Unified Approach in the Application of the Finite Element Method
Approche unifiée dans l'application de la méthode des éléments finis
Vereinheitlichter Ansatz bei der Anwendung der Methode der Finiten Elemente

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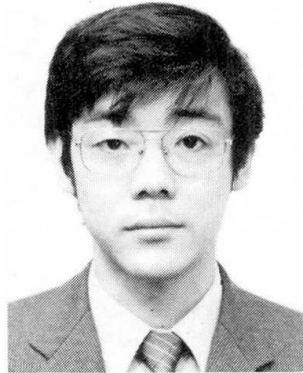
SUMMARY
The authors investigate problems concerning the application of the finite element method to the design of reinforced concrete structures in Japan, and describe approaches for modeling methodology and evaluating results.

RÉSUMÉ
Les auteurs étudient les problèmes relatifs à l'application d'une méthode des éléments finis pour le projet de structures en béton armé au Japon. Ils décrivent la méthodologie proposée pour l'étude par modèle et commentent les résultats.

ZUSAMMENFASSUNG
Die Autoren untersuchen Probleme der Anwendung der FE-Methode beim Entwurf von Stahlbetonkonstruktionen in Japan, beschreiben Möglichkeiten der Modellmethodologie und werten Resultate aus.

1.INTRODUCTION

Recently, the increase in large-scale and complex structures coupled with the improvement of the availability and popularization of computer technology have created opportunities for the direct and indirect use of the finite element method (FEM) as a tool for designing concrete structures. FEM analysis has proven to be an extremely effective means of obtaining section forces and stress distributions that could not be obtained by frame analysis. In actual applications, however, there are as yet no generally standardized guidelines for the analytical method, modeling methodology, or interpretation of results. In practice, these matters are left up to the individual designer.

Accordingly, the Committee on Finite Element Analysis of Reinforced Concrete (RC) structures (chairman Hiroshi NOGUCHI) organized by the Japan Institute, had commenced its activities in order to establish guidelines for the application of FEM analysis to the actual design of RC structures. At the beginning, the committee made inquiries about application examples of FEM analysis to design and problems encountered in these applications, to structural designers and researchers that are almost members of the committee. This report summarizes the responses and briefly describes current practices in modeling techniques incorporating treatment of nonlinearity through the evaluation of results in Japan.

Forty-four specific applications were reported. As indicated in Table 1, FEM is being employed in work ranging from large-scale structures such as nuclear reactor plants and underground tanks to localized analysis of the structural components.

Table 1 Examples of FEM Design Applications Cited in Response to Questionnaire

Examples of Design Applications	Number of response
Foundation slabs, abutments,underground walls, etc.	8
Tanks for liquefied natural gas,liquefied propane gas	8
Floor slab ,etc	7
joint, opening, etc.	4
Nuclear reactor plants	4
Bridges	3
Tunnels	2
Other structures (dams, towers, etc.)	8
TOTAL	44

2. TREATMENT OF NONLINEARITY

In most design applications, the FEM analysis is conducted with linear rather than nonlinear conditions, partly because of computational cost restrictions, partly because it is considered that linear analysis generally shows safe results, partly because of difficulties in evaluating results, and because of the unreliability of nonlinear analysis. Of the 44 applications described in response to the questionnaire, only 8 used nonlinear analysis, and the proportion would probably have been even smaller if the survey had been limited to designs that were actually executed. Several engineers pointed that nonlinear analysis or treatment of nonlinearity was appropriate for the following.

[1]Designs involving problems of cracking or deformation
[2]When a more economical design could be achieved by considering the
    cracking behavior through excessive resisting stress
[3]Design of structures such as nuclear reactor plants that must be made
    fail-safe.

At present, the nonlinearity of concrete is reflected in several ways in which
thermal stress causes cracking on a scale extensive enough to have a large
effect on stress distribution and rigidity. As indicated in Table 2, non-
linearity was frequently taken into direct or indirect consideration in this
problem.

