Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles
Part 4: Overall Evaluation of Local Damage

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1 INTRODUCTION

In order to establish a rational evaluation method for the local damage to reinforced concrete structures due to the impact of aircraft engine missiles, three types of scaled (small, 1:7.5; intermediate, 1:2.5; and full size) impact tests have been planned and executed. The results and investigations of the individual tests are discussed in companion papers [1,2,3]. However, for establishing a final evaluation method, an overall summary of the results of the three tests was considered to be important and necessary. In this report, the results of the overall evaluations of the local damage are described.

2 PURPOSE OF THE OVERALL EVALUATION

The purpose of the overall evaluation is as follows;

1) To investigate the appropriateness of the similarity law and the modeling method of the actual engine to the deformable missile model used in the scale model tests.
2) To select the applicable empirical formulas for predicting the local damage due to rigid missiles.
3) To determine the reduction factors of the local damage for the deformable engine missile from those for the rigid missile.
4) To evaluate the effect of the reinforcement ratio on the local damage.
5) To evaluate the effect of the steel liner attached to the rear face of the panel on preventing scabbing damage.

3 RESULTS and CONSIDERATIONS

3.1 Similarity Law and Modeling of the Actual Engine

The observed damage of the test panels used in the small-, intermediate- and full-scale tests are compared in Fig. 1. These panels correspond to each other in accordance with the similarity law. Though it can be observed that the damage tends to increase as the scale decreases, the damage of the corresponding three specimens of small-, intermediate- and full-scale tests closely resemble each other. The agreement in the extent of the damage indicates that the similarity law employed in the scale model tests is appropriate.

In order to investigate the modeling method of the simplified deformable missile from the actual engine, static compression tests of the deformable missiles of the small- and intermediate-scale tests together with a compression test of the actual engine have been carried out.

The load-displacement curves in the axial direction for each missile are compared in Fig. 2(a). In this figure, the results of the scale model tests are increased in accordance with the similarity law. This figure shows that the rigidity and the ultimate crushing capacity of the deformable missiles employed in the scale model tests are larger than those of the actual engine. As shown in Fig. 2(b), however, there is almost no difference in the energy absorption capacity, until final crushing, between the scale model missile tests and the engine test.

The appropriateness of the modeling method of the actual engine can be also evaluated from the comparison of the damage of the No.4 and No.5 test panel of the full-scale tests. These two panels have the same thickness of 1.6 m and the same reinforcement ratio of 0.4%, but the missile is different. The actual GE J79 engine was employed for the test panel No.4 and the simplified deformable missile, corresponding to the full-scale model of the deformable missile employed in the scale tests, for the test No.5. The damage of the two test panels can be referred to Fig. 4 of the companion paper [3]. The damage to the rear face of the panels are similar. The damage to the front face of the No.5 panel indicates more severe damage than to the No.4 panel.

These results indicate that the deformable missile models employed in the scale tests had a greater stiffness and crushing capacity than those of the actual engine. Thus, it can be concluded that the results of the scale model tests give more conservative evaluations than those of the full-scale tests with the actual engine.

3.2 Selection of the Applicable Empirical Formulas for Rigid Missile

From the results of the small- and intermediate-scale tests, the empirical formulas of Degen, Chang, CEA-DEF and CRIEPI [1,2] were selected as the applicable formulas for predicting the perforation thickness for the rigid missiles. However, the average compressive strength of the concrete was different between the small- and intermediate-scale tests. Therefore, in order to investigate the applicability of the formulas, the difference in the compressive strength of the concrete should be adjusted. With this intention, the results of the small- and intermediate-scale tests were revised assuming that the compressive strength of concrete had the same value of 23.5 MPa (240 kgf/cm^2).

Furthermore, the results of the scale tests are converted to the full-scale, since it is better to evaluate the formulas for the actual scale. The comparison between the modified test results and the perforation thickness calculated from the selected four formulas is shown in Fig. 3. From this comparison, the formulas of Degen and Chang remain as suitable formulas giving a conservative evaluation.

