2. Finite Element Analysis of Reinforced Concrete Structures in Japan

2.1 Introduction

Many analytical studies of reinforced concrete members or structures have been done recently by the Finite Element Method due to the development of computers and analytical methods based on fundamental experimental data. When the general view of the studies is observed, many cases are found in which experimental results were investigated analytically, and the specific problems for reinforced concrete were made clear by the feedback between the experiments and the analyses. This approach should clarify the unknown which might be impossible to investigate only with experimental studies. Further for the buildings of nuclear power plants or offshore structures, the analytical studies are sometimes considered to be more favorable because the structures are so large and complicated, hence, experimental studies are very difficult in the adequate scale. Such thoughts are also seen in the case where the number of necessary test specimens is excessively large in accordance with the variety of loading and boundary conditions. Currently this approach is still supplemental but it should become possible to make up for experimental studies and reduce the number of necessary test specimens when the accuracy of the analyses becomes higher in future. From the view of structural design the current design formulae are established empirically from the test results obtained for each member such as columns, beams or shear walls. This sometimes causes discrepancy when a formula is used in the inapplicable range or a formula is applied as a matter of convenience to the structure which does not belong to any member under classification. For these members FEM in considered to be useful to clarify their behavior, but this approach is still thought as being supplemental.

From these backgrounds active movements have appeared to rearrange the present status and to look over the future prospects of the FEM. In Europe IABSE held a colloquium on "Advanced Mechanics of Reinforced Concrete" at Delft in 1981 [2-1] and in the United States the ASCE published the "State-of-the-Art-Report" [2-2]. In Japan the Japan Concrete Institute held the colloquium on "Shear Analysis of RC Structures" in 1982 and 1983 [2-3], where the fundamental problems of reinforced concrete were discussed especially on analytical procedures In the colloquium the authors [2-4] presented the review of the analytical approaches by FEM and pointed out future problems concerning each basic item as follows: (a) Stress-strain relation of concrete under multi-axial stresses, (b) behavior of concrete after peak stress (c) cracking and its propagation, (d) internal shear transfer, (e) modelling of reinforcing bars, (f) bond between reinforcing bars and concrete, (g) dowel action of reinforcing bars

In this chapter the application of FEM is reviewed in accordance with each member such as columns, beams, beam-column joints, shear walls and structures of nuclear power plants These members have distinct characteristics from one another in the size, space and arrangement of bars, the effect of bond and the dimension in which calculations are performed. Consequently it seems wise to assort respective items to which applications are made so that the problems may be clarified. In the presentation herein only short time loads are considered excluding creep, thermal loads and impact loads The subjects are selected from among those that are comparatively new and have distinct characteristics.

2.2 Columns

A column contains comparatively thick reinforcing bars which are arranged rather sparsely. From this specific feature the characteristics of bars including the effect of correlation with surrounding concrete, are shown remarkably well, hence the bond behavior and the dowel action become important. From an analytical view each bar can be modelled individually, and the bond behavior can be represented easily by bond links which have assumed bond-slip relation. The failure modes of columns are classified into the bending-type, the shear-type, the bond-type etc. corresponding with the shear span ratio and the quantity of reinforcement. But it is considered very difficult for only one model to simulate all of the failure mode types. As to the loading condition a column is subjected to not only lateral forces but also axial ones and besides the direction of stresses change every moment in accordance with the increase of lateral forces. This sometimes causes difficulty so that some additional means for modelling of cracking or its propagation are necessary, or in some cases the questions have to be left undecided. Furthermore in case of analyzing a column with axial forces, which is deformed in two horizontal directions like circular displacements, the analytical method is required which can treat cyclic loads in the three dimension. In this model it is worthwhile to note that the concrete confined by hoops is in 3-dimensional stress condition, and for its evaluation the 3-dimensional constitutive law is applied

Nomura et al. [2-5] defined the yield and failure of concrete by the Mohr-Coulomb's formula and represented reinforcement by axial elements. Bond was modelled by bond links in which the strength of the bond was reduced corresponding with the distance from a crack surface. Columns under cyclic loads were analyzed, and the influence of axial forces to the shape of hysteresis was presented. In the results the area surrounded by the hysteresis loop was small comparatively (Fig. 2.1) The assumption of the hysteresis characteristics should be reconsidered. Furthermore from the study [2-6] in which the pullout of main bars at the end was represented by spring elements, the influence of the pullout was pointed out to be very important because the obtained story deflection increased 35% to 25% when this effect was considered. In considering that Okamura et al. [2-7] represented the bond behavior of reinforcement embedded in massive concrete from the strain in reinforcement vs. slip relation, this procedure seems effective for modelling the anchorage problems.

Noguchi et al. [2-8] represented concrete by an orthogonally anisotropic model and modelled reinforcement by two-dimensional elements for expressing the dowel effect (Fig. 2.2). Bond was represented by bond links in which the detailed characteristics of bond were incorporated, such as the difference of their properties after the bar yielding or the arrival of the ultimate bond strength.

Further the varied properties were assumed for the upper portion and the lower portion, and the deterioration of bond near a crack surface was given consideration. From the analyzed results the fact was pointed out that the assumed bond characteristics severely affected the distribution of the strain of main bars, the bond stress and the bond slip. In this study the detailed analyses were executed on the basis of the precise properties of each material although crack locations were predetermined to represent them by crack lines. This shows that FEM is an useful approach to clarify the influence of each factor to the behavior of reinforced concrete members.

Watanabe [2-9] investigated the shear failure mechanisms of columns caused by the splitting bond failure by considering the ultimate bond stress obtained by experiments for splitting bond failure. In the analytical model the stress-strain relation of concrete was represented by a simple bi-linear curve, and reinforcement was modelled by axial elements. Bond was represented by bond links, and cracks were modelled by crack links of which locations were established beforehand (Fig. 2.3). Furthermore from the obtained stress distribution of concrete the failure mechanism was simplified, and the macroscopic model which could represent its failure more adequately was established. In this study a microscopic model like FEM was used to create a macroscopic model. This approach seems to be the future trend

Inoue et al. [2-10] proposed a nonlinear three-dimensional model in which the core concrete confined by hoops was represented by three-dimensional elements with the plastic theory, and reinforcement and bond were modelled by axial elements and bond links, respectively. In this model the hysteretic characteristics of each element were assumed. This approach was applied to analyze columns under cyclic lateral forces in one direction and to those which were deformed in two horizontal directions (Fig. 2.4). The obtained results showed that their three-dimensional behavior was simulated well. When analyzing a column under two-directional lateral forces, the three-dimensional FEM like this becomes necessary to investigate the effect of shear forces which cannot be estimated by a fiber model, although this analysis is comparatively difficult because the stresses change every moment in accordance with the looped hysteresis But in the results of the

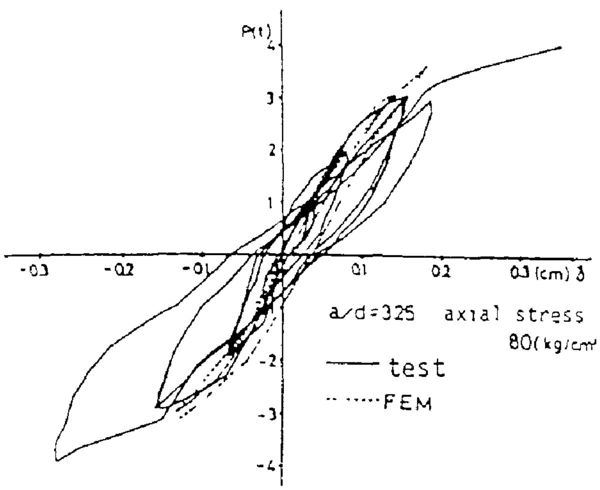


Fig. 2.1 Cyclic Load - Deflection Diagram [2-5]

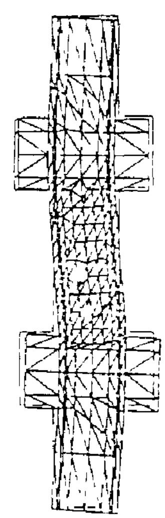


Fig. 2.2 Deformation of Column [2-8]

shear-deflection relation, the obtained area surrounded by the hysteretic loop was small comparatively. This tendency was also seen in the Nomura's analysis [2-5], so the assumption of the hysteretic characteristics require reconsideration.

