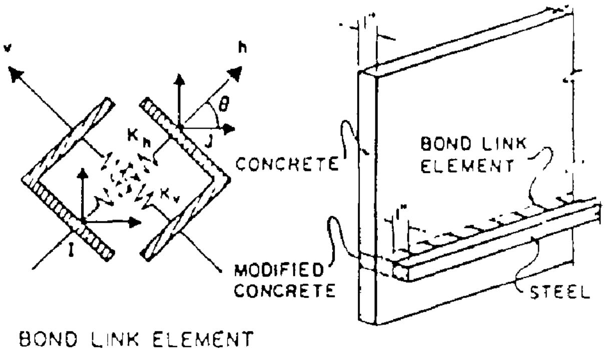
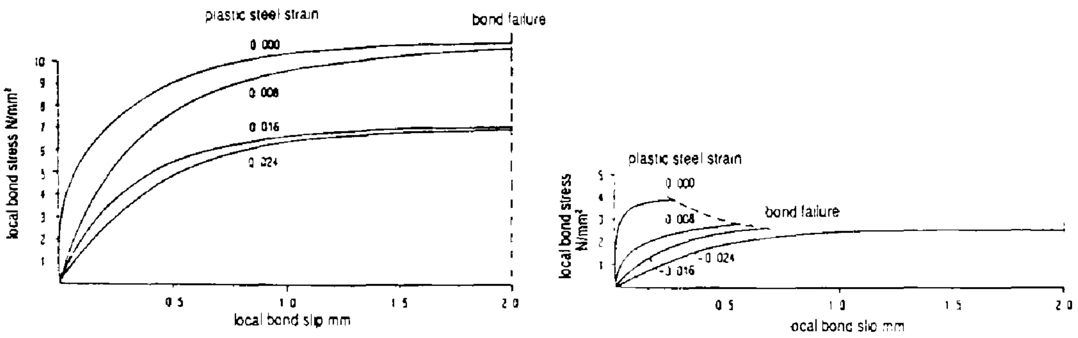


Fig. 1.37 Bond Link Model (Ngo and Scordelis, 1967)



(a) Bond Stress-Slip Relations for Bond in Uncracked Regions or in Some Distance from Cracks

(b) Bond Stress-Slip Relations for Bond near Cracks

Fig. 1.38 Different Bond Properties near Cracks and between Cracks (Eifler, 1974)

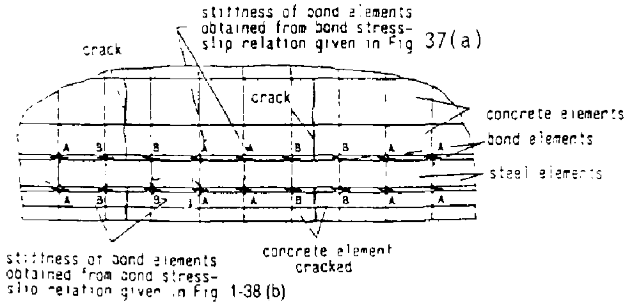


Fig. 1.39 Representation of Bond in Cracked Reinforced Concrete Beam (Plauk, 1981)

1.7 Modelling of Reinforcing Bars

The reinforcing bar was generally assumed to be a linear element in the previous finite element analysis of RC members. In the analysis of shear walls, the reinforcing bars were often distributed uniformly throughout the concrete element. It is necessary to consider the dowel action from the local bending of the reinforcing bar in the analysis of the shear dominant member. In this case, the reinforcing bar was often represented by the linear strain two-dimensional element.

The stress-strain relations of the reinforcing bar was often assumed to be linear elastic or bilinear (perfect elasto-plastic or strain-hardening type) The von Mises criterion was frequently used in the two-dimensional element.

The above-mentioned simplified model has been used in the previous shear analyses under the monotonic loading. However, the more refined model under the reversed cyclic loading will be necessary in order to study on the restoring force characteristics and the shear failure after the flexural yielding. The material model under the reversed cyclic loading, which was used in the previous fiber model for the flexural dominant member, will be a good reference. (Fujii and Aoyama (1973), Bazant (1977), Kokusyo and Takiguchi (1980))

1.8 Bond Between Reinforcing Bars and Concrete

The analytical model for the bond between the reinforcing bar and concrete was reviewed in detail by Noguchi (1976), (1977) and AIJ Committee (1980). Therefore, the recent analytical model will be mainly reviewed in this chapter.

