J. Materials, Conc. Struct., Pavement No. 502／V-25, pp. 155～161, November 1994

ANALYTICAL ASSESSMENT OF SHEAR RIGIDITY DEGRADATION OF EMBEDDED BOX-TYPE REINFORCED CONCRETE STRUCTURES

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Investigation of the behavior of embedded box-type reinforced concrete (RC) structures for nuclear power stations subjected to lateral earthquake earth pressure, concerning shear rigidity and its reduction, has been conducted analytically in this study. A nonlinear finite element approach based on smeared crack model of RC plate element was utilized. From the parametric study of a real RC duct for accommodating emergency cooling water pipes in nuclear power stations, it was found that lower reduced shear rigidity factor, which was defined as the ratio of reduced and initial shear rigidity, could be attained by arranging lower concrete compressive strength, higher yield strength of reinforcing bar, higher reinforcement ratio and thinner wall thickness of the RC duct. Finally, a formula to predict the reduced shear rigidity factor has been proposed based on the parametric study.

Key Words *: reinforced concrete ; nuclear power stations ; shear rigidity ; reduced shear rigidity factor ; nonlinear analysis ; parametric study*

1. INTRODUCTION

Generally, box-type reinforced concrete ducts for accommodating emergency cooling water pipes in nuclear power facilities are embedded underground. From the past dynamic soil-structure interaction analysis(6), it was found that, during a strong earthquake, the RC ducts were subjected to reversed shear deformations indirectly through the deformation of the surrounding soil, and the most critical mode of deformation was a shear-type deformation, i. e., when a relative horizontal displacement between the upper slab and the lower slab became maximum. For this type of structure subjected to a strong ground motion, a ratio of the shear rigidity of the structure to that of the soil displaced by the structure acts as the main parameter on its structural behavior(6).

In the current design practice of the embedded RC ducts used in nuclear power stations(4), the limit states design method has been proposed, and due to effects of inherent nonlinearity of reinforced concrete, a stiffness degradation of the structures is used when the design internal forces are to be determined. It was recommended that the shear rigidity degradation could be treated as a constant value equal to 50% of the initial shear rigidity in case of a strong earthquake (magnitude in Japanese scale is about 6.5)(4) . In fact, a shear rigidity of the RC ducts is not constant, but depends on the level of loading applied due to a nonlinear effect of reinforced concrete including cracking of concrete, yielding of reinforcing bars and their interaction. Hence, there is a need to verify the proposed 50% stiffness degradation in the current practice.

In the past research works, investigation on the reduced shear rigidity was mostly carried out experimentally(1),(2). However, due to successful development of finite element program for a nonlinear analysis of reinforced concrete structures(5),(7), it has become possible to perform analytically the parametric study on the reduced shear rigidity which might be difficult to be achieved by experimental work because of high cost and time-consumption involved.

The objective of this study is to clarify the influence of the main parameters on the shear rigidity of the embedded RC structures used in nuclear power stations, and its reduction due to effects of material nonlinearity of the RC ducts. The present analysis is performed by using the so-called"WCOMR" (Reinforced Concrete Model for Walls subjected to Reversed Cyclic Load)(5) which is one of the most versatile packages for a nonlinear analysis of reinforced concrete structures. This program utilizes a two-dimensional plate element considering effects of material nonlinearity of reinforced concrete in view of smeared crack model. One feature of WCOMR is its reliable constitutive model of reinforced concrete material which was well verified by several experimental

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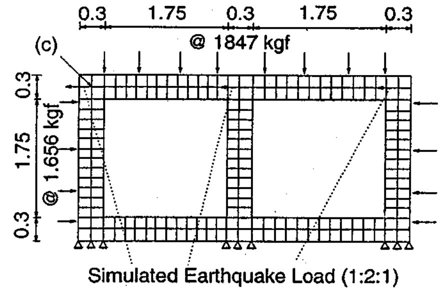

Fig. 1 Mesh discretization and loading conditions of tested RC duct (unit of length in metre)

results[5]. From the results of parametric study by varying main parameters of the RC ducts, the regression formula to predict the degradation of shear rigidity is derived.