A column is a member which carries vertical loads. Its failure leads directly to the collapse of the building, and so it is very important to investigate the ductility after its yielding. Especially the influence of cyclic loads should be clarified. But in many cases the analyses by FEM were executed under monotonical loading up only to the adequate strength. This tendency of loading below the strength is seen also in the analyses of cyclic loading. Further the influence by axial forces to the shear capacity of a column has not been cleared by experiments, and the ductility after the peak loads is still beyond comprehension. From now on its is hoped that a proposal will be made for the analytical model in which the ductility of a column after peak loads can be evaluated with consideration for the effect of axial forces and in which the influence of cyclic loading can be discussed.

2.3 Beams

A beam is a fundamental member which has often been analyzed by FEM to clarify the mechanisms of shear resistance in reinforced concrete. The making of analytical model is almost the same as for columns, from the structural characteristics. The authors [2-4] have already made presentations on the detailed review about the beams in past colloquium, so in this report the researches after the review are presented.

Noguchi et al. [2-11] made simple-supported beams without stirrups in which cracks were installed beforehand with the different crack depth, and measured the shear resistance of the elements after the occurrence of inclined cracks, as following: concrete, dowel action of reinforcement and aggregate interlock. In the analytical study by FEM the mechanism of each

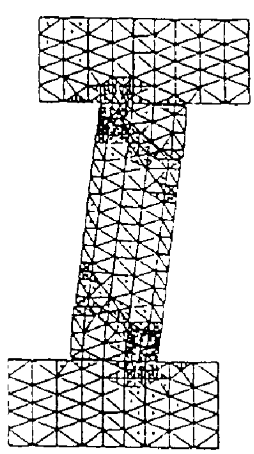


Fig. 2.3 Deformation of Column [2-9]

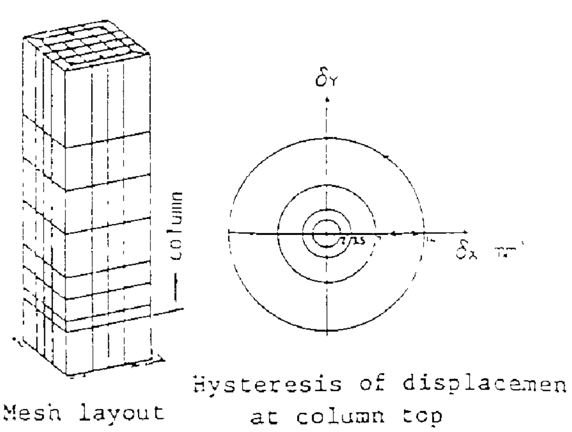


Fig. 2.4 3-Dimensional Model of Column [2-10]

factor was presented, and the obtained shear stress well explained the experimental results in the resistance ratio (Fig. 2.5). This approach seems effective to clarify the resistance role of each element in reinforced concrete by both experiments and analyses.

Kokusho and Hayashi et al. [2-12] executed the test of a beam under bending and shearing forces with prior installed cracks to investigate the bond-slip characteristics of a cracked member. From the analytical results by FEM in which the bond characteristics obtained by the tests was assumed as bond links (Fig. 2.6), it was pointed out that the bond-slip relation should be varied with the correspondence to the distance from a crack surface to simulate the distribution of the strain of longitudinal bars and bond stresses. In this approach one dominant factor for the behavior of reinforced concrete was picked out and investigated by both experiments and analyses. This is a favorable approach expected in the future.

Fukuhara [2-13] made parametric analyses of beams with prior cracks by an elastic model to grasp their mechanical behavior in the vicinity of the inclined cracks which occurred at the ultimate stage under shear forces and to gain the fundamental data for proposing experimental formulae of ultimate shear strength (Fig. 2.7). The obtained results were studied quantitatively in stresses and crack width. This elastic analysis seems to be useful when considering the fact that many specimens have to be calculated to obtain the formulae of the ultimate strength analytically.

Niwa [2-14] analyzed deep beams by a nonlinear FEM assuming smeared cracks in order to clarify the mechanism of their shear resistance (Fig. 2.8). Some parameters which affected the shear capacity were picked out, and their influence to the distribution of compressive stresses in the diagonal concrete struts was grasped quantitatively. Finally from these results a formula of the ultimate shear strength for deep beams was proposed. This approach, in which a design formula was obtained analytically by the parametric calculations, is highly significant to connect the FEM with the design.

Kokusho et al. [2-15] analyzed beams with an opening to study the effect of the reinforcement around it (Fig 2.9). In this study two models, with and without bond, were calculated The obtained results showed that the bond influenced the behavior of a X-shaped reinforcement largely, but it did not influence that of a ring-shaped reinforcement. This is an example that certain fundamental behaviors can be grasped by a simple approach like the elastic analysis.

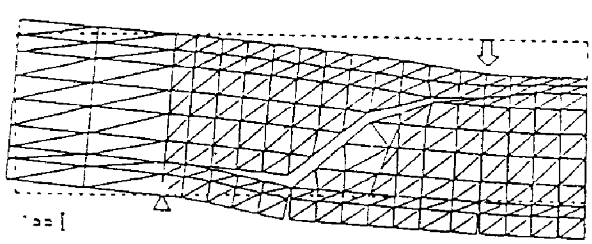


Fig. 2.5 Deformation of Beam [2-11]

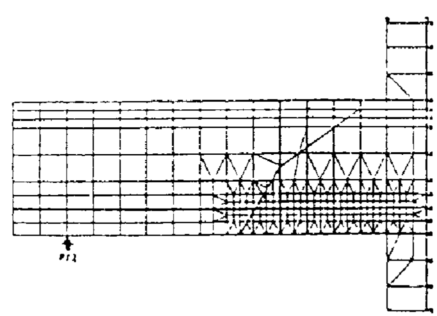


Fig. 2.6 Mesh Layout of Beam [2-12]

Obata and Katsumizu [2-16] pointed out that the applied element mesh layout affected the strength, deformation, crack distribution and stress in longitudinal reinforcement in the analysis of a simple-supported beam. In this study the variations were considered, such as the fineness or coarseness of the mesh size and the orthogonal or oblique division (Fig. 2.10).

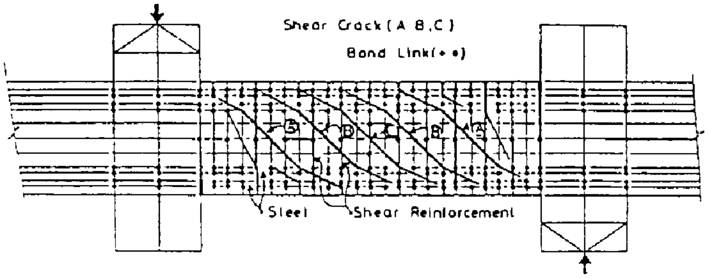


Fig. 2.7 Mesh Layout of Beam [2-13]

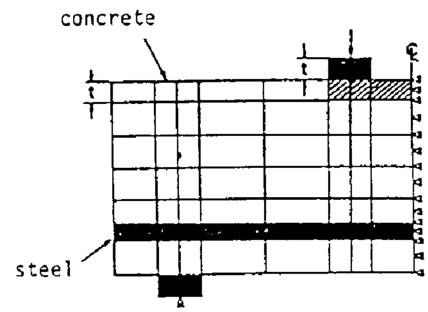


Fig. 2.8 Mesh Layout of Deep Beam [2-14]

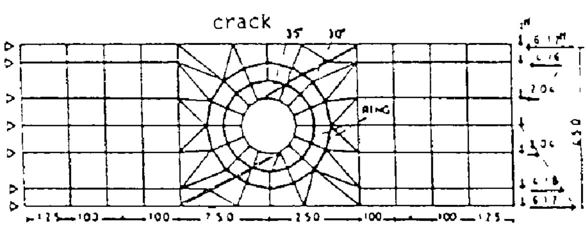


Fig. 2.9 Mesh Layout of Beam with Opening [2-15]

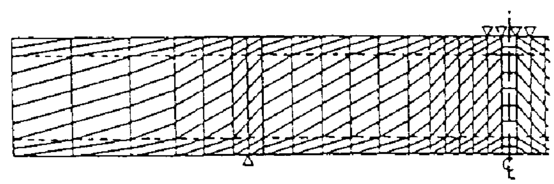


Fig. 2.10 Oblique Mesh Layout of Beam [2-16]

The FEM analyses make it possible to grasp the internal stress and strain in a beam which cannot be obtained easily by experiments. Consequently it is expected that the various failure mechanisms of a beam corresponding with the quantity of lateral reinforcement, and the shear span ratio is clarified by FEM. Furthermore by investigating the resistance ratio of each element quantitatively and comparing it with the results from a macroscopic model, it is desired that the current experimental formulae are substantiated analytically, and a more reasonable design formula is proposed in reference with the results of parametric studies by FEM. Regarding the method of modelling, the degree of minuteness in the adopted method should be considered in accordance with the degree as to how it will affect the analytical results.