The same comparison was carried out for selection of the formulas for the scabbing thickness and the results are shown in Fig. 4. From this figure, the formulas of Chang, CRIEPI and Bechtel, which were selected in the scale model tests, give conservative evaluations. Among these three formulas, the CRIEPI formula indicates a good agreement with the test results in the low velocity range (less than 150 m/s) and the Chang formula gives the most conservative evaluation in the high velocity range (higher than 150 m/s).

3.3 Evaluation of the Reduction Factor

As for the reduction factor, defined in a companion paper [1], various values were derived from the individual test results. Thus, it is necessary to investigate the test results collectively for determining the unified value of the reduction factor. For that reason the difference of the compressive strength of the concrete between the individual tests should be adjusted, as discussed in the previous section, and the results of the scale model tests should be increased to full scale.

After performing these modifications for the test results, they are compared with the perforation thickness derived by multiplying the reduction factor to the selected empirical formulas. For example, the result of the comparison based on the Degen formula is shown in Fig. 5, assuming the compressive strength of concrete as 23.5 MPa. From this figure, the reduction factor (α_e) for the perforation thickness is seen to be between 0.6 and 0.7.

However, as discussed before, the results of the scale model tests give conservative evaluations, and α_e obtained from the full-scale tests (α_e= 0.6) is considered to be the most reliable data for evaluating the damage reduction of the target due to a deformable engine missile. Therefore, when taking these investigations into consideration, the unified reduction factor for the perforation thickness can be regarded conservatively as 0.65.

The same investigation was carried out for evaluating the reduction factor (α_s) for the scabbing thickness. The investigated results are shown in Fig. 6; in this case the Chang formula is selected for the evaluation. From this figure, it is seen that α_s is between 0.55 and 0.65, while the most reliable value is 0.55 from the full-scale test. When the same investigations as used in the perforation thickness are taken into consideration, the unified reduction factor for the scabbing thickness can be regarded conservatively as 0.6.

3.4 Effect of the Reinforcement Ratio on the Local Damage

Judging from the test results of the small- and intermediate-scale tests, the increase in the amount of the main rebar and the addition of the shear reinforcement decrease the damage of the target a small amount, but the effects on the damage mode is barely recognizable.

3.5 Effect of the Steel Liner on Preventing the Scabbing Damage

The effect of the steel liner attached to the rear face of the target on preventing the scattering of concrete debris is confirmed through the intermediate- and full-scale tests. The effect is evaluated quantitatively in the full-scale tests.

4 CONCLUSIONS

From the overall evaluation of the impact tests with three different scales, the rational evaluation methods for the local damage of the deformable engine missile have been firmly established.

The suitable empirical formulas for predicting the local damage by the rigid missile were selected and the reduction factors for the local damage due to the deformability of the engine missile were determined quantitatively. The effects of the reinforcement ratio and the steel liner were also confirmed. Finally, the results obtained through the series of impact tests can be reflected in the structural design of reinforced concrete structures against the local damage caused by the impact of aircraft engine missiles.

REFERENCES

[1] Muto, K. et al. (1989). Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles, Part 1: Outline of Test Program and Small-Scale Tests. Proc. 10th SMiRT Conference.

[2] Esashi, Y. et al. (1989). Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles, Part 2: Intermediate-Scale Tests. Proc. 10th SMiRT Conference.

[3] Muto, K. et al. (1989). Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles, Part 3: Full-Scale Tests. Proc. 10th SMiRT Conference.