2. APPLICATION OF WCOMR TO FRAME–TYPE RC STRUCTURES

WCOMR was originally developed for the analysis of reinforced concrete panel structures with uniformly dispersed reinforcement subjected to in-plane loading. In order to verify an application of WCOMR to the frame–type structures such as RC ducts for emergency cooling water pipes in this study, the comparison of the numerical results obtained by WCOMR with the experimental results has been made. The test model selected in the present study is a 1 : 2 scale model of a double box reinforced concrete duct tested by Aoyagi and Endo[1]. A finite element mesh discretization and loading conditions are shown in **Fig. 1**. For the loading path of the test, the vertical and horizontal distributed loads simulating earth and water pressure at the service condition are treated as the constant loads, and the horizontal concentrated loads at three points of upper slab of the model are varied proportionally with the ratio of 1 (side) : 2 (middle) : 1 (side). These loads simulates earth pressure at the time of earthquake. It is noted that, for the duct structure subjected to the loads as shown in **Fig.** 1, its behavior is predominated by combined flexure and axial force. Hence, it is natural to divide meshes in a thickness direction as much as possible to incorporate the flexural effect by using smeared crack plate element in WCOMR. However, the results of analyses of similar structures with two different meshes of 2 and 3 layers in a thickness direction by using WCOMR showed that there was no significant difference between two results up to the yielding point[3]. Hence, 2–layer model in **Fig.** 1 is applied in this study. It is also noted that for each smeared crack element, a two–dimensional constitutive model of concrete and constitutive models of bars in the direction parallel to the member axis (longitudinal bars) and bars in the direction perpendicular to the member axis (stirrups) are considered.

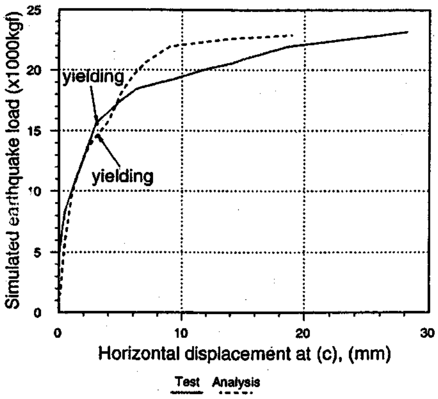

Fig. 2 Load–displacement relationship of tested RC duct

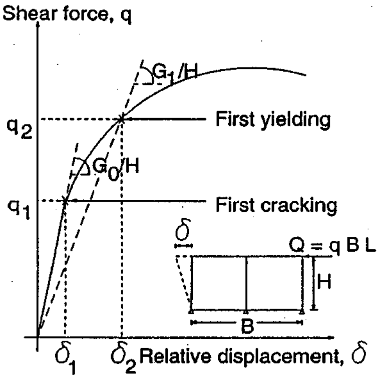

Fig. 3 Definition of shear rigidity

The result of load–displacement curve plotted between the simulated earthquake load and the horizontal displacement at node (c) (see **Fig. 1**) is illustrated in **Fig. 2**. From the result in **Fig. 2**, it can be seen that the difference of the yielding load, i. e., the load level at which one of the reinforcing bars of the structure starts to yield, is less than 7% while the yielding displacement is almost identical. Since, as explained in the later part, the load–displacement curve up to yielding point is a major concern in the present study, WCOMR can be employed for a determination of the shear rigidity of this type of structures, which is defined by a secant modulus of load–displacement curve (see next section), without losing any significant accuracy. For the cracking load, the load and displacement of the analytical results are almost the same as those of the test results. In addition, from the analytical results, the first yielding load of a tensile longitudinal steel occurs near the left-upper corner of the structure, which coincides with the test result.

3. DEFINITION OF SHEAR RIGIDITY

By considering the overall behavior of duct structures subjected to the horizontal shear force as shown in **Fig. 3**, shear rigidities can be obtained from the secant modulus of a nonlinear load-displacement curve, and are defined at two particular points on the curve as

At the first cracking, $G_0 = q_1 H/\delta_1$ ……………(1)

At the first yielding, $G_1 = q_2 H/\delta_2$ ……………(2)

where G_0 and G_1 are called as initial and reduced shear rigidity, respectively; q=shear force per unit area, which is defined as q=Q/ (BL); Q=shear force; B=width of the structure; L=length of the structure in longitudinal direction; δ=relative horizontal displacement at the top of the structure; H=height of the structure (see **Fig. 3**).

