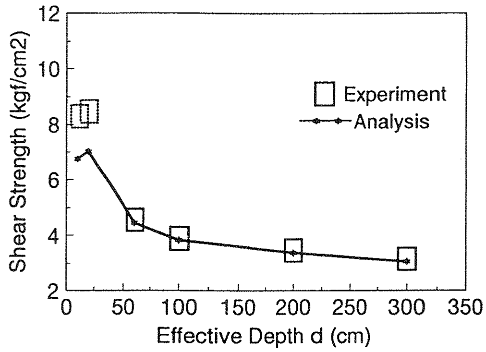


Fig. 8. Shear strength and effective depth

5.2.2 Size effect on shear strength

Fig. 8 shows the shear strength results of the comparison between analytical results and experimentals. The lines in this figure show the computed shear strengths. According to this figure, the analytical results which have good agreement with the experiment results, show the tendency of shear strength to decrease with an increase in beam size. This agreement ascertained the validity of proposed cracked concrete model and capability of the computational scheme to predict the size effect on shear strength.

The specimen No.1, and No.2 failed due to flexural mode, and the experiment results are higher than the analysis results. In fact, the tested bending capacity for these two small beams is much higher than the bending capacity which is computed by RC beam theory of cross section. It is guessed that the loading membrane made of rubber would act as fiber resistant component and affected the experiment results. Actually, the program can simulate the shear capacity of small beams very well according to many computation examples, Okamura et al. (1991).

5.2.3 Crack pattern

Fig. 9 shows the crack pattern of specimen No.3. The short lines in computed crack pattern picture should not be associated with individual discrete cracks. They represent the smeared cracks, whereas the thickness indicates the magnitude of opening of the cracks and from the direction of the short lines, the shear cracks and tension cracks can be distinguished. It can be seen that the computation can get the shear cracks almost at the same place with the experiments and the crack

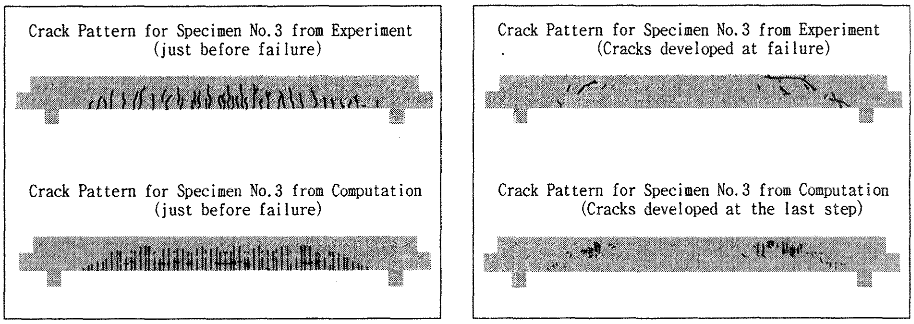


Fig. 9. Crack patterns for specimen No.3

opening is bigger near the right side support. Also the cracks which developed at failure in the experiment are similar to the cracks which occurred in the last computation step. It shows that the program can simulate the sudden shear failure successfully, in the instable propagation mode of diagonal cracks.

6 Conclusions

The shear behavior of reinforced concrete beams without shear reinforcement was investigated using the program WCOMD-SJ. From this study, it was concluded that even for the very large beam, the shear behavior of reinforced concrete beam without shear reinforcement can be well predicted by the proposed concrete models applied to both RC and plain concrete domains.

It can be noted that the size effect in shear of reinforced concrete beams can be analytically shown by using the finite element method. The shear capacity which is predicated by the finite element method shows good agreement with the result of experiment. Both of the analysis and the experiment exhibited that the shear strength behavior of reinforced concrete beam is generally affected by the beam size. The shear strength is gradually decreased as the depth of beam increases.

In this study, different sensitivity of apparent size effects was computed in accordance with the shape of beams, comparing with JSCE code. In the next step, more clear understanding of the size effect sensitivity should be quantitatively sought.