2.4 Beam-Column Joints

In the recent design of reinforced concrete frames the stresses in a beam-column joint have become large comparatively in accordance with the increase of the ultimate strength of beams and columns, because it is emphasized that the strength and ductility must be secure in the beams and columns. Consequently the necessity of its study has increased, but there exist not many analytical researches. This is because it is very difficult to model the nonlinear behavior such as the cracking and crush of concrete under complicated high stress condition, and the bond slip of longitudinal reinforcement in a beam at the joint in correspondence with the deterioration of bond.

Shimodaira et al. [2-17] analyzed cross-shaped joints under low stresses (Fig. 2.11). In this model the concrete was assumed to be elastic. Cracking was represented by separating the adjoining nodal points, and the bond was modelled by bi-linear springs. The obtained results showed good coincidences with the experimental ones in the distribution of stress and strain, cracking and its propagation at the joint.

Otsuki et al. [2-18] analyzed statically indeterminate frames with joints by a nonlinear model to comprehend the influence of the difference in assumptions like the mesh layout, the stress-strain relation and failure criteria of concrete and the bond-slip relation. In this study the inclined cracks were neglected at the joint because the assumed failure mode was restricted to the yield of a beam and the bond failure of main bars (Fig. 2.12).

Ohwada [2-19] analyzed joints elastically by 3-dimensional FEM to investigate the influence of the parameters such as the shape of joints, the existence of orthogonal beams and the width of beams. Recently in another research [2-20] the behavior after cracking was studied elastically with a model, incorporating reinforcement and bond, in which cracks were installed beforehand (Fig. 2.13). In considering that the effect of orthogonal beams may decrease when they are subjected to cyclic loads up to the vicinity of their bending yield, such study in nonlinear behavior is desired.

Kamimura et al. [2-21] investigated by three-dimensional elastic analysis the influence of the eccentricity of beams jointed eccentric to a column.

Noguchi et al. [2-22] analyzed cross-shaped joints under cyclic loads, paying attention to the constitutive relation of concrete, the opening and closing of a crack and the bond property

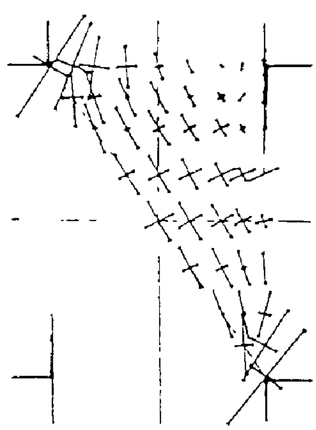


Fig. 2.11 Principal Stress Distribution in Beam-Column Joint [2-17]

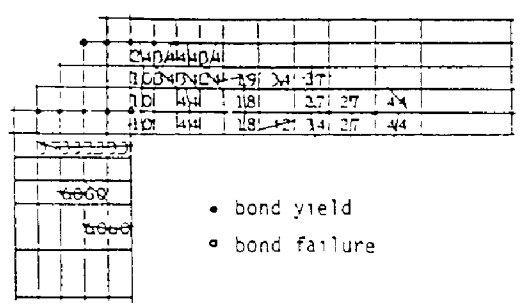


Fig. 2.12 Distribution of Crack in Beam and Column [2-18]

The obtained results indicated the experimental behavior that the deterioration of hysteretic characteristics was influenced by the shear failure of concrete and the deterioration of bond of the beam main bar in the joint (Fig. 2.14).

Hayashi and Kokusho et al. [2-23] analyzed a joint by applying assumed bond characteristics equal to that obtainable from an experiment in which the bond property of beam reinforcement was measured preponderantly within the joint. The results showed a good coincidence with the experimental ones. Especially it is an interesting indication that the deterioration of bond near a crack surface and the axial stress near the surface of a column were influential in expressing the bond properties of a beam.

Until now the number of the analytical examples on beam-column joints is small. Hereafter it is expected that the mechanisms of shear resistance are clarified by investigating analytically the change of internal stress distribution and the deterioration of bond, and that the analysis becomes useful for establishing the design method of joints. Especially the important problems are as follows; the correlation between the bond deterioration of beam reinforcement and the shear failure of a joint, the effect of lateral reinforcement in a joint, the change of the mechanisms of shear failure under cyclic loads after the bending yield of beams.

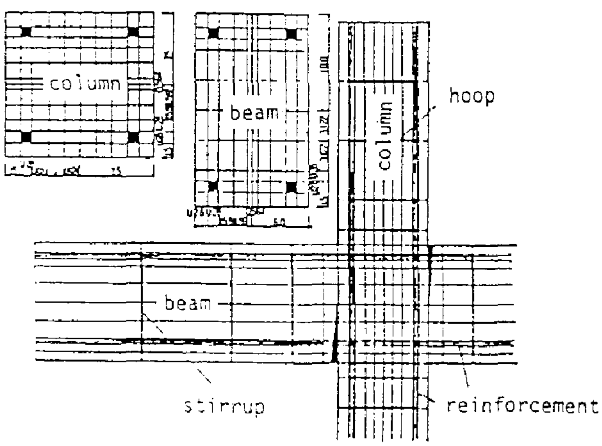


Fig. 2.13 3-Dimensional Mesh Layout of Beam-Column Joint [2-19]

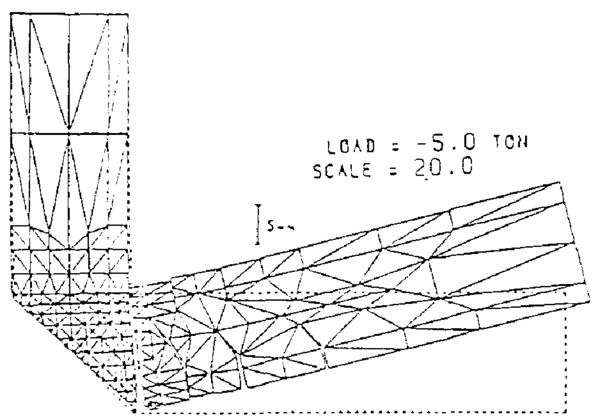


Fig. 2.14 Deformation of Beam-Column Joint [2-22]

2.5 Shear Walls

Generally in a shear wall many number of reinforcing bars are placed. Due to this feature it is rather difficult to model each reinforcement individually and to represent bond by bond links. Consequently in many cases the average behavior of a shear wall was studied by using a distributed representation of the reinforcement. In this modelling, there are cases whereas the bond is considered as perfect, but better results were obtained when evaluation was made of tension stiffening for the bond behavior. But for the investigation of bar arrangement or the bond behavior in detail, the modelling methods used in the analysis of a column or a beam, in which a bar is modelled by an axial element and bond represented by bond links, are sometimes adopted. As to the purpose of the analysis the adopted modelling method retains certain specific feature corresponding with the subjects of the investigation, such as, to evaluate experimental results of the total behavior of a shear wall, or the microscopic behavior of the crack spacing and the bond characteristics. In the study to design a shear wall there are many problems to be investigated as follows: the adequate arrangement of reinforcing bars around an opening, the behavior of the joints in a precast wall or postcast wall, the stiffness and strength of partial walls (wing, wainscot and/or hanging portion of a wall). When these subjects were analyzed, the most respective suitable modelling method was proposed for evaluating the most noted points and the studies corresponding with its aim was executed.

Mochizuki et al. [2-24] represented the nonlinear behavior of concrete by the Darwin-Pecknold's method, and assumed the uniform distribution of reinforcement and perfect bond. By using this method shear walls with surrounding frames, under cyclic pure shear forces, were analyzed, in which a nondimensional hysteretic loop was assumed from the experimental results of stress vs. crack width relation (Fig. 2.15). This showed a simple method to simulate the cyclic behavior but some problems to be cleared remain such as generality of the hysteretic loop obtained from the specific test specimens, and the application to a shear wall in which the yield of concrete in compression was dominant.

Shirai et al. [2-25] assumed the plastic theory for concrete and the uniform distribution of reinforcement. Cracks were represented by the smeared model, but the proposed procedure was able to evaluate tension stiffening, crack spacing and width, aggregate interlock and dowel action quantitatively by using the bond theory which was based on the results of pullout tests under two axial stresses considering the perpendicular compression to the direction of reinforcement. The application to a shear wall of three stories and one span showed good results (Fig. 2 16) This approach is useful to evaluate each factor in detail although cracks are modelled by smearing.