And, the reduced shear rigidity factor G_r is written as

$G_r = (G_1/G_0) \times 100\%$ ………………………………(3)

It is noted that the above definition of reduced shear rigidity factor is based on the fact that the first yielding of reinforcing bars is chosen as a design reference point of the limit state in the current design practice[4]. In other words, the structure is designed to resist a strong earthquake in the range up to the first yielding point. Hence, the reduced shear rigidity factor is taken to be a ratio of the rigidity at the limit state where the first yielding occurs and that at the initial state where the structure behaves elastically prior to the first crackings.

4. OUTLINE OF INVESTIGATION

The structure under investigation is a prototype double box reinforced concrete duct for emergency cooling water pipes. A dimension of inner space of the duct is 3.5×3.5m², which is typical section used in nuclear power facilities[4] as shown in **Fig. 4**. The load considered here consists of a horizontal point load at the top of the structure which simulates the earthquake load on the structure. This load is increased gradually up to the first yielding point. The finite element mesh and supporting condition used for this investigation can be seen in **Fig. 4**. It is noted that the model in **Fig. 4** is constructed in order to produce the horizontal shear-type deformation which is the critical mode of deformation of this embedded box-type structure. As described in Chapter 1, this critical mode was found from the results of the past dynamic soil-structure interaction analysis[6].

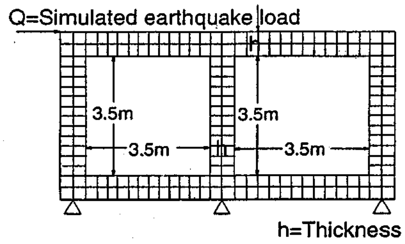

Fig. 4 Double box reinforced concrete duct

Table 1 Parametric study on shear rigidity

Model	Thickness h cm	Concrete strength f'_c kgf/cm²	Yield strength of bar f_y kgf/cm²	Reinforcement ratio p percent	Initial rigidity G_0 x10³ kgf/cm²	Reduced rigidity G_1 x10³ kgf/cm²	Reduced rigidity factor G_{r1} percent
1	40	400	4000	0.24	4892.63	3078.55	62.92
2	50	300		0.24	7717.92	3646.60	47.25
3		400	3500		8826.99	7080.33	80.21
4			4000		8826.99	5460.42	61.86
5			4500		8826.99	4046.94	45.85
6		500	4000		9769.82	7376.73	75.50
7		240			6957.90	3437.19	49.40
8		400		0.32	8895.12	4147.06	46.42
9				0.40	8963.84	4015.74	44.80
10	60			0.24	13752.89	8867.53	64.48
11	50			0.28	8860.71	4434.80	50.05
12				0.36	8929.53	4032.15	45.15
13	45			0.24	6800.50	4173.50	60.37
14	55			0.24	11135.46	7088.79	63.66

Four parameters mainly affecting reduced shear rigidity factor are selected in the present study and are composed of the concrete compressive strength, the yield strength of reinforcing bars, the reinforcement ratio, and the thickness of RC duct (see **Fig. 4**). It is noted that ratio of longitudinal tension reinforcement of the RC duct is considered. The reasons of selecting four parameters are as follows: a concrete compressive strength and a yield strength of reinforcing bars represent a material characteristic of the concrete and the bars, respectively, a reinforcement ratio reflects an interaction effect between the concrete and the bar, and the thickness of RC duct is a main dimension of the duct. Parametric study is carried out by analyzing 14 models with different parameters as tabulated in **Table 1**.

For the constitutive models of reinforced concrete material, the smeared crack models including three concrete models, namely, compression, shear transfer and tension stiffenning model, and a model of reinforcing bar are considered. More details of these models can be found in Ref. 5). It is noted that the tensile strength of concrete is set to be $0.5f_c'^{2/3}$, where f_c' is a compressive strength[4], and the Young's modulus of the bar is equal to $2.1 \times 10^6 \mathrm{kg/cm^2}$.