The analytical deflection, which was obtained on the assumption of the perfect bond, showed a tendency to become smaller than the experimental deflection, as the failure progressed in the member. This is more remarkable in case of the concentrated reinforcing arrangement like a beam and a column than a shear wall and a slab, and indicates that it is necessary to consider the bond-slip behavior in the analysis of reinforced concrete.

The bond link element proposed by Ngo and Scordelis (1967) has been used most generally as the analytical model of the bond mechanism. The reinforcement node and the concrete node are connected by the bond link element which was composed of the two orthogonal springs, as shown in Fig. 1.37. The bond slip between the reinforcing bar and concrete and the corresponding bond stress transfer are expressed by the deformation characteristics of the springs, which are given on the assumption that the bond stress is represented as the function of the relative slip.

Muguruma (1972), Kosaka (1973), Kokusho (1974), Labib (1978) investigated the applicability of the bond link model by applying the model into the simplified specimen like the pull out bond specimen. Kokusho indicated that the analytical strain in concrete within twice as much distance from the surface of the deformed bar as the diameter of the deformed bar was smaller than

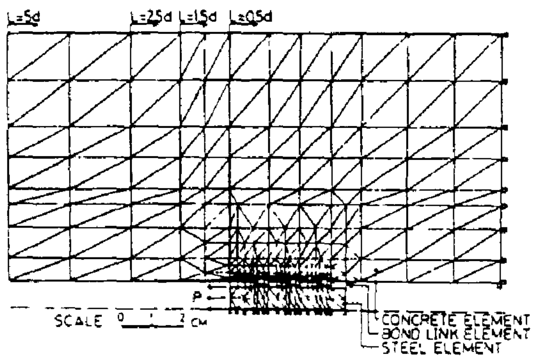


Fig. 1.40 Finite Element Idealization (Kokusho and Yoshida, 1981)

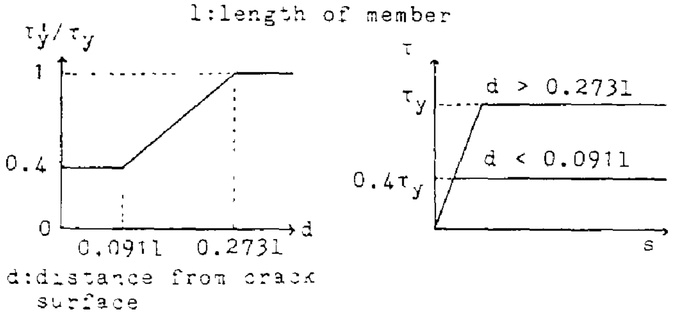
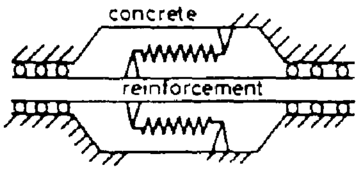
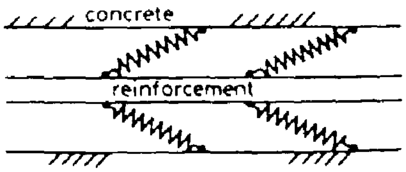


Fig. 1.41 Reduction of Bond Elastic Limit according to Distance from Crack Surface (Nomura and Sato, 1978)



(a) One-directional Spring Model
(Stauder, 1973; Schafer, 1975)



(b) Inclined Spring Model
(Van Mier, 1978)

Fig. 1.42 Spring Models

the experimental strain from the analysis of pull out specimens, but there was little difference between the analytical and experimental strains at more than twice as much distance as the diameter of the deformed bar. Labib analyzed the tensile specimens, considering the crack which occurred around the deformed bar. It was indicated that the analytical primary crack pattern and crack spacing gave a good agreement with the experimental results. In this model, the modelling of the deformation characteristics of the bond link spring perpendicular to the axis of the deformed bar was made a trial, and it was shown that the bond behavior of the deformed bar could be predicted to a certain extent.