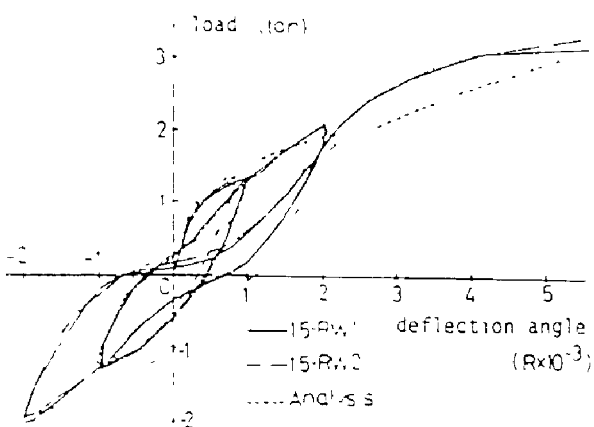


Fig. 2.15 Cyclic Load - Deflection Angle Diagram [2-24]

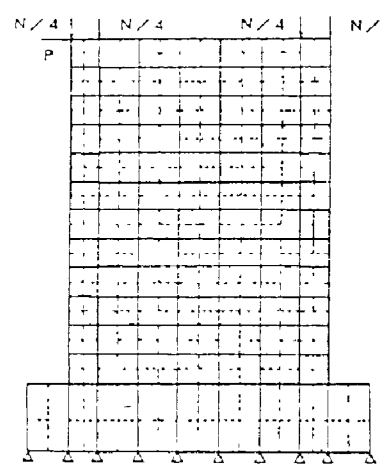


Fig. 2.16 Mesh Layout of Shear Wall [2-25]

Noguchi et al. [2-26] executed microscopic analyses of the Collins' panel tests by a discrete crack model (Fig. 2.17). In this study the dominant factors, such as strength of concrete, reinforcement ratio, yielding strength of reinforcement and loading method, were selected and the shear stress vs. shear strain relation of panels were compared in correspondence with each parameter. Finally by evaluating the influence of each parameter, the formulae to evaluate the maximum shear capacity were proposed. Here not only qualitative but also quantitative analyses were executed instead of experimental studies in which difficulty was seen to conduct the many tests corresponding to each parameter. This approach showed the useful applicability of FEM. However, panels with deformed bars should be investigated in the future because the bond characteristics might show special difference in the Collins' tests in which welded wire meshes are used. Inoue and Koshika et al. [2-27] analyzed a reinforced concrete panel under pure shear by a smeared crack model (Fig. 2.18) In this study reinforcement was modelled by axial elements and the property of bond links were assumed with consideration for the difference of bond strength corresponding with the distance from a crack surface. Furthermore the mesh dimension of the concrete was kept smaller than the crack space From the results it was concluded that in order to simulate the crack pattern the bond strength near a crack surface should be decreased. In considering that these studies of panel tests were conducted mainly to grasp the total behavior macroscopically and to obtain the constitutive relation of a reinforced concrete panel, the meaning of a microscopic analysis by FEM can be said to exist in the study to pick up the dominant factors, which cannot be evaluated well only by experiments, and to substantiate the constitutive relation analytically.

Inoue et al. [2-28] [2-29] presented a method in which the principal stress strain relation proposed by Collins, from reinforced concrete panel tests, was assumed in compression-tension, and the orthogonally anisotropic model was assumed in compression-compression. In the applications to shear walls with different shear span ratios and reinforcement ratios, it was shown that this method could grasp the yielding propagation and ultimate strength corresponding with each parameter (Fig 2.19). This approach had less assumptions comparatively because it was

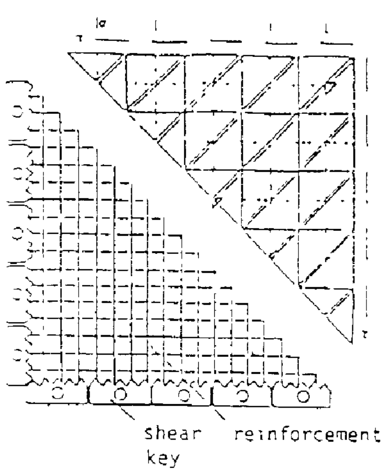


Fig. 2.17 Reinforced Concrete Panel and Mesh Layout [2-26]

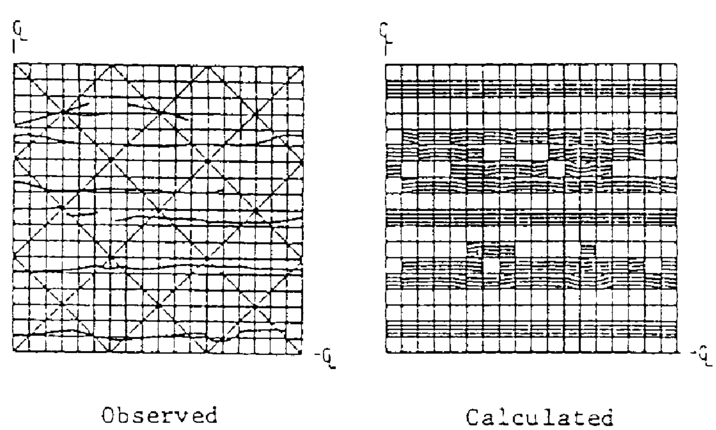
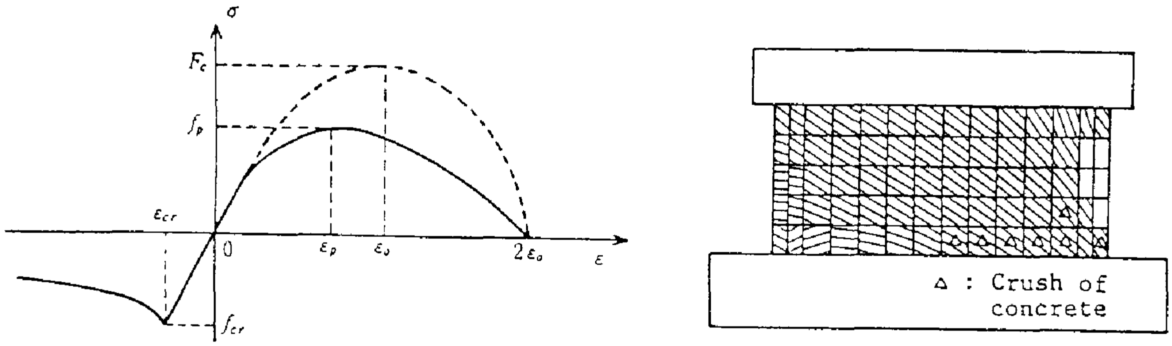


Fig. 2.18 Crack Pattern of Reinforced Concrete Panel [2-27]

more macroscopic on the basis of the test results in which reinforced concrete panels were considered to be the minimum elements. Consequently in cooperation with the iterative calculation procedure using secant modulus, the inquiry of obtained results was simple and this approach is thought to be useful for the design purpose. However, it is very important to know the applicability of the test results on which this approach is based.



Assumed stress - strain curve of cracked concrete

Crack pattern

Fig. 2.19 FEM Analysis of Shear Wall based on Collins' Theory [2-28] [2-29]

As to the study of openings, Seya et al. [2-30] analyzed shear walls with an opening by a model in which the plastic theory was assumed for concrete and reinforcement was modelled by an axial element. From the obtained stress distribution and crack pattern, it was concluded that the analyses could give the feature of the ultimate failure in the experimental results. Sotomura et al. [2-31] analyzed shear walls with many small openings by the ADINA program and presented that the obtained results showed good coincidences with the experiments regarding the shear vs. deformation relation, the loads at initial cracking and the feature of crack propagation (Fig. 2.20). Noguchi et al. [2-32] analyzed shear walls with different arrangement of reinforcement for an opening with a model in which reinforcement was modelled by axial elements and bond was represented by bond links (Fig. 2.21). The obtained results showed that the difference in the reinforcing method had much influence on the deformation and the failure behavior of shear walls.