Table 2   Consideration of Nonlinearity in Thermal Stress Analysis

Treatment of Nonlinearity	Number of responses
[1] Nonlinearity Considered	1 3
- ⟨items⟩	
Nonlinear analysis	2
Pseudo elasto-plastic analysis	5
Using a uniform decreasing rate of rigidity	5
Using empirical formula of rigidity	1
[2] Nonlinearity ignored	2

3.MODELING

3.1 Analysis Area and Boundary Conditions

When the scale of the structure is too big to permit analysis of the whole
structure, FEM analysis may be carried out for part rather than the whole. The
problems in this case are to determine the area of analysis and the boundary
conditions.

At present, the following two methods are generally used;
    [1]The analysis is carried out over an area large enough that the effect of
        boundary conditions can be ignored.
    [2]A rough analysis is made for the entire structure, and the results are
        used to set the boundary conditions .

boundary conditions are
determined from whole
structure analysis
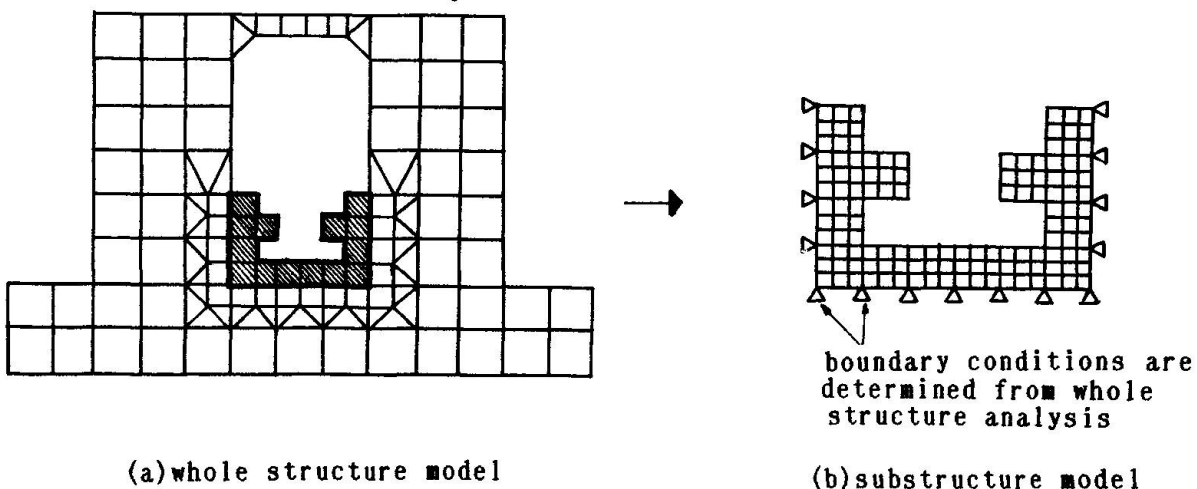
(a)whole structure model

(b)substructure model

Fig. 1 An example of substructure model

In case of method[1], some of the respondents calculated the displacement and stress distributions of rough whole model, while others used a model for which the size is 3 to 7 times of the area acted on by the load.

For method [2], the boundary conditions were in general set according to an overall analysis of a rough model to have on equal displacement in the boundary area.

3.2 Element types

When FEM analysis is applied to the design of an RC structure consisting of slabs and walls, the section forces are required directly, so shell elements or axial-symmetric shell elements is usually used.

On the other hand, 2-dimensional plane elements and 3-dimensional solid elements are not frequently used for the purpose of estimating section forces that are applied to the actual design, because the section force cannot be obtained easily. In many cases, these elements were used for obtaining the properties of deformation, those of stress distribution, those of cracking, and that of failure.

For the 3-dimensional analysis in the design applications, the use of shell elements predominated as shown in Table 3. Solid elements tended to be used only for massive parts such as foundation slabs.