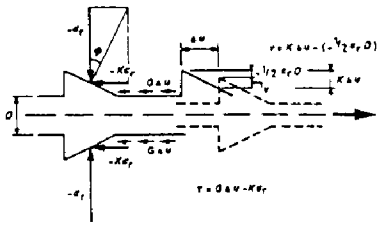
The bond link model was applied to the analysis of the member in many studies. Franklin (1970) investigated the effect of the bond characteristics on the failure mode of the beam. Kokusho and Takiguchi (1971) inquired into the difference of the crack pattern, deformation, strain according to the bond characteristics. Consequently, it was pointed out that the analytical shear cracking load and the load when the stirrup strain began to increase got higher, as the bond properties became poorer. Ohtzuki (1975) investigated the effect of the modelling for the bond stress-relative slip curve, the concrete stress-strain curve, the failure criterion on the analytical results of RC beams without stirrups. It was indicated that the effect of the bond characteristics on the crack propagation, deformation and strength was the most distinguished, and the shear cracking load got higher and the shear strength got lower, as the bond properties became poorer.

Muto and Inoue (1976), (1981), Sugano and Inoue (1980), (1982) adopted the bond link into the three-dimensional analytical model under the reversed cyclic loading, and investigated the confinement effect of the tie in the analysis of the column.

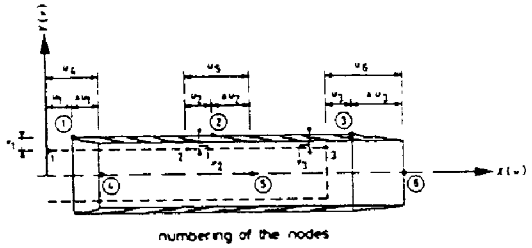
In the analysis of the shear wall, the perfect bond had been generally assumed by Darwin (1976) and others. Mitsukawa and Baba (1978) analyzed the shear wall using the bond link, assuming that the deformation characteristics of the spring parallel to the reinforcement axis were based on the bond stress-bond slip rule under the reversed cyclic loading, which had been proposed by Morita (1975). The distributions of the bond stress and bond slip were investigated in this analysis.

Noguchi (1980), (1981) studied the effect of the bond characteristics of the beam main bar in the beam-column joint on the shear resistance mechanisms of the joint and the restoring force characteristics of the overall frame, using the bond link model.

Plauk (1981) pointed out that the bond stiffness and bond stress near cracks were significantly lower than in some distance from the crack surface or in uncracked regions for equal values of bond slip, as shown in Fig. 1.38, from the results of Eifler's test (1974), and the different bond properties near cracks and between cracks were incorporated in to the finite element model with the bond link, as shown in Fig. 1.39. The analytical crack spacing of a simple beam gave a good agreement with the experimental result, even if the smeared crack model was used.



(a) Teeth Model



(b) Bond Element Model

Fig. 1.43 Bond Models for Deformed Bars

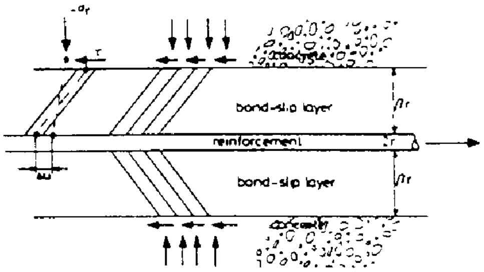


Fig. 1.44 Bond-Slip Model (De Groot, 1981)

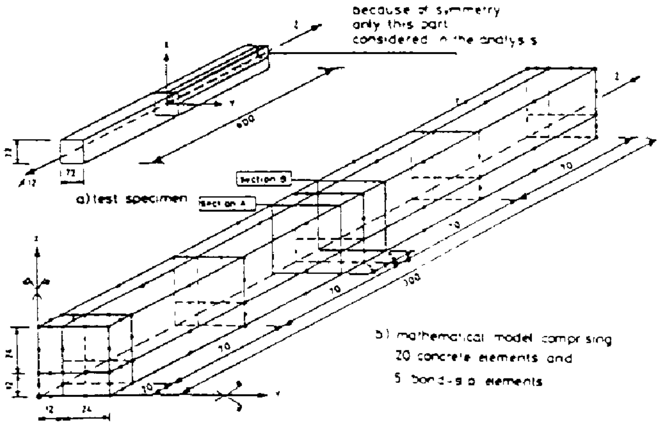


Fig. 1.45 Finite Element Idealization in Three-dimensional Analysis of Tensile Specimen (De Groot, 1981)