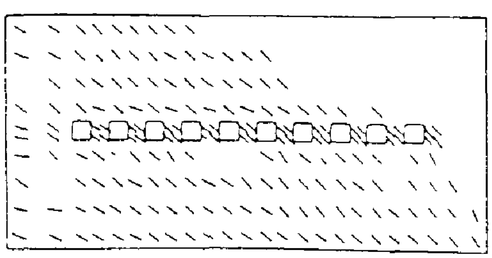


Fig. 2.20 Crack Pattern of Shear Wall with Many Openings [2-31]

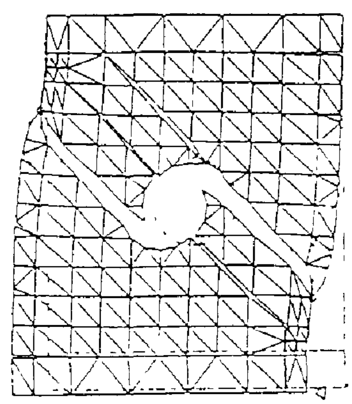


Fig. 2.21 Deformation of Shear Wall with Opening [2-32]

It can be said that in the microscopic study like this a corresponding microscopic modelling is necessary. In this study cracks were assumed beforehand by crack links at determined portion derived from the experimental results. But from the view of the structural design it will be an important point whether the location of cracks can be presumed adequately without preliminary experiments.

On the study paying attention to concrete joints, Kokusho et al. [2-33] analyzed a postcasted shear wall which was placed with dowell reinforcement to strengthen an existing building (Fig. 2.22). In this analysis the joints were modelled from the experimental results of joints with the dowel reinforcement by spring elements which were orthogonal mutually. From the analytical results in which the resistance ratio of the dowel and concrete was estimated, it was concluded that the behavior of a postcasted shear wall could be grasped if the property of the joint was given. Suenage et al. [2-34] represented the joint by an anisotropic finite element considering the friction, bond and dowel action to analyze a precasted shear wall with the horizontal joints. The application to a walled frame well represented the load vs. deformation relation and the nonlinear behavior. Higashi et al. [2-35] represented the vertical and horizontal joints of a precasted shear wall by bond link elements, and determined the horizontal stiffness from shear tests and the vertical stiffness from uni-axial compression tests. Noguchi and Muruta [2-36] estimated the stiffness and the failure criteria of the spring elements which jointed the frame and the postcasted shear wall on the basis of the latest test data of dowel and the analytical results presented by Kokusho et al. The application showed that the failure process of the joints had much influence on the total behavior of a shear wall from the study in which the dowel effect was investigated on the ultimate strength and deformability of the postcasted shear wall (Fig 2 23).

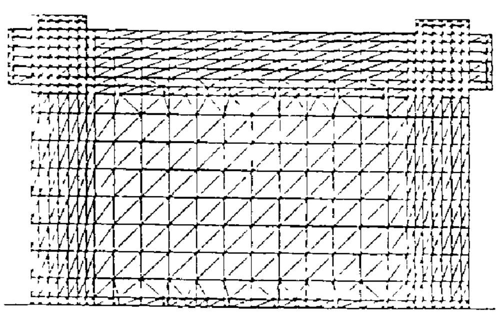


Fig. 2.22 Mesh Layout of Postcasted Shear Wall [2-33]

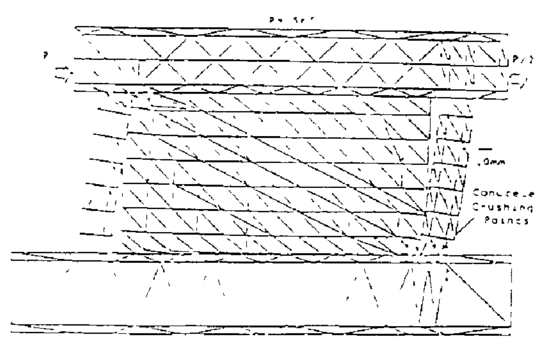


Fig. 2.23 Deformation of Infilled Shear Wall [2-36]

Nomura et al. [2-37] studied the effect of partial walls which were placed in a frame (Fig. 2.24). In the analysis the nonlinear behavior of concrete and reinforcement was evaluated by assuming the equivalent elastic stiffness. Here the initial stiffness, the yielding strength and the ultimate strength were compared with the current design formulae to investigate their applicability. Aizawa et al [2-38] analyzed walled frames with an opening of different shapes and sizes to obtain the equivalent opening ratio and presented the applicable limit of the modelling by frames. These studies investigated the applicability of the design formulae by parametric analyses and should increase in accordance with the improvement of the analytical accuracy.

Furthermore Ono and Adachi et al. [2-39] investigated the resistance ratio of the shear wall panel and its surrounding frame in a multi-storied shear wall by a discrete crack model (Fig. 2.25). Kano et al. [2-40] studied the same problem by the smeared crack model As to the calculation approach Arai [2-41] proposed an iterative method for monotonically increasing loading, and Mitsukawa and Baba [2-42] pointed out the usefulness of a generalized code with many options of modelling.

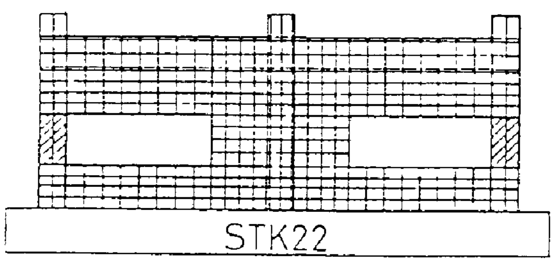


Fig. 2.24 Mesh Layout of Shear Wall [2-37]

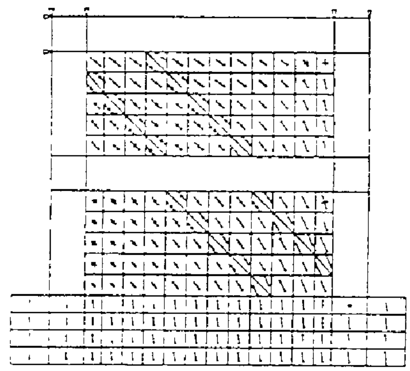


Fig. 2.25 Principal Stress Distribution of Shear Wall [2-39]

In considering that the greater parts of a shear wall are under tension-compression stresses in shear failure, it is very important in the analysis how to consider the decline of the compressive strength and stiffness in cracked concrete, which was shown in the reinforced concrete panel tests by Collins. Ueda et al [2-52], Maekawa [2-43] and Morikawa [2-53] used methods to decrease them beforehand, and Noguchi [2-26] represented their decline by assuming the characteristics under bi-axial tension-compression stresses without deteriorating the concrete strength itself Inoue et al. [2-28] [2-29] assumed the stress strain relation proposed by Collins as it was. This problem should be cleared urgently About the shear slip failure observed in experiments some studies have been started like the Ueda's proposition [2-52] in which the failure was represented by assuming the limit criteria of shear strain. But this is a future problem and should be investigated to clear its mechanism and the means to represent it by analyses. Furthermore there are problems to be studied such as the change of the ultimate shear strength corresponding with the confinement of the surrounding frame and the influence induced by the difference of the following loading methods; push, push-pull and distributed loading

2.6 Structure of Nuclear Power Plant

As to the structure of nuclear power plants there are the box-typed and cylinder-typed shear walls, and prestressed concrete reactor vessels (PCRV) among others. In the analyses they should be handled as three dimensional structures because they are subjected to out-of-plane forces besides in-plane forces. The loading condition is very complicated. A cylinder-typed shear wall under internal pressures or thermal loads can be analyzed as an axisymmetric problem and can be handled like a two dimensional problem by using solid plane elements for concrete and axial elements for reinforcement. But when subjected to non-axisymmetric forces like earthquake loads the entire structure must be considered and then in many cases it is analyzed by the model in which the out-of-plane bending is represented by layered elements, reinforcement is replaced with equivalent plates and smeared cracks are assumed. On the occasion when subjected to earthquake loads after cracking by internal pressures, the direction of principal stresses changes greatly, and new cracks occur in the aslant direction to the previous cracks. So it becomes very difficult to represent the cracks by the generally used method in which the orthogonally anisotropic model is assumed after cracking. Also, it becomes a basically complicated problem because the shear transfer between cracks is dominant. For these reasons the studies to such loading conditions are very few.