Table 3 Applications Classified by Types of Elements

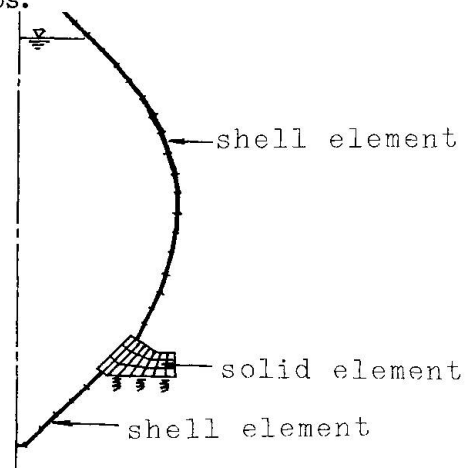| Type of element used	Number of responses
shell elements	1 8
shell+solid elements	5
2-dimensional plane elements	1 0
3-dimensional solid elements	9
multi-layered element	2
T O T A L	4 4

Fig. 2 An example of a model with shell elements and solid elements (egg-shaped tank)

3.3 Element Discretization Techniques

It is generally recognized that a fine mesh raises the accuracy of the analysis but also raises its cost. In this trade-off between accuracy and cost, the guideline generally followed has been to employ a fine mesh in [1] area of particular interest, [2] area of stress concentration, [3] areas acted on by loads, and [4] the vicinity of joints between different types of materials, and to employ a coarse mesh wherever this will not significantly affect the accuracy of the analysis.

All the respondents recognized that the ideal length-to-width ratio of rectangular elements is 1:1, but most designers allow length-to-width ratios up to 1:5 where necessary.

It is advisable to avoid joining isoparametric elements in high-order interpolation functions to triangular elements and elements with low-order interpolation functions. The concentration of stress in the low-order elements in this

type of mesh has a deleterious effect on the results.

3.4 Modeling with Shell Elements

Though using shell elements instead of 2-dimensional plane elements or 3-dimensional solid elements enable section forces to be obtained directly, the use of thin-plate theory to treat objects having a finite thickness requires decisions concerning the following modeling problems:

(1) Treatment of the rigid zone
In only a few cases were joints between walls and floors or between two walls modeled by setting a rigid zone. When a rigid zone was used, the reported practice was to set the area of the rigid zone in accordance with the specifications of RC structures and performed the analysis by increasing the flexural rigidity of this portion, or to use the thickness of the orthogonally joined members as a rigid zone.

Many designers reported that they did not use the results of the analysis near the regions of joints.

(2) Scope of shell elements application
Recently most commomly-used FEM software is able to treat out-of-plane shearing .deformation of shell elements. This function enables the limits of the applicability of shell elements to be greatly widened.

Some respondents, however, reported difficulty in determining the location of external forces on foundation slabs etc. unless the element does not have a thickness ,for which reason solid elements were used. Solid elements were also used when gradients of thickness variations could not be represented with shell elements.

(3)Treatment of abrupt change in thickness
A problem in the use of shell elements with axial-symmetry is the unreliability of analysis results in regions with abrupt changes in thickness. Most designers took steps in their models to deal with this problem, such as subdividing the cross-section at the massive end of such regions with solid elements and using the principle of 'plane section remains plane' regarding the joints between the solid and shell elements, or by creating a separate and more detailed model for these regions.

(4) Modeling joins between beams and plates
When a section like Fig. 3 is modeled using a beam element and shell element, three types of models can be considered: Model (a) gives the true cross-sectional area; model (b) gives a better evaluation of flexural rigidity than model (a) and is easier to apply to ordinary sectional design; model (c) ignores the flexural rigidity of the plate and incorporates it into the effective width of the beam. Model (b) is the one of most commonly used.