Kokusho and Yoshida (1981) investigated the relations between the bond stress-bond slip curve and the distance from a crack surface by both the analytical and experimental approaches. The finite element idealization in the axi-symmetric nonlinear analysis was shown in Fig. 1 40. The spring stiffness of the bond link which connected the lug of a deformed bar and concrete was given as the very large value in compression, and as the almost zero value in tension and in shear. The analytical bond stress and bond slip were fairly smaller than the experimental results, but gave a good agreement in a qualitative tendency.

It is known that the bond properties in round bars are dependent upon the strain in reinforcing bars and the distance from the crack surface. Nomura and Sato (1978) analyzed the column with the bond link, assuming the reduction of the elastic limit of the bond according to the distance from the crack surface, as shown in Fig. 1.41. There was a remarkable difference between the normal bond and the perfect bond in the analysis of the shear failure type column with the shear span ratio, a/h = 2.0, subjected to the monotonic loading In the perfect bond model, the crack pattern was almost flexural type and the maximum strength was fairly lower than the experimental result. In the normal bond model, the deflection was fairly smaller than the experimental result, but the crack propagation was not far from the experimental result. In the analysis under the reversed cyclic loading, it was pointed out that the deflection was smaller than the experimental result, and the shape of the hysteresis loop under the unloading was different from the experimental result. It was indicated that the elucidation on the bond mechanism of the round bar under the reversed cyclic loading was necessary in future.

The slip on the reinforcing bar surface is represented by the bond link. In case of the deformed bar, the concrete around the bar follows the displacement of the bar to the tolerable degree, making contact with the lug of the bar. Consequently, the internal cracks occur from the bar lug, and propagate into the surrounding concrete. Therefore, it seems to be difficult to explain the behavior of the concrete around the deformed bar by the bond link model.

Ikeda (1973) proposed the finite element model composed of the spring system, considering the inclined crack around the deformed bar. In this model, the coupling springs were arranged in the axial direction between the deformed bar and concrete elements in order to represent the shear deformation of the concrete and the flexural deformation after the internal crack occurred.

Kokusyo and Yamanaka (1974) proposed the bond zone model The relative slip was transformed into the shear deformation of the bond zone around the deformed bar, by reducing the shear stiffness of the concrete in the bond zone. It was shown that the analytical strain in concrete within twice as much distance from the surface of the deformed bar as the diameter of the deformed bar by the bond zone model, was nearer to the experimental result than by the bond link model.

Noguchi (1977) applied the orthotropic theory into the internal crack zone around the deformed bars In this model, the elasticity modulus, nearly perpendicular to the internal crack was decreased together with the shear modulus. It was indicated that the analytical longitudinal strain in the concrete around the deformed bar gave a good agreement with the experimental result from the analyses of the previous pull out and tensile specimens.

Ma and Bertero (1976) developed the stiffness reduction method in the concrete layer around the deformed bar, and proposed the model in which the initiation and propagation of the internal crack were considered by modelling the lugs of the deformed bar with fairly good approximation to reality It was shown that the inclination of the analytical internal cracks gave a good agreement with the Goto's experimental results, and the stiffness degradation of the bond stress-bond slip curve from the internal crack initiation was observed