Isobata [2-44] proposed an orthogonally anisotropic model by introducing parameters concerning Young's modulus and Poisson's ratio to analyze three dimensional structures like a prestressed concrete pressure vessel (PCPV) as a three dimensional axisymmetric problem (Fig. 2.26). The application to the PCPV under internal pressures showed that not only the deformation but also

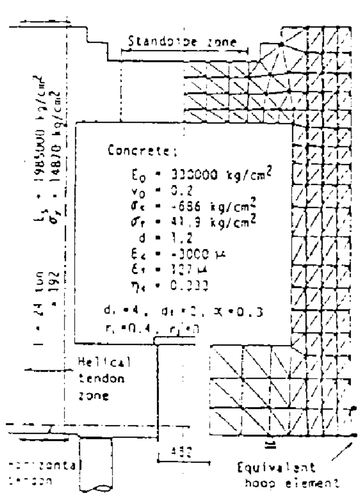


Fig. 2.26 Model of PCPV [2-44]

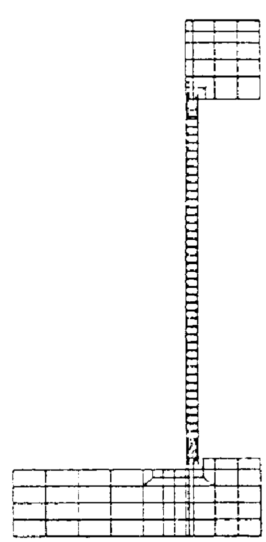


Fig. 2.27 Mesh Layout of Reinforced Concrete Containment Vessel [2-45]

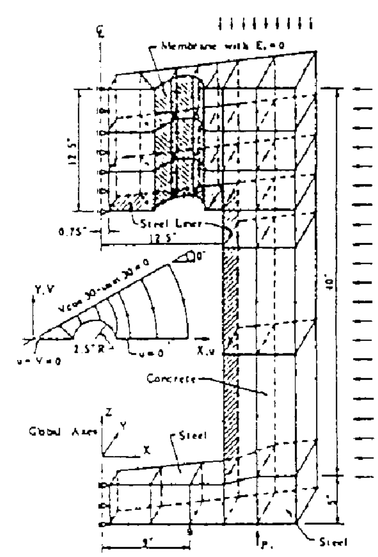


Fig. 2.28 3-Dimensional Model of PCRV [2-46]

the crack propagation could be grasped in a three dimensional structure with thick cross sections and that the obtained results simulated the experimental crack pattern.

Miyashita and Morikawa et al. [2-45] analyzed a reinforced concrete containment vessel under internal pressures by the three dimensional axisymmetric model in which the constitutive relation of concrete was defined by the plastic theory, and reinforcement and bond were represented, respectively (Fig. 2.27). This is the same approach as the two dimensional problem and makes it possible to investigate the deformation and the propagation of nonlinearity in a structure of revolution with thick cross sections like the Isobata's model.

Imoto [2-46] proposed an analytical method using three dimensional solid elements for three dimensional structures with complicated shapes like a PCRV. As to the yield condition of concrete a cracking criterion reflecting the effect of the intermediate principal stress for tension, and a generalized Drucker-Prager's criterion for compression were adopted to precisely represent the three dimensional stress state. The application to a PCRV under internal pressures showed a good coincidence with the observed deformation and yielding propagation (Fig. 2.28). In future the clarification of the applicability to the stress strain relation of plain concrete under triaxial stresses is desired, although this is a problem in experiments.

Ohuchi et al. [2-47] analyzed a cooling tower under horizontal forces by a layered model assuming that the in-plane stiffness of concrete was obtained from the plastic theory and reinforcement was replaced with the equivalent plates (Fig. 2 29). The obtained results simulated the experimental ones on the deformation, the crack pattern and the strain in reinforcement. But it was pointed out that the observed shear failure at the throat of the cooling tower could not be interpreted by the analysis although its possibility was shown. The clarification of this failure is a very important problem pertaining to shear walls in general.

Fujita et al. [2-48] analyzed a cylindrical shear wall under internal pressures and a box-typed shear wall under lateral forces by the layered model using the orthogonally anisotropic theory

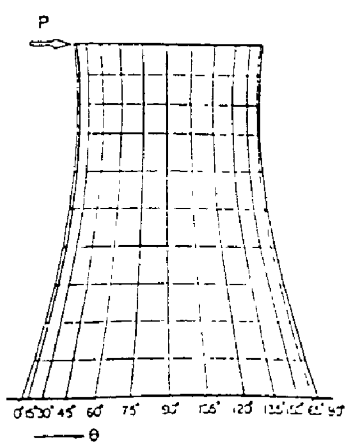


Fig. 2.29 Model of Cooling Tower [2-47]

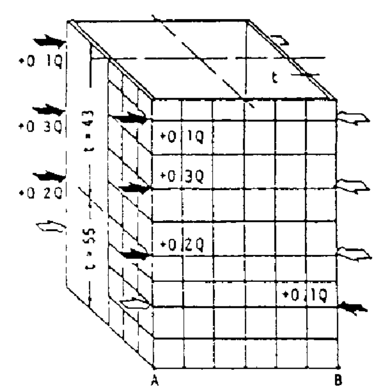


Fig. 2.30 Model of Box-Typed Shear Wall [2-48]

proposed by Isobata (Fig. 2.30). Obtained results showed good coincidences with the observed ones on the deformation, the stress distribution and the strain distribution of reinforcement.

Imoto et al. [2-49] analyzed a prestressed concrete containment vessel (PCCV) using the Ohuchi's method and investigated the method of estimating the bending and shear stiffness for the lumped mass models, which have been used widely in earthquake response analyses (Fig. 2.31). This was conducted by separating the rotation, the bending deformation and the shear deformation from the FEM results to obtain each nonlinear characteristic. This approach seems to be very useful for obtaining the necessary load-deflection curve in the executing dynamic analyses.

To obtain the load-deflection curve of box-typed shear walls, Inada et al. [2-50] made parametric studies with the Fujita's layered model using the orthogonally anisotropic theory and investigated the influence of each parameter such as the reducing ratio of shear rigidity, the shear span ratio, the reinforcement ratio, the axial stress and the loading method (Fig. 2.32). Furthermore the shear stress vs. shear strain relation, which was obtained by separating the bending and shear deformation from the analytical results, was simplified to the trilinear curves and compared with the current formulae. In considering that there are not many experiments of box-typed shear walls and that it is difficult to generalize the load-deflection curve only with the test data, this is a useful approach to fill up the insufficient data.

Shiraishi et al. [2-51] analyzed a reinforced concrete cylindrical shell and a prestressed concrete one under horizontal forces with the layered model using the Darwin-Pecknold's for the constitutive relation of concrete. From the results it was concluded that the deformation, the strain in reinforcement and the crack pattern were well grasped and that the induced prestresses caused the increase of ultimate strength and the decrease of the ductility. But the observed shear failure could not be simulated although the obtained shear distribution showed possibility.

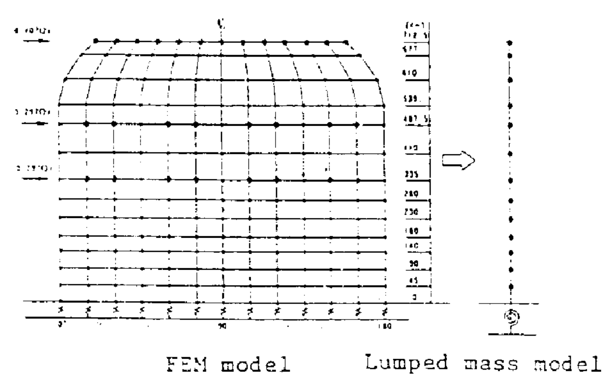


Fig. 2.31 FEM Model and Lumped Mass Model of PCCV [2-49]

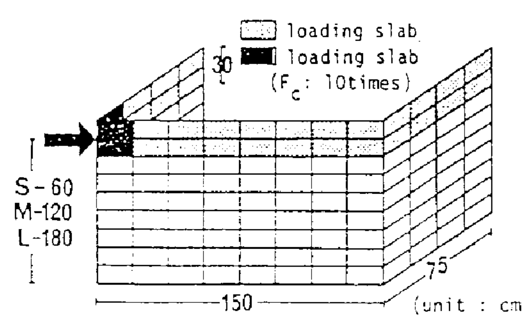


Fig. 2.32 Model of Box-Typed Shear Wall [2-50]

Ueda et al. [2-52] defined the constitutive relation of concrete used in the layered model with reference to the experimental results of the reinforced concrete panel tests by Collins (Fig. 2.33). That is, it was assumed that the stiffness and strength of concrete in the parallel direction to a crack after cracking were reduced in tension-compression region and that the stiffness of concrete dropped to zero when the shear deformation reached the assumed limit value. The former represented the deterioration of concrete after cracking and the latter represented the shear slip failure by shear strain. These assumptions are very important and should be cleared urgently as a general problem of shear walls, in considering that the greater parts of the wall are in the tension-compression stresses when shear failure occurs. The applications to a cylindrical shell and a box-typed shear wall showed good agreements with the experimental results on the load vs. deformation relation and the failure pattern.