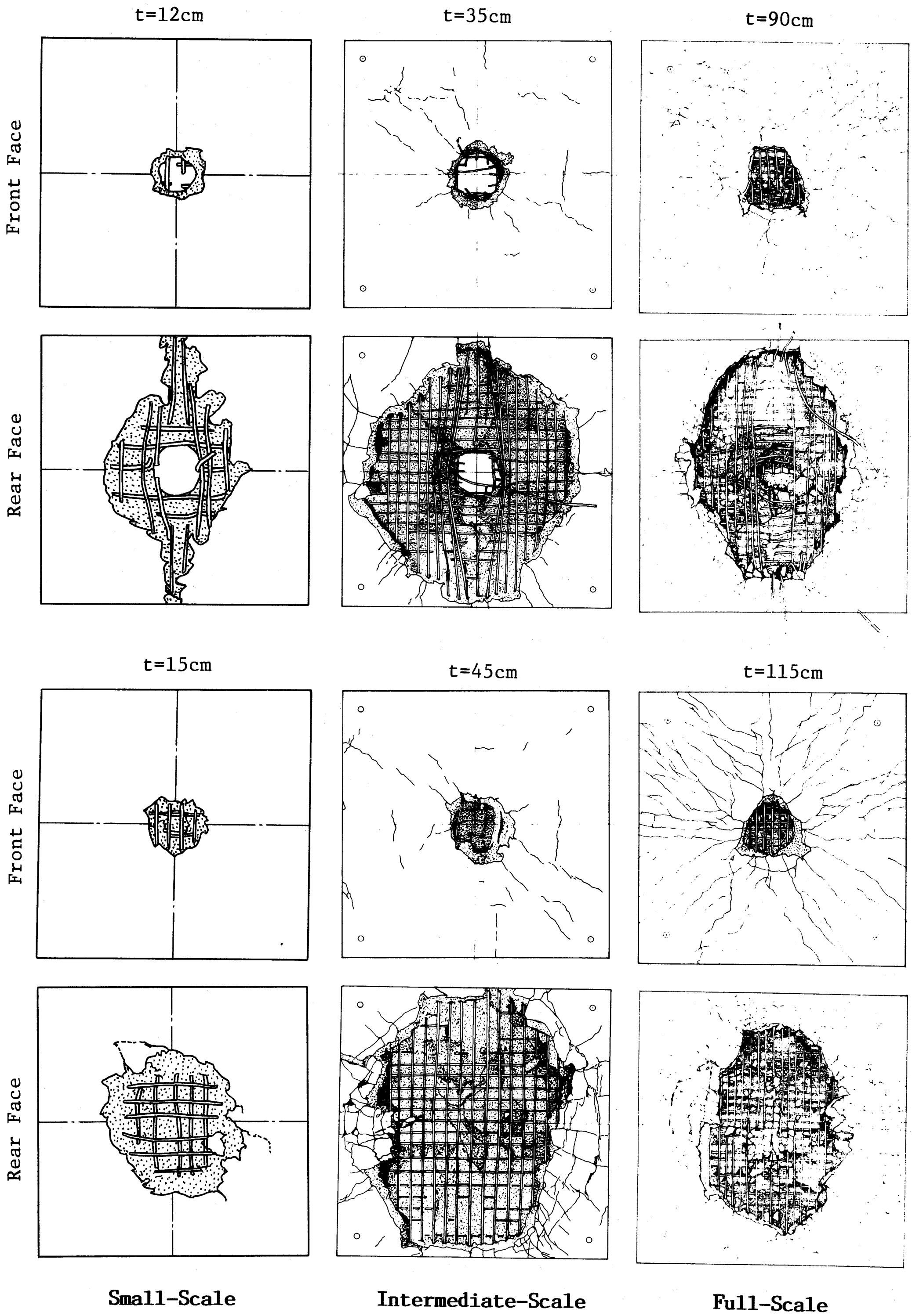

Fig. 1 Comparison of Local Damage to Test Panel

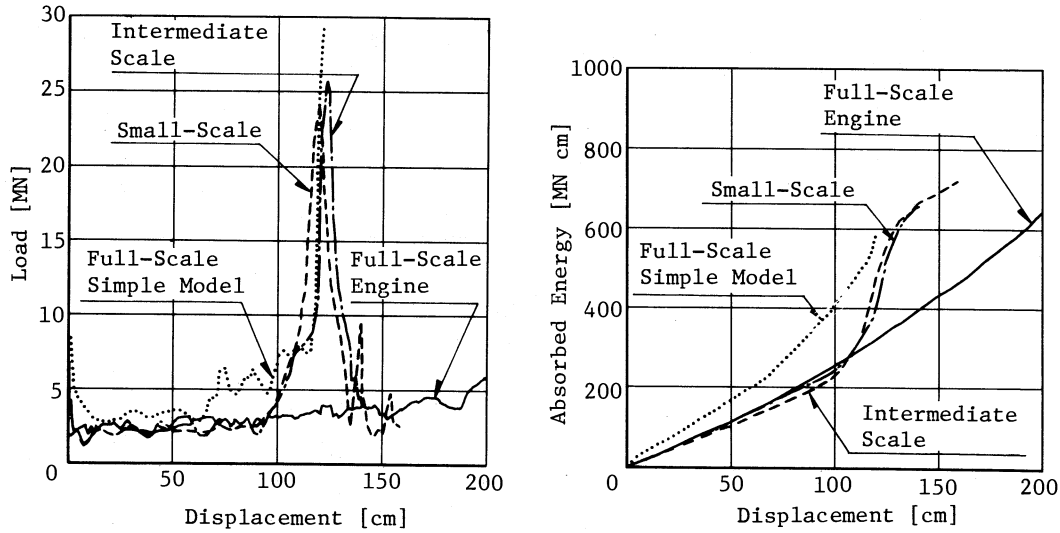

Fig. 2 Results of Static Compression Test for Missiles