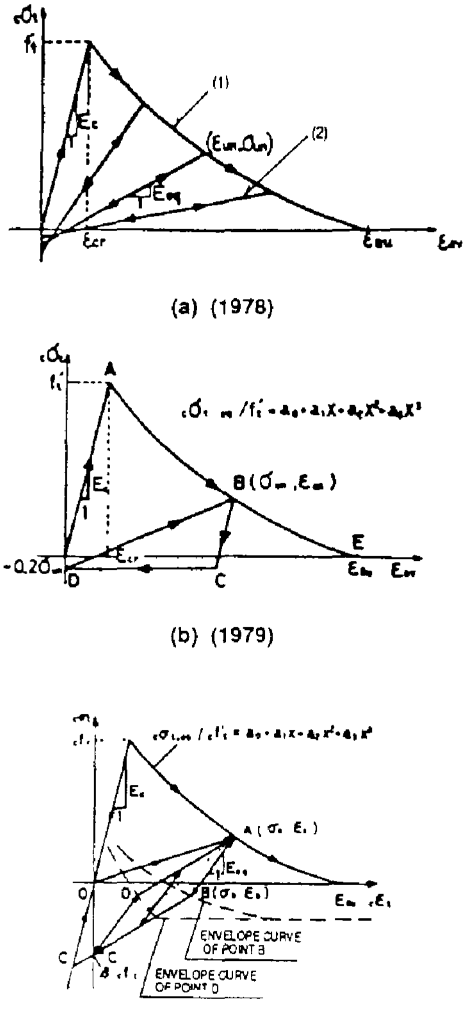
As the one-directional spring model proposed by Stauder (1973) and Schafer (1975), as shown in Fig. 1.42 (a), and the two-directional independent springs model were difficult to represent the bond mechanism of the deformed bar, Van Mier (1978) proposed the inclined spring model, as shown in Fig. 1.42 (b).

Gijsbers (1978) considered the roles of the surface friction and the interlock friction, which were the components of the bond mechanism of the deformed bar, in the teeth model as shown in Fig. 1.43 (a), and analyzed the tensile specimen using the bond element model, as shown in Fig. 1.43 (b). De Groot (1981) developed this model into the bond-slip model, as shown in Fig. 1.44, and conducted the two-dimensional and three-dimensional elastic plastic analysis of the tensile specimen, using the bond-slip element, in which the bond-slip model and the deformed bar element were incorporated. The finite element idealization in the three-dimensional analysis was shown in Fig. 1.45

As the other models of the bond mechanism, Hassan (1973) assumed the bond stress distribution along the reinforcing bar. Viwathanatepa (1979) and Sauma (1980) represented the bond behavior by the bond layer and the shear element in the almost same way as the Bertero's original model (1976) and the Kokusho and Yamanaka's bond zone model (1974) Bazant (1981) proposed the bond model which was adapted to his proposed crack band model.

When the reinforcing bars are distributed closely in the overall member like a slab and a shear wall, the concrete between cracks restrains the reinforcing bar by bond, and bears a part of tensile forces In this case, the tension-stiffening of concrete is assumed after cracking, and the downward portion of the tensile stress is provided in the apparent tensile stress-strain curve of concrete. Arai (1978) gave a consideration to the confinement of the concrete between cracks by bond in the estimation of the reinforcement stiffness in the cracking zone of the shear wall Sato and Shirai (1978) adopted the effective tensile stress-average strain curves for the concrete, as shown in fig. 1.46 (a), in the analysis of the shear wall, and the modified models were proposed, as shown in Fig 1.46 (b), (1979), (c), (1980)

The many analytical models for the bond mechanism have been proposed as stated above. In



(a) (1978)

(b) (1979)

(c) (1980)

Fig. 1.46 Effective Tensile Stress - Average Strain Curves for Concrete (Sato and Shirai)

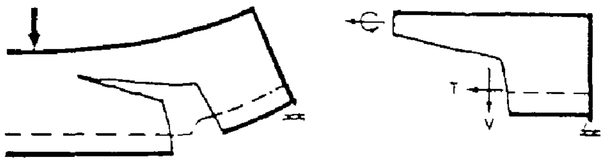


Fig. 1.47 Dowel Action of Reinforcing Bars (Ngo, 1970)

the most of the previous analytical studies with the bond link, the bond stress-slip relations are assumed to be independent on the position of reinforcing bars, but it is necessary to consider the degradation of the bond characteristics near cracks. The relations to the modelling method of cracks, the deformation characteristics in the direction perpendicular to the reinforcement axis and the modelling of the downward portion of the bond stress-slip relations are pointed out as the future subject.