5. RESULTS OF PARAMETRIC STUDY

The analytical results of reduced shear rigidity factors denoted by G_{r1} (G_{r1} is the value obtained from the analytical results, whereas G_{r2} is the value predicted by the regression formula explained below) for all 14 models are shown in **Table 1**. It can be seen that an average value of reduced shear rigidity factor is about 57% which is larger than 50% adopted in the current design practice[4)]. In the present study, only static analyses are performed, i. e., an effect of reversed cyclic loading which is a nature of earthquake loads, is neglected. More drop in reduced shear rigidity factor is expected when the effect of reversed cyclic loading is to be included. Hence, from the present analytical results, it might be concluded that a value of reduced shear rigidity equal to 50% in the current design manual[4)] is appropriate.

The effects of the above-mentioned four parameters are investigated one by one. The relationship between the reduced shear rigidity factor and each parameter is obtained by changing values of only the single parameter to be investigated, while the others are kept constant. The equation is derived so that the best fit for the plots can be obtained by using the regression analysis. To simplify the derivation, standardized reduced shear rigidity factor (μ_g) is defined as the ratio of the reduced shear rigidity factor to that of a reference model which can be arbitrarily selected among 14 models in **Table 1**, i. e.,

$$\mu_g = G_{r1}/G_{rref} \quad \cdots\cdots (4)$$

where G_{rref} is taken to be G_{r1} of model no. 4 in **Table 1** throughout this study.

(1) Effect of Concrete Compressive Strength

From **Fig. 5** (a), it can be seen that increment in the concrete compressive strength increases both the initial and reduced shear rigidities. This can be explained by the fact that higher concrete strength results in larger modulus of elasticity of concrete which is directly related to shear rigidity. The plot between the concrete compressive strength and standardized reduced shear rigidity factor is shown in **Fig. 5** (b). The following equation expressing the influence of only concrete compressive strength on the reduced shear rigidity factor can be derived by using the regression analysis as

$$\beta_c = \mu_g - 1 = 0.000006 f_c'^2 - 0.002599 f_c' + 0.06071 \quad \cdots\cdots (5)$$

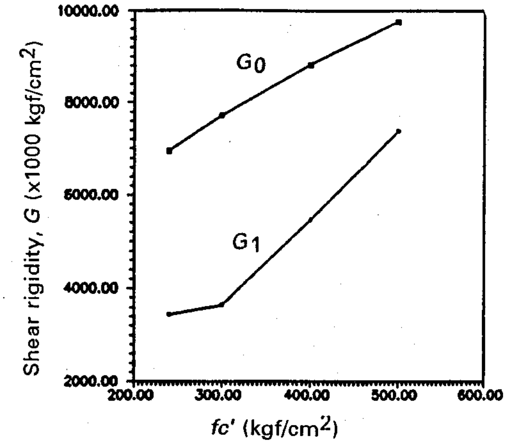

Fig. 5(a)

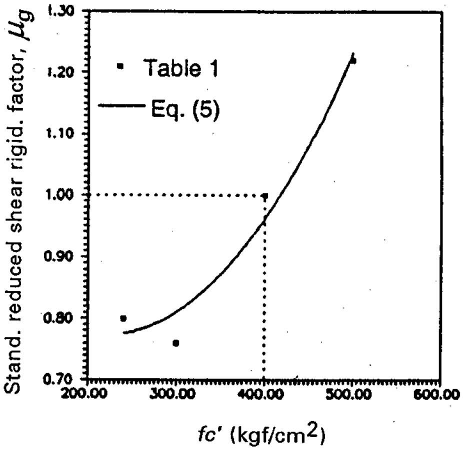

Fig. 5(b)

Fig. 5 Effect of concrete compressive strength

where, β_c=coefficient expressing effect of only concrete compressive strength; μ_g=standardized reduced shear rigidity factor defined by Eq. (4); f_c'=concrete compressive strength (unit: $\mathrm{kgf/cm^2}$).