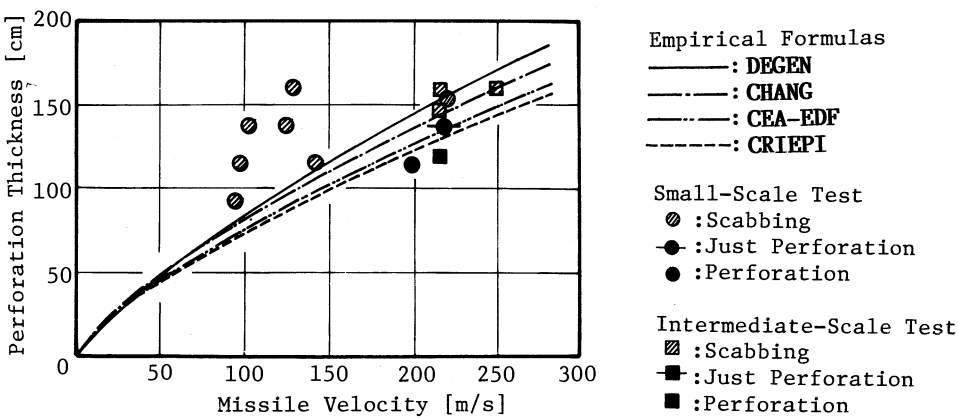

Fig. 3 Empirical Formulas and Test Results for Rigid Missile(Perforation)

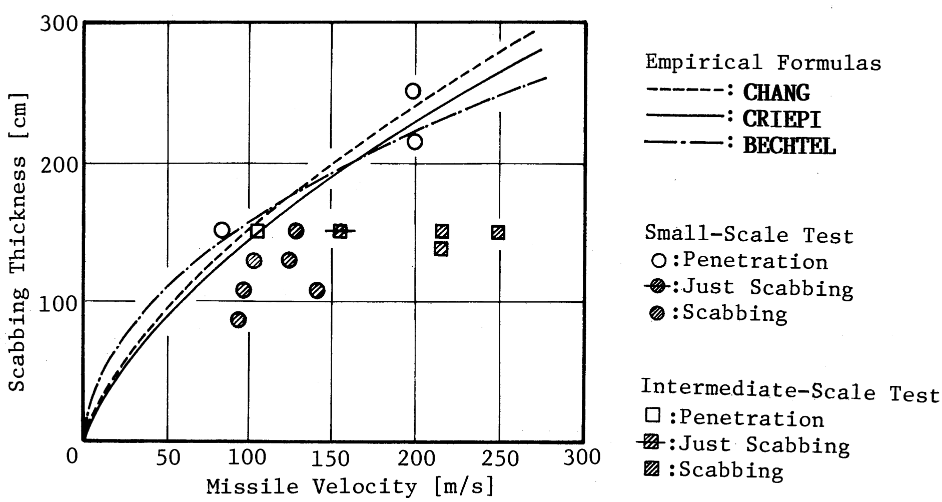

Fig. 4 Empirical Formulas and Test Results for Rigid Missile(Scabbing)