For the bond mechanism of a deformed bar, it will be necessary to study the contact problem between the lug of the deformed bar and concrete in detail with a good approximation to reality in order to quantify the characteristic values for the envelope curve of the bond stress-slip relations. It is also an important subject to study the effect of the bond mechanism of the deformed bar including the bond splitting crack, especially the displacement of concrete in the perpendicular direction to the reinforcement axis by the wedging action, on the behavior of the overall member.

The bond stress-slip relations were often assumed from the results of the previous bond test in the analysis of RC member with the analytical bond model. Kaku (1978) pointed out that the bond characteristics in the member was affected by the magnitude of shear forces, the existence of the shear reinforcement, the combination effects of the bond splitting and the dowel action, the reaction forces of the support. The bond characteristics in beam-column joints were affected furthermore by axial forces, flexural forces and the effect of transverse beams. Viwathanatepa (1979) indicated that the bond characteristics of the beam main bar through the joint were affected by the stress condition of the main bar and the confinement effects of column main bars and ties on concrete, and underwent a change according to the position of the main bar. In future, it will be necessary to make both experimental and analytical investigation of the bond characteristics of the member, and to investigate the effect of the bond on the shear behavior and the shear strength of the member.

1.9 Dowel Action of Reinforcing Bars

The some shear forces are contributed by the dowel action of reinforcing bars, which is caused by the local bending of the reinforcing bars at the location where an inclined crack and longitudinal reinforcing bars intersect in a simple beam. (Fig. 1.47)

Ngo (1970) modelled the reinforcing bar in a linear strain triangular element which was able to represent the local flexural behavior In this study, the effective dowel length was defined as the length of the section where the bond was in failure, as shown in Fig. 1.48. The dowel stiffness was in inverse proportion to the effective dowel length. As it was difficult to quantify the effective dowel length, it was assumed to be about 5 cm for the diameter of the reinforcing bar, 2.9 cm as a matter of convenience When the dowel shear force increased, the dowel splitting crack occurred along the longitudinal reinforcing bars from the location where an inclined crack and longitudinal bars intersected. This phenomenon was represented by separating the concrete elements along the longitudinal bars. The redistribution of stress and the decrease of the dowel shear force were

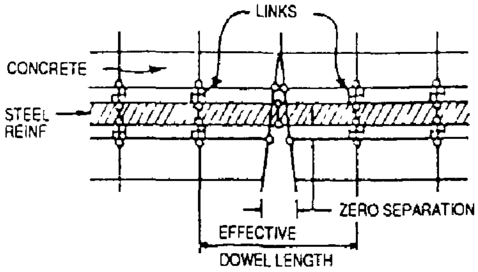


Fig. 1.48 Effective Dowel Length (Ngo, 1970)

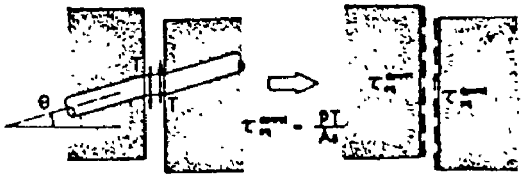


Fig. 1.49 Analytical Model for Dowel Action (Sato and Shirai, 1978)

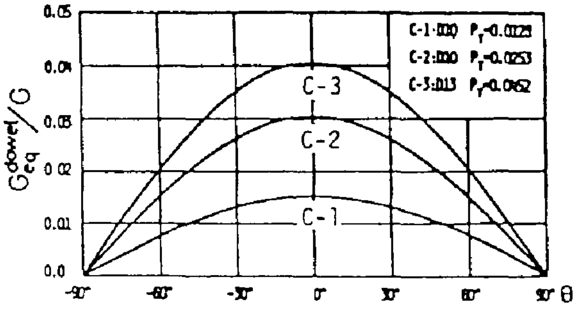


Fig. 1.50 Equivalent Shear Stiffness of Dowel Action (Sato and Shirai, 1978)