Morikawa [2-53] analyzed reinforced concrete cylindrical shells under lateral forces with internal pressures or thermal loads with the layered model assuming the plastic theory for concrete (Fig. 2.34). To represent this complex loading condition, it was proposed that the aggregate interlock after cracking in two directions was modelled precisely assuming the equivalent shear rigidity and that the previous cracks in two directions closed and an inclined crack occurred newly when the principal stresses in the inclined direction reached the assumed cracking criterion. The obtained results indicated good comprehension of the experimental behavior although the shear slip failure could not be simulated. This approach seems to be useful when the loading direction greatly changes.

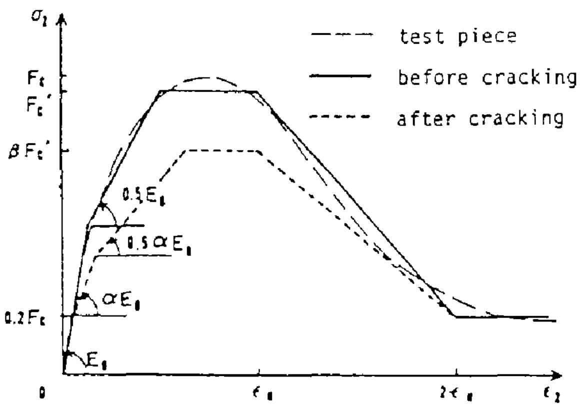


Fig. 2.33 Assumed Stress - Strain Curve of Cracked Concrete [2-52]

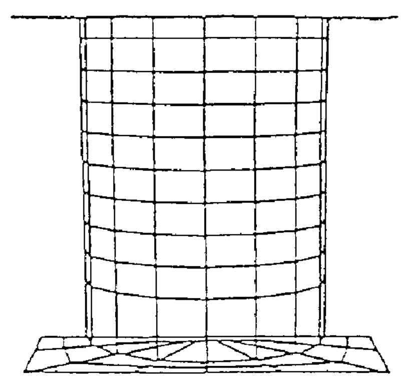


Fig. 2.34 Model of Cylindrical Shell [2-53]

The structures of a nuclear power plant are generally very stiff, but in many cases their dynamic studies are demanded due to their importance. In such analyses the adequate load-deflection curve has to be assumed and the certain suitable formulae based on the experimental studies are used. But until now there are not enough experimental data and so the FEM analyses possess expectation to fill the insufficient points. Furthermore because the structures have in general very complicated shapes and are under complicated loading combination due to their functions, the current design formulae might not be applied adequately in some cases. These reasons make the necessity of the FEM analysis very high. Especially in considering that the confirmation has become necessary lately of their safety on the nonlinear behavior in the worst earthquakes besides the allowable design, the FEM application to these structures may be the most popular and useful. From the experimental view, as the actual structure is so huge, the test specimens become very small comparatively. Namely, in many cases the scale is reduced to approximately 1/30. Consequently the scale effect should be studied by the analyses on the basis of the material property besides experimental investigations.

2.7 Conclusions

In this chapter a description was presented for the respective structural specific features. As to the future direction to proceed it depends on each researcher's opinion whether the development of computing program codes being applied to each structural feature is a better approach or not. But the authors think it is preferable to solve structural members, such as columns, beams, beam-column joints and shear walls, by one program. Because they are made from the composite material of reinforcement and concrete with not such difference in size, and they could be calculated by the same model if it was assumed on the basis of the true material property. Furthermore such possibility of the FEM analyses is its strong point over the macroscopic analyses. However, as each member has its own structural feature it seems effective to use a general code in which a suitable option can be selected corresponding with the following points; the discrete crack or the smeared crack, modelling reinforcement by an individual element or by a distributed element, representing the dowel action and the aggregate interlock by a discrete model or by an distributed model. Furthermore when calculating the whole structure it will be necessary to develop a more macroscopic model on the basis of the test results of fundamental members like the Collins' panel tests or the analytical results obtained by the microscopic FEM analyses. In these analyses it is desirable that the better modelling is proposed on the basis of the latest knowledge concerning the dominant factors to the nonlinear behavior of reinforced concrete, and that the FEM analyses can contribute to the clarification of actual phenomena and are applied to the actual design by promoting their usefulness.

Finally in considering that similar analytical results are obtained in some cases even though researchers use rather different models individually, it is desired that they should exchange their knowledge and make a comparison with each other without keeping it on the personal basis. Such opportunities are desired not only domestically but also on a world-wide basis.

References

[2-1] IABSE, "Final Report on Advanced Mechanics of Reinforced Concrete," IABSE Colloquium Delft, 1981

[2-2] Committee on Concrete and Masonry Structures, "State-of-the-Art Report on Finite Element Analysis of Reinforced Concrete," ASCE, 1982

[2-3] Research Committee on Shear Strength of Reinforced Concrete Structures, "Proceedings of JCI Colloquium on Shear Analysis of RC Structures," JCI, June 1982 (in Japanese), Sep. 1983, Oct. 1983 (in Japanese)

[2-4] Noguchi, H. and Inoue, N., "Analytical Techniques of Shear in Reinforced Concrete Structures by Finite Element Method," Proceedings of JCI Colloquium on Shear Analysis of RC Structures, JCI, Sep. 1983, pp.57-92

[2-5] Nomura, S., Sato, K. and Ono, H., "Analysis of Hysteretic Behavior of Reinforced Concrete Member by FEM," Proc. Annual Conv., AIJ, Sep. 1978, pp. 1469-1470 (in Japanese)

[2-6] Nomura, S., Sato, K. and Ono, H., "Study on Effect of Bond Characteristic to Hysteretic Behavior of Reinforced Concrete Column, " Proc. of Annual Conv., AIJ, Sep. 1980, pp. 1799-1800 (in Japanese)

[2-7] Chou, L., Niwa, J. and Okamura, H., "Bond Model of Steel Embedded in Massive Concrete, " Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 45-52 (in Japanese)

[2-8] Noguchi, H. and Iizuka, S., "Nonlinear Analysis of the Effect of the Bond Characteristics on the Mechanical Behavior of R/C Short Columns," Proc. Annual Conv., AIJ, Sep. 1983, pp. 2105-2106 (in Japanese)

[2-9] Watanabe, F., "Mechanism of Shear Failure of R/C Column due to Bond Splitting," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 61-68 (in Japanese)

[2-10] Sugano, T., Inoue, N , Koshika, N., Hironaka, Y. and Hayami, Y., "3-Dimensional Nonlinear Analysis of Reinforced Concrete Columns under Repeated Bending and Shearing Forces," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 87-96 (in Japanese)

[2-11] Noguchi, H. and Maruta, M., "Nonlinear Finite Element Analysis of Shear Resistance Mechanism of Reinforced Concrete Beams," Proceedings of JCI Colloquium on Shear Analysis of RC Structures, June 1982, pp. 99-106 (in Japanese)

[2-12] Kokusho, S., Hayashi, S., Kobayashi, K. and Yoshida, H , "Fundamental Study on Bond between Deformed Bar and Concrete-Part 3," Proc. Annual Conv , AIJ, Oct. 1982, pp. 1329-1330 (in Japanese)

[2-13] Fukuhara, M., "Examination of Behavior of RC Beam Near Inclined Crack Using FEM Linear Analysis," Proc of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 111-118 (in Japanese)

[2-14] Niwa, J., "Equation for Shear Strength of Reinforced Concrete Deep Beams Based on FEM Analysis," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 119-126 (in Japanese)

[2-15] Kokusho, S., Hayashi, S., Shinke, H., Iwakura, T. and Honda, Y., "Experimental Study on Reinforced Concrete Beam with Opening," Proc. of Annual Conv., AIJ, Sep. 1981, pp. 1505-1506 (in Japanese)

[2-16] Obata, M. and Katsumizu, Y., "Nonlinear Analysis of Reinforced Concrete Beams by the Finite Element Method," Proc. of Annual Conv., AIJ, Sep. 1983, pp. 1781-1782 (in Japanese)

[2-17] Shimodaira, H. and Higashi, Y., "Analysis of Reinforced Concrete Beam-Column Joint by FEM," Proc. of Annual Conv., AIJ, Nov. 1971, pp. 843-844 (in Japanese)

[2-18] Kimura, H., Otsuki, K. and Obata, M., "Nonlinear Analysis of Frame with Infinite Uniform Span by FEM-Part 1," Proc. of Annual Conv., AIJ, Oct. 1975, pp. 771-772 (in Japanese)

[2-19] Ohwada, Y., "Three-Dimensional Stress Analysis of Reinforced Concrete Beam-Column Joints under Seismic Stress," Proc. of JCI Colloquium on Shear Analysis of RC Structures, June 1982, pp. 107-114 (in Japanese)