4. EVALUATION OF ANALYSIS RESULTS

It is considered that it is important for designers to establish guidelines for evaluating the results of FEM analysis rather than to solve the problem in the techniques in applying FEM analysis itself. Several problems and current practices for them concerning evaluation of results are described below.
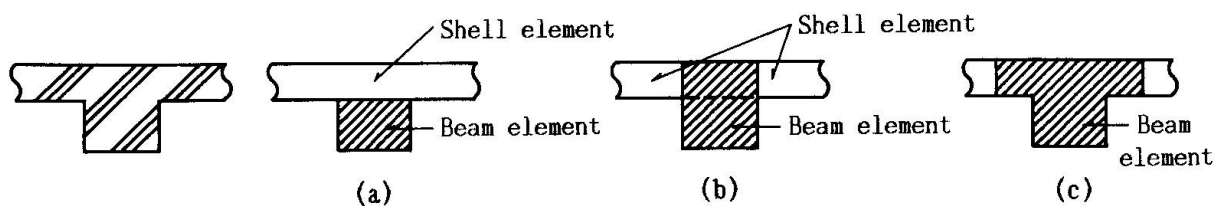
Fig. 3 Modeling of beam and shell elements

4.1 Evaluation of Shell Analysis Result

(1) Treatment of section forces on elements

In the responses to the questionnaire there were many cases in which the section forces at the center of the element were employed as a result. Section forces at nodal points were employed when the reliability of the figures justified their use, because they sometimes give unreasonable value.

The bending moment at intermediate points was generally calculated from the value at the element center points by linear interpolation. For axial forces and shearing force, the general practice was to assume a constant value within the element.

Sectional design is usually performed on an element-by-element basis, but for local stress concentrations it is common to extend the sectional design to include the surrounding elements. It is important that guidelines be given concerning how far to extend the section and what degree of stress concentration can be ignored. In the near future guidelines must be developed and specified.

(2) Treatment of shearing force in plane and torsional moment

There are two general methods of treating shearing force in plane and torsional moment .
    [1]They can be treated as equivalent section forces, combining shearing
        force with axial force or torsional moment with bending moment.
    [2]The design formula can be applied to each component individually.
In most cases in which method [2] was reported, torsional moment was ignored. If the magnitude of torsional moment cannot be neglected, some effective treatment must be carried out.

4.2 Evaluation of Results of Plane Stress Analysis and 3-Dimensional Stress
     Analysis

Since plane stress analysis or 3-dimensional stress analysis give stress itself , these results can be reflected in designs in two ways:
    [1]Stress values to be converted to section force values.
    [2]The quantity and position of reinforcing bars to be calculated
        directly from the stress values.

In method [1], the section forces are found by integrating the nodal force or element stress at the center of gravity of the element or at Gaussian integral-point around the axis at the center of gravity.

In method [2], the quantity of steel bars is determined as the quantity needed to deal with the total tensile force or the tensile force exceeding the allowable stress. The bars are either positioned to match the stress distribution or placed in the vicinity of the tension line. It is required that the appropriate method should be specified according to the type of structure and type of load.
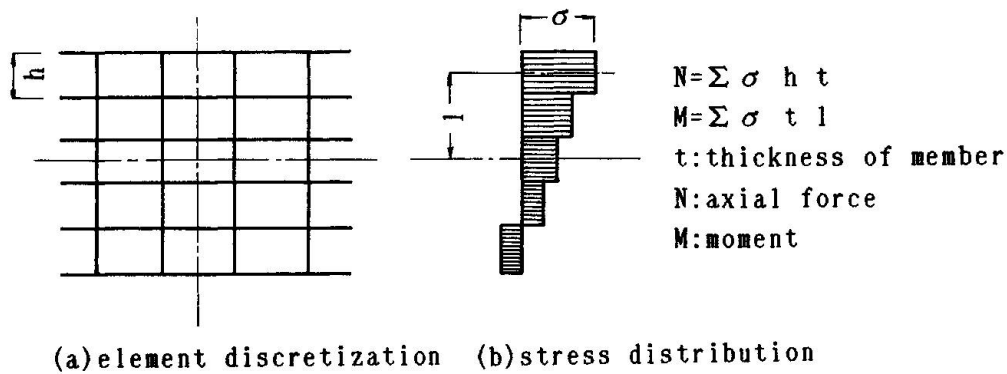
$$N = \Sigma \sigma \ h \ t$$
$$M = \Sigma \sigma \ t \ l$$