(2) Effect of Yield Strength of Reinforcing Bar

As can be seen in **Fig. 6** (a), the effects of the yield strength of reinforcing bar on the initial shear rigidity are negligibly small. This indicates that, during the pre-cracking stage, reinforcing bar does not take its role in the RC composite material. However, increasing yield strength of reinforcing bar reduces the shear rigidity because of increasing yield strain as shown in **Fig. 6** (a). **Fig. 6** (b) illustrates the relation between the yield strength of reinforcement and standardized reduced shear rigidity factor. It is clear that the relation between them is almost linear and can be obtained as

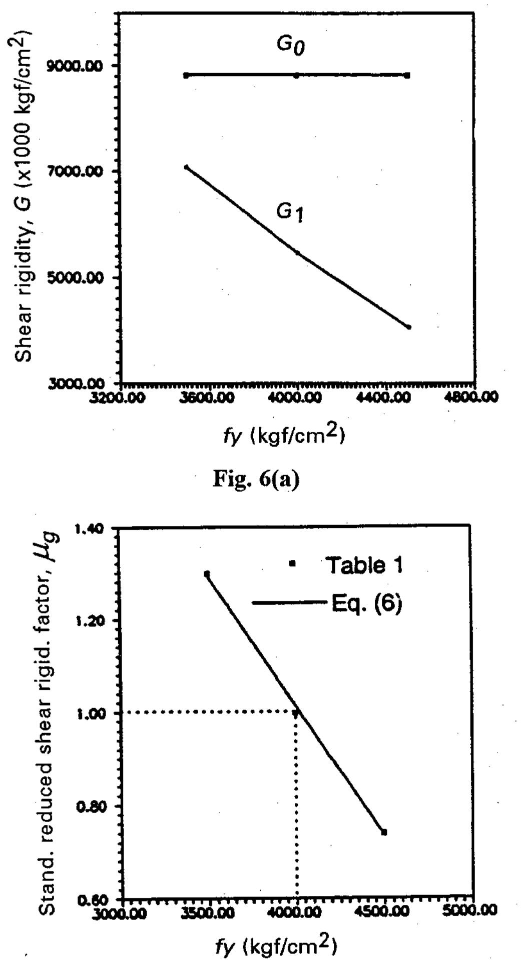

Fig. 6(a)

Fig. 6(b)

Fig. 6 Effect of yield strength of reinforcing bar

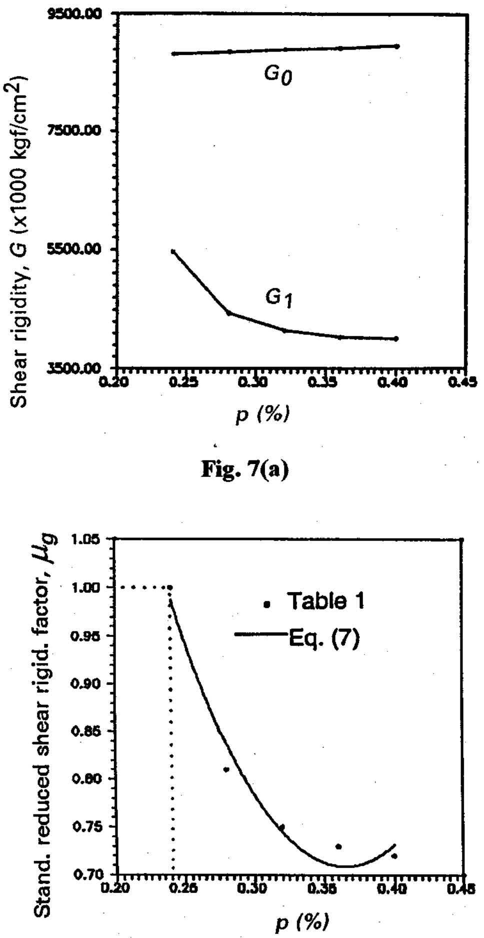

Fig. 7(a)

Fig. 7(b)

Fig. 7 Effect of reinforcement ratio

$$\beta_s=\mu_g-1=-0.00056f_y+2.25333 \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where, β_s=coefficient expressing effect of only yield strength of reinforcing bar; f_y=yield strength of reinforcing bar (unit: kgf/cm^2).