[2-20] Ohwada, Y., "Stress Analysis of Reinforced Concrete Beam-Column Joint by Three-Dimensional FEM-Part 2," Proc. of Kanto District Symp., AIJ, 1984, pp. 193-196 (in Japanese)

[2-21] Umemura, H., Yamada, D., Matsuda, O. and Kamimura, T., "Experimental Study on Reinforced Concrete Beam-Column Joint with Eccentric Wall Girder-Part 7," Proc. of Annual Conv., AIJ, Oct. 1982, pp. 1661-1662 (in Japanese)

[2-22] Noguchi, H. and Naganuma, K., "Nonlinear Analysis of Reinforced Concrete Beam-Column Joints under Reversed Cyclic Loading," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct 1983, pp. 139-146 (in Japanese)

[2-23] Hayashi, S , Kokusho, S. and Morimoto, T., "Experimental Study of Bond Behavior of Reinforcing Bars through the Interior Beam-Column Joint," Report of the Research Laboratory of Engineering Materials, Tokyo Institute of Technology, No. 9, 1984, pp. 283-297

[2-24] Mochizuki, S. and Kawabe, S., "Experiment of Shear Wall with Surrounding Frame under Reversed Cyclic Pure Shear-Part 3," Proc. of Annual Conv., AIJ, Sep. 1980, pp. 1619-1620 (in Japanese)

[2-25] Shirai, N. and Sato, T , "Bond-Cracking Model for Reinforced Concrete," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 9-16 (in Japanese)

[2-26] Noguchi, H. and Naganuma, K., "Nonlinear Parametric Analysis of Reinforced Concrete Panels," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 147-154 (in Japanese)

[2-27] Inoue, N., Koshika, N., Suzuki, N. Hayami, Y., "Nonlinear Analysis of Reinforced Concrete Panel Subjected to In-Plane Shear by the Finite Element Method," Transaction of JCI, 1984

[2-28] Inoue, N., Koshika, N., Suzuki, N. and Hayami, Y., "Nonlinear Analysis Method of Reinforced Concrete Based on Collins' Theory," Proc. of JCI, 7th Conference, 1985 (in Japanese)

[2-29] Sugano, T., Inoue, N., Koshika, N. and Suzuki, N., "Nonlinear Parametric Study of Reinforced Concrete Shear Wall," Proc. of JCI, 7th Conference, 1985 (in Japanese)

[2-30] Seya, Y. and Matsui, G., "Study of Stress and Displacement of Shear Wall with Opening-Part 2," Trans. of AIJ, No. 301, March 1981, pp. 101-105 (in Japanese)

[2-31] Murakado, Y., Sotomura, K. Yoshizaki, S. and Ezaki, T., "Strength and Deformation of Reinforced Concrete Shear Wall with Many Small Openings," Proc. of Annual Conv., AIJ, Sep. 1981, pp. 1627-1628 (in Japanese)

[2-32] Noguchi, H. and Maruta, M., "Nonlinear Analysis of the Detailing of Reinforcement in R/C Shear Walls with Opening," Proc. of Annual Conv., AIJ, Sep. 1983, pp. 2959-2060 (in Japanese)

[2-33] Kokusho, S., Hayashi, S. and Aya, M., "Study on the Effect of Joint to the Behavior of Postcast Reinforced Concrete Shear Wall," Proc. of Kanto District Symp., AIJ, 1978, pp. 161-164 (in Japanese)

[2-34] Suenaga, Y. and Halim, J.K., "2-Dimensional Nonlinear Stress Analysis of Precast Reinforced Concrete Shear Wall," Proc. of Annual Conv., AIJ, Oct. 1982, pp. 1705-1706 (in Japanese)

[2-35] Higashi, Y., Iso, K. and Tachi, M., "Studies on Shear Behavior of Precast Reinforced Concrete Shear Wall-Part 5," Proc. of Annual Conv., Sep. 1983, pp. 1839-1840 (in Japanese)

[2-36] Noguchi, H. and Maruta, M., "Nonlinear Analysis of Strength and Ductility of Infilled RC Shear Walls," Proc. of JCI, 6th Conference, pp. 745-748 (in Japanese)

[2-37] Nomura, S., Sato, K , Zama, Y. and Yamada, T., "Nonlinear Behavior of Reinforced Concrete Structure with Partial Wall," Proc. of Kanto District Sym., AIJ, 1980, pp. 161-168 (in Japanese)

[2-38] Aizawa, S., Tanno, Y., Tohata, Y., Ueda, M., Hayami, H., Yamaguchi, I., "Study on Nonlinear Behavior of Frame with Shear Wall," Proc. of Annual Conv., AIJ, Oct. 1982, pp. 1529-1532 (in Japanese)

[2-39] Ono, A., Adachi, H , Nakanishi, M. and Tanaka, N , "Study on Aseismic Capacity of Reinforced Concrete Shear Wall-Part 15," Proc. of Annual Conv., AIJ, Oct. 1976, pp. 1617-1618

[2-40] Kano, Y., Takagi, H. and Morinaga, K., "Experimental Study on Strength and Deformation of 3-storied Small Reinforced Concrete Shear Wall-Part 2," Proc. of Annual Conv., AIJ, Sep. 1981, pp. 1653-1654 (in Japanese)

[2-41] Arai, Y., "Nonlinear Analysis of a Shear Wall-Frame System of Reinforced Concrete," Trans. of AIJ, No. 265, Feb. 1978, pp. 41-49 (in Japanese)

[2-42] Mitsukawa, E. and Baba, K., "Study on Hysteretic Characteristic of Shear Wall," Proc. of Kanto District Sym., AIJ, 1978, pp. 169-176 (in Japanese)

[2-43] Maekawa, K., "Constitutive Law of Concrete Based on the Elasto-Plastic and Fracture Theory," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp. 1-8 (in Japanese)

[2-44] Isobata, O., "On an Anisotropic Constitutive Model of Concrete for the FEM Nonlinear Stress Analysis," Trans of AIJ, No. 265, March 1978, pp. 11-18 (in Japanese)

[2-45] Uchida, T., Miyashita, T., Endo, A. and Morikawa, H., "Model Experiment of Reinforced Concrete Containment Vessel for Nuclear Power Plant under Accidental Internal Pressure and Lateral Force-Part 3," Proc. of Annual Conv., AIJ, Sep. 1978, pp 1831-1832

[2-46] Imoto, K., "Analytical Method for Three-Dimensional of Prestressed Concrete Nuclear Reactor Vessels," 6SMIRT, 1981 H3/7

[2-47] Ohuchi, H., Koike, K., Ito, M. and Takeda, T., "Experimental and Analytical Study on Inelastic Behavior of the RC Cooling Tower Model Subjected to Horizontal Loads," Proc. of JSCE, No. 266, Oct. 1977, pp 39-59 (in Japanese)

[2-48] Fujita, F., Isobata, O., Kawamata, S and Tsuboi, Y., "Finite Element Elasto-Plastic Analysis of Thin Walled Structures of Reinforced Concrete as Applied to Reactor Facilities," 6SMIRT, 1981, M 1/3

[2-49] Imoto, K., Matsumoto, T. and Tomura, H., "Nonlinear Analysis of Prestressed Concrete Containment Vessel," Proc. of Annual Conv., AIJ, Oct. 1982, pp 945-946 (in Japanese)

[2-50] Inada, Y., Ogawa, Y. and Saruta, M., "Parametric Study on the Seismic Behavior of 3-Dimensional Shear Walls for the Reinforced Concrete Reactor Building Using Nonlinear FEM Analysis," Proc. of annual Conv., Sep. 1983, (in Japanese)

[2-51] Shiraishi, I., Machida, N. and Nakamura, Y., "Experimental and Analytical Study on Prestressed Concrete Cylindrical Wall Subjected to Lateral Force," Proc of Annual Conv., AIJ, Sep. 1983, pp. 1537-1538 (in Japanese)

[2-52] Ueda, M., Seya, H. and Kei, T., "Nonlinear Analysis of RC Cylinder and Box Type Wall Subjected to Shear Force," Proc. of JCI 2nd Colloquium on Shear Analysis of RC Structures, Oct. 1983, pp 163-170 (in Japanese)

[2-53] Morikawa, H., "Nonlinear Analysis of Reinforced Concrete Cylindrical Shell Subjected to Internal Pressure and/or Thermal Loads with Seismic Loads," Dec 1984, pp 165-172

— From Proc of Seminar on Finite Element Analysis of Reinforced Concrete Structures, Tokyo, 1985, Vol. 2, JCI

Co-author: Prof Norio Inoue, Associate Professor, Tohoku University (Former in Kajima Corporation) —