t:thickness of member
N:axial force
M:moment

(a)element discretization (b)stress distribution

Fig. 4 An example of a conversion to section force
in plane stress analysis

tension

reinforcing bars

reinforcing bars

compression
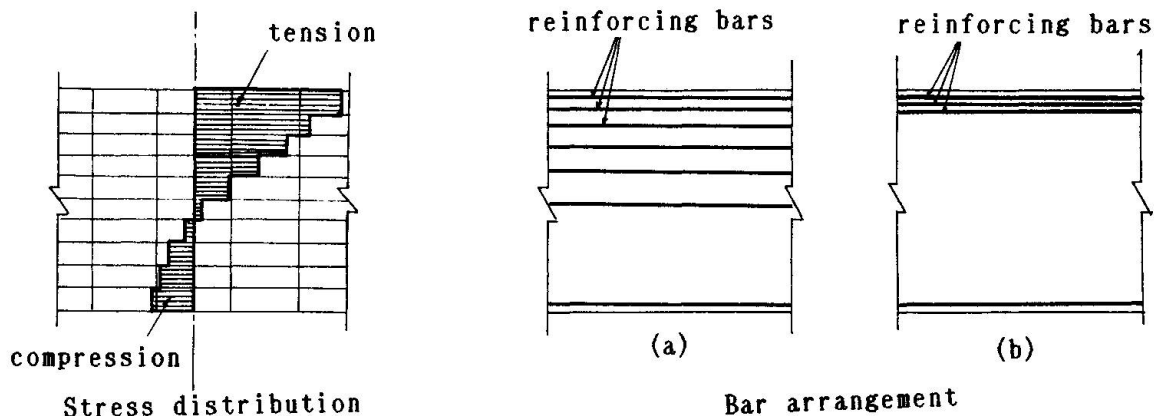
Stress distribution

(a)

(b)

Bar arrangement

Fig. 5 Reinforcing bar arrangement example
according to plane stress analysis

4.3 Evaluation of Dynamic Analysis

When the dynamic response of a structure including ground behavior is studied, it is inappropriate to apply the resulting peak values directly to the design in some cases ,depending on the magnitude of the input seismic oscillations, the scale of the structures, and the importance of the structure. The survey indicated a variety of ways in which results are being applied:

[1]The peak value is used directly
[2]The r.m.s.(root-mean-square) value for the principal oscillation is used
[3]Since the r.m.s. value is normally 60% to 70% of the peak value, 70% of the peak value is added statically to the model.

The following practices were reported concerning the comparison of results of static and dynamic analysis:

[1]The base shear coefficient is made to match the seismic coefficient.
[2]The response acceleration at the center of gravity of the structure is made to match the static seismic coefficient.
[3]Priority is given to the static analysis.
[4]Sectional calculation is made from static analysis, then tested against dynamic analysis, and this procedure is iterated .
[5]Use of large value of static calculation results and dynamic one
It is pointed out that there is at present few commonly accepted procedures for applying the analysis results to design while rapid progress is being made in techniques of dynamic analysis.

5.CONCLUSION

A survey of the actual FEM design applications has found that FEM analysis is a widely employed, but that much is left to the individual designer's judgment in the process of modeling, setting the analysis conditions, and evaluating the results.

This report is intended as an initial step toward setting guidelines for the application of FEM analysis to the design of an RC structure. It has briefly presented some problems, principally in linear FEM analysis which is the most generally employed method at present, and summarized the solutions to these problems that are currently employed in Japan. In the future it will be essential to prepare a wider and more detailed set of guidelines, including those for nonlinear analysis. We hope that this report, by summarizing current practice regarding the application of FEM analysis to design, will help in the attainment of more efficient and reliable designs.