(3) Effect of Reinforcement Ratio

Practically, it can be deduced from **Fig. 7** (a) that there is almost no influence of the reinforcement ratio on the initial shear rigidity. This can be explained by the same reason as mentioned in the previous section. For the reduced shear rigidity, increasing the reinforcement ratio allows larger deformation to take place before the reinforcement starts yielding, and hence larger reinforcement ratio gives less reduced shear rigidity as depicted in **Fig. 7** (a). **Fig. 7** (b) shows the relation between the reinforcement ratio and standardized reduced shear rigidity factor. The following equation can be derived as

$$\beta_p=\mu_g-1=17.8571p^2-13.0286p+2.0854 \cdots\cdots (7)$$

where, β_p=coefficient expressing effect of reinforcement ratio; p=reinforcement ratio (unit: percent).

(4) Effect of Thickness of RC Duct

The thickness of RC duct is directly related to the stiffness of RC duct. Hence, changing the thickness significantly affected both the initial and reduced shear rigidity, i.e., the more the thickness of RC duct, the larger the initial and reduced shear rigidity, as can be observed in **Fig. 8** (a). The relation between the thickness of RC duct and standardized reduced shear rigidity factor is shown in **Fig. 8** (b) and can be obtained as

$$\beta_h=\mu_g-1=0.000314h^2-0.029628h+0.694 \cdots (8)$$

where, β_h=coefficient expressing effect of thickness of RC duct; h=thickness of RC duct (unit: cm).

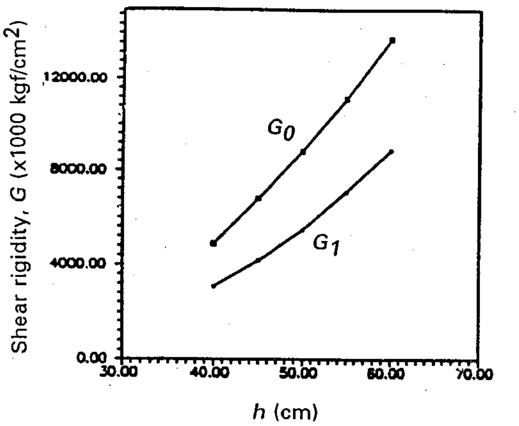

Fig. 8(a)

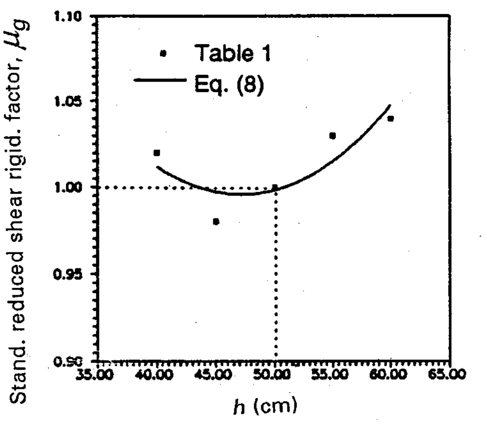

Fig. 8(b)

Fig. 8 Effect of thickness of RC duct

It is noted that there exist some discrepancies between the analytical results and the results of Eq. (5)-(8) obtained by the regression analysis, e.g., the case of the effect of thickness RC duct in **Fig.** 8 (b). This might be due to an insufficient order of the polynomial function used in the regression formula. In fact, a higher order polynomial function can be used to give the best fit for the plots. However, since in this study, the empirical formula for predicting the reduced shear rigidity factor is proposed for a practical use in the preliminary design, the simple formula involving less than or equal to the second order polynomial function is proposed. As can be seen below, the combination of Eq. (5)-(8) to represent the overall effect gives quite a good prediction of the reduced shear rigidity factor.