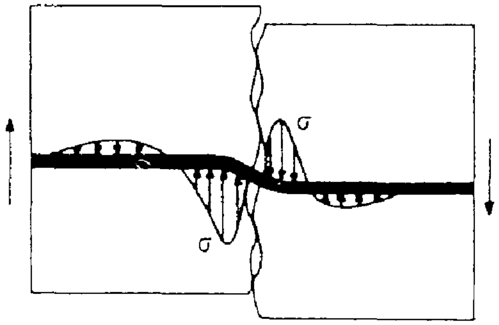


Fig. 1.51 Normal Stress Distribution Caused by Dowel Deformation of Reinforcing Bar (Grootenboer, 1981)

remarkable in the dowel splitting crack model. In this analysis, many unknown phenomena for the dowel action were explained. Though the focus was placed on the effective dowel length in this analytical model, and the large value was assumed for the spring stiffness of the bond link in the perpendicular direction to the reinforcing bar, it seems that the role of this spring is important in the actual dowel action, and the effective dowel length is dependent upon the spring stiffness.

Sato and Ono (1975) analyzed the simple beams with the predicted crack pattern, considering the dowel action of the longitudinal bars by a similar model to Ngo's (1970), and compared the analytical dowel shear force with the experimental result

Sato and Shirai (1978) transformed the dowel force into the equivalent shear stress as shown in Fig. 1.49 in the analytical model of shear walls, and proposed the equivalent shear stress-shear strain relations based on the Dulacska's relative slip-dowel force relations (1972). The ratios of the equivalent shear stiffness to the elastic shear stiffness were plotted against the angle at which the reinforcing bar inclined with crack surfaces, as shown in Fig. 1.50. From this figure, it was pointed out that the equivalent shear stiffness of the dowel action was no more than 5 x 10-2 of the elastic shear stiffness.

Grootenboer (1981) indicated that it was necessary to provide the separate bond layers at the both sides of a reinforcing bar, because the bond layers did not remain in the axi-symmetric condition on account of the high normal stress in the concrete at the one side of the reinforcing bar caused by the dowel deformation of the reinforcing bar. (Fig. 1.51) But the perfect elastic plastic was assumed in the relations between the dowel force and the displacement in the perpendicular direction to the reinforcement axis in the plane stress program. The effect and the magnitude of the dowel force were pointed out as the future subject.

There are not so many researches for the modelling of the dowel action. It is necessary to compare the parametric analysis for the effecting factors of the dowel action like the spring constants of the bond link with the simple test, in which the focus is placed on the dowel action. As there is much accumulation of the experimental data on the contribution rates of major shear resistant elements including the dowel action in beams, it will be possible to clarify the effect of the dowel action on the overall behavior of a beam by comparing the above-stated parametric analysis of the dowel action with the previous experiment.

1.10 Conclusions

In this paper, the characteristics of the shear analysis of RC structures by the finite element method were generally reviewed, and the previous studies on the modelling of the basic mechanical properties of reinforced concrete were reviewed

The primary points at issue in the shear analysis of RC structures by the FEM seem to be as follows.

1. There are limits on the experimental information on the modelling of materials.
2. It yet remains to be difficult to analyze the shear dominant RC member.
3. The computational program is complexed, and requires a lot of computational time.
4. It is difficult to develop the equation for design from the nature of the numerical computation.

On the other hand, there are many advantages as follows.

1. Very wide application is possible to the subject of the analysis.
2. Not only the strength but also the deformation and the internal stress state can be obtained.
3. The institution of the boundary condition is easy.

These advantages outweigh the drawbacks, and the finite element method has developed into one of the most powerful shear analytical methods.

As subjects for further investigation, it will be necessary to develop the analytical model for the basic properties of reinforced concrete into the more rational one, comparing with the simplified experimental results. Not only are the analytical results of a few specimens compared with the corresponding experimental results, but also it is necessary to investigate the shear resistance mechanisms under the reversed cyclic loading by the more systematic parametric analysis, observing the internal stress state which is difficult to be grasped in the experimental studies.

It will be an important subject for the further investigation to develop the macroscopic model by which the overall structural behavior can be grasped more easily from the feedback of the analytical results by the finite element method in order to bind up the products of research with the design.

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