Legend	Small-Scale	Intermediate-Scale	Full-Scale
Perforation Mode	●	■	▲
Just Perforation Mode	-●-	-■-	-▲-
Scabbing Mode	◍	▨	◭
Just Scabbing Mode	-◍-	-▨-	-◭-
Penetration Mode	○	□	△

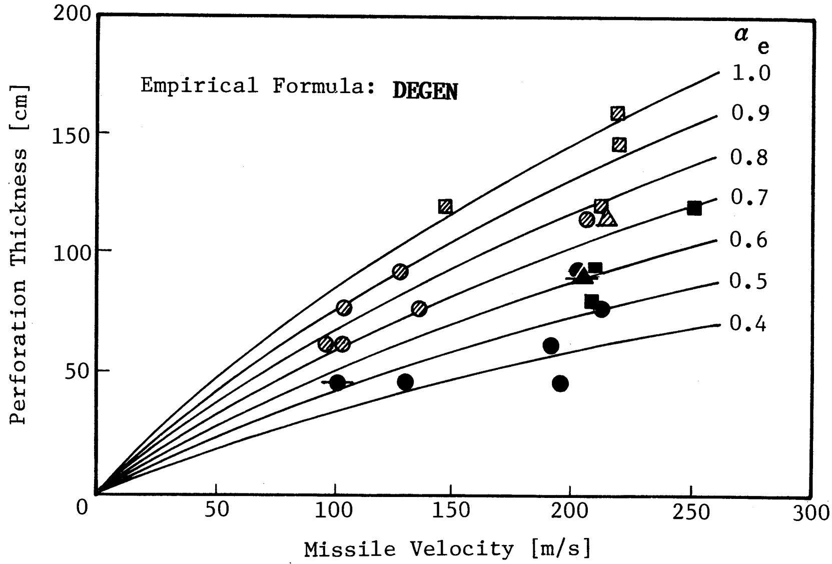

Fig. 5 Overall Evaluation of Reduction Factor for Perforation

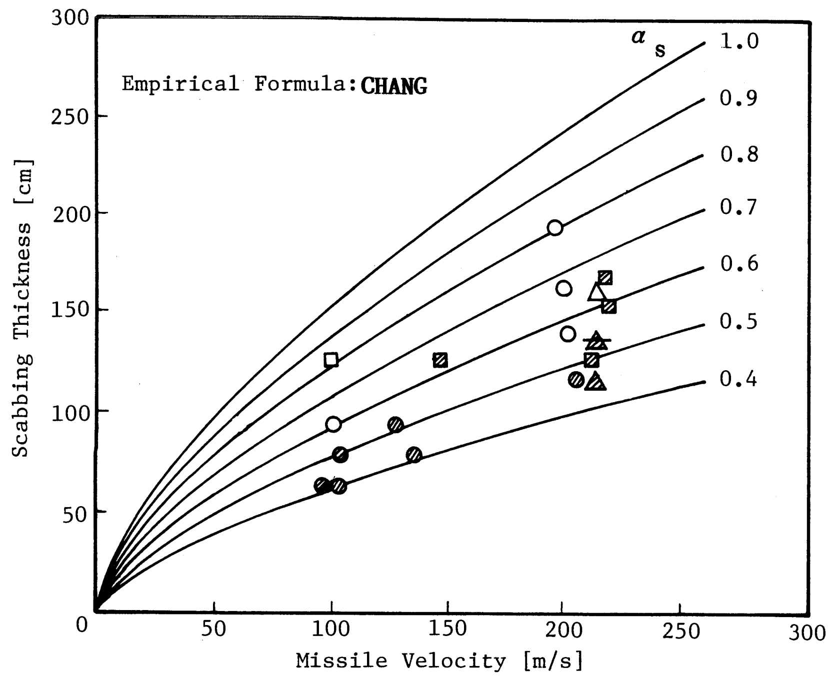

Fig. 6 Overall Evaluation of Reduction Factor for Scabbing