Model	Predicted reduced rigidity factor G_{r2} percent	Analytical reduced rigidity factor G_{r1} percent	Ratio of predicted and analytical values G_{r2}/G_{r1}
1	61.41	62.92	0.98
2	50.67	47.25	1.07
3	77.89	80.21	0.97
4	60.57	61.86	0.98
5	43.25	45.85	0.94
6	77.90	75.50	1.03
7	48.29	49.40	0.98
8	45.58	46.42	0.98
9	44.74	44.80	1.00
10	63.61	64.48	0.99
11	51.31	50.05	1.03
12	43.39	45.15	0.96
13	60.51	60.37	1.00
14	61.61	63.66	0.97
	Average	value =	0.99
	Standard	deviation =	3.2%

Table 2 Comparison of predicted and analytical values of reduced shear rigidity factor

(5) Overall Effect

The following equation to evaluate the reduced shear rigidity factor quantitatively is proposed in the form of a summation of the above coefficients expressing effects of four parameters on the reduced shear rigidity factor. Hence, by taking a sum of Eqs. (5)-(8) the standardized reduced shear rigidity factor taking into account of overall effects (μ) can be expressed by

$$\mu=1+\beta_c+\beta_s+\beta_p+\beta_h \cdots\cdots\cdots\cdots\cdots\cdots(9)$$

Then, the predicted reduced shear rigidity factor (G_{r2}) can be obtained from Eq. (4) as follows:

$$G_{r2}=\mu G_{rref} \cdots\cdots\cdots\cdots\cdots\cdots(10)$$

where G_{rref} is defined after Eq. (4).

The values of reduced shear rigidity factor predicted by Eqs. (10) are compared with the analytical results in **Table 1**. This comparison is shown in **Table 2**, where the ratio of predicted and analytical results is used to indicate an accuracy of the proposed formula. As can be seen in **Table 2**, its average value is very close to 1.00. In other words, the assumption of independent correlation among four parameters can be applied to a prediction of reduced shear rigidity factor of the RC duct structure with a high accuracy.

It is emphasized that the application of proposed formula is limited to the problem of the embedded double box RC structure subjected to a shear-type deformation which is a critical mode under a reversed cyclic loading. In addition, it should be noted that the proposed formula is obtained from the study of four parameters within the following ranges (see **Table** 1)

- Concrete compressive strength, $f'_c=240$-500kgf/cm^2
- Yield strength of reinforcing bar, $f_y=3500$-4500 kgf/cm^2

- Reinforcement ratio, $p=0.24$–0.40%
- Thickness of RC duct, $h=40$–60cm

The above ranges are usually adopted in practical design of the embedded RC duct structure for emergency cooling water pipes. However, in order to apply the proposed formula out of the range given above, more investigation is needed.

6. CONCLUDING REMARKS

The following concluding remarks have been obtained from this study:

1) Parametric study on influences of various paramenters on the reduced shear rigidity factor of the embedded double box reinforced concrete duct used for emergency cooling water pipes in nuclear power facilities has been performed. Lower reduced shear rigidity factor can be obtained by arranging

- Lower concrete compressive strength
- Higher yield strength of reinforcing bar
- Higher reinforcement ratio
- Thinner RC duct wall thickness

2) Formula to predict the reduced shear rigidity factor has been derived by assuming that the effects of various parameters on the shear rigidity were independent one to each other. The proposed formula might be used for a preliminary design of the embedded box-type reinforced concrete structures. However, in order to apply this formula to the detailed design of this type of structures, more elaborate analysis, such as nonlinear dynamic analysis, is needed to verify a validity of the proposed formula.

3) For the usual design cases of the embedded box-type reinforced concrete ducts for emergency cooling water pipes in nuclear power stations, the current provision of the Japanese design manual[4] is considered appropriate in terms of the evaluation on the shear rigidity reduction factor of 50%.

ACKNOWLEDGMENT

The authors express their deepest appreciation to Dr. K. Maekawa, Associate Professor of University of Tokyo for his helpful suggestion and kind cooperation.

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(Received March 17, 1994)

地中に埋設された鉄筋コンクリート製ダクトのせん断剛性の解析的評価

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2連式の原子力発電所非常用海水管ダクトのせん断剛性の低減を解析的に評価するため，鉄筋コンクリート板要素の非線形解析（WCOMR）の適用を試みた．解析結果が実験結果と比較的良好に照合することを確かめた後，コンクリートの圧縮強度，鉄筋の降伏点，軸方向鉄筋比および壁厚をパラメータとしてダクトのせん断剛性を求めた．これらパラメータの影響を回帰解析し，せん断剛性の低減率を与え，簡易式を提案した．