Full-Scale Aircraft Impact Test for Evaluation of Impact Force
Part 2: Analysis of the Results

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1 INTRODUCTION

For estimating the global elasto-plastic structural response of critical concrete structures subjected to an aircraft crash, the time dependent impact force of a rigid barrier against head-on impacting aircraft was first evaluated and then the response, to the impact force, was calculated.

In this approach, a significant problem was to determine the impact force for the aircraft against a rigid target. A review of the method proposed to determine the impact forces showed that all were based on analytical methods. However, in these analytical methods, there were many assumptions and many questions remained to be answered. Because of the uncertainty involved in the analytical prediction of the impact force, a full-scale aircraft impact test was performed and an extensive suite of response measurements was obtained [4].

In this paper, these measurements are analyzed to evaluate the impact force accurately. Also, the results were used to evaluate existing analytical methods for prediction of the impact force.

2 EVALUATION OF IMPACT FORCE

2.1 Review

One of the first papers on aircraft impact was written by Riera [1]. He introduced certain assumptions which form the basis of the so-called "Riera approach"; for a normal impact on a rigid target. It was assumed that (a) the aircraft will crush only at the cross-section next to the target, and (b) the buckling of this cross-section decelerates the remaining uncrushed portion which behaves rigidly. Based on these assumptions, the impact force F(t) against the rigid target can be derived from the momentum equation and is given by

$$F(t) = P_c(x(t)) + \mu(x(t))\, V(t)^2 \qquad (1)$$

in which x(t) = distance from nose of aircraft, P_c = crushing load necessary to crush the fuselage, μ = mass per unit length of the uncrushed aircraft, and V(t) = velocity of uncrushed portion of aircraft.

In an attempt to improve the preceding formula, Kar [2] considered that the remaining material piled up at the impacting end of an aircraft and introduced a coefficient α in the second term of the right-hand side of Eq.(1). Then,

$$F(t) = P_c(x(t)) + \alpha\,\mu(x(t))\, V(t)^2 \qquad (2)$$

Riera [3], Bahar and Rice [4] and several other researchers have also proposed the improvement of the simple assumptions of Riera [1], but there was no way to verify the various formulations due to the lack of experimental evidence.

2.2 Evaluation Method of Impact Force from the Test Measurements

In principle, an impact force F(t) generated in a time interval of dt corresponds to the changing rate of a momentum (M(t)V(t)) during dt. Therefore,

$$F(t) = \frac{d}{dt}[M(t)V(t)] \tag{3}$$

in which V(t) is a velocity of mass M(t). The right-hand side of Eq.(3) consists of an inertial force caused by the change in velocity and the force required to decelerate the mass of the impinging cross-section. Eq.(3) can be written as,

$$F(t) = M(t)\frac{d}{dt}[V(t)] + V(t)\frac{d}{dt}[M(t)] \tag{4}$$

In the test, kinematic measurements were made with the sensors mounted on the aircraft and the test panel as mentioned in a companion paper [5]. Therefore, the total impact force F(t) can be evaluated from the change in momentum of the target or independently from the aircraft measurements.

For the target, (a) the target was essentially rigid and therefore little energy went into structural deformation of the target, and there was essentially no change in mass of the target, (b) the target mass was about 25 times the aircraft mass, (c) the friction force was very small (less than 0.2%). Therefore, essentially all the energy went into movement of the target and the second term of Eq.(4) is negligible. Introducing the measured mass and acceleration of the panel into Eq. (3), the total impact force $F_t(t)$ can be evaluated.

On the other hand, each term of Eq.(4) is known from the response measurements (accelerometers) of the aircraft. Writing

$$\frac{d}{dt}[M(t)] = \alpha\,\mu(t)V(t) \tag{5}$$

Eq.(4) becomes

$$F_m(t) = M_m(t)\frac{d}{dt}[V_m(t)] + \alpha\,\mu(t)V(t)^2 \tag{6}$$

in which, $F_m(t)$ = the impact force evaluated from the measurement of the aircraft missile, M_m = the mass of the uncrushed portion of aircraft, and α is defined as a coefficient of effective mass in impact.

2.3 Target Response

The data from each sensor and each location are described in [5]. In evaluating $F_t(t)$, only the horizontal acceleration of rigid motion as shown in Fig. 1 was extracted by excluding the additional components due to rocking and other vibrations from the measured raw acceleration data. A similar data reduction of the raw velocity data was used and the results are shown in Fig. 2.

2.4 Kinematic Measurement on the Aircraft

Ten accelerometers were placed along the fuselage of the aircraft and one accelerometer was placed on each engine. The data from all of the accelerometers were fairly good. However, some raw acceleration records included many shock pulses transmitted from the crushed portion of the aircraft. To remove these, suitable filtering techniques were employed. Finally, the velocity changes of the uncrushed portion of the fuselage and engines were determined from the time integration of the filtered acceleration data (J10, J13 [5]) as shown in Fig. 3.

Furthermore, $F_m(t)$ was evaluated by separating the forces caused by the sleds and engines from that of the fuselage, because the sleds and engines were detached from the fuselage at the time when their front edges touched the target. The individual impact forces were calculated independently and the total $F_m(t)$ was derived by summing them.

2.5 **Impact Force**

Consequently, two impact force functions as shown in Fig. 4, F_t (target) and F_m (aircraft), are derived from the test measurements. The two functions should be essentially the same if the principle of momentum conservation is applicable and there are no other energy losses. Comparing the two functions, $F_t(t)$ can be regarded more reliable and accurate than $F_m(t)$, because F_t is derived directly from the accurate measured data, while F_m includes an factor α which is not known precisely. In Fig. 4, four functions of $F_m(t)$ are indicated by changing from 0.7 to 1.0.

In order to determine a suitable value for α , the impulses are calculated by integrating the impact force functions, and they are compared in Fig. 5. The total impulse is defined as the impulse after the end of the application of the impact force, and is considered to be the most important value to evaluate the characteristics of the impact phenomena. Therefore, the factor α is determined so that the final impulse of F_m equals to that of F_t. From Fig. 5, the most suitable value of α can be regarded as approximately 0.9.

The impact force function of $F_m(t)$, using α as 0.9, is shown again in Fig. 6, by separating each of the components.

3 **Other Considerations**

3.1 **Impact Force Operating Area**

For the dynamic response analysis of a structure subjected to an impact load, the area of the impact load must be evaluated. Judging from the damage on the surface of the target, the impact area is about 10 square meters. This area corresponds to twice the projected area of the fuselage, Fig. 7.

3.2 **Crushing Load of Aircraft**

According to the simple assumption proposed by Riera [1], the crushing load P_c is in equilibrium with the inertial force of the remaining portion of the aircraft. Then,

$$P_c(t) = M_m(t) \frac{dV_m(t)}{dt} \qquad (7)$$

For examination of the appropriateness of Eq.(7), the crippling load of the compressive structural elements of the aircraft was calculated based on the method proposed by Gerard [5]. The dimensions of the elements were estimated from the skeleton of the fuselage. The comparison between the calculated and measured P_c from the test is shown in Fig. 8; good agreement is found between the two independent methods.

In past papers, Drittler and Gruner [7] and Zorn and Schuëller [8] evaluated the crushing load of an F-4 Phantom using a yield strength. The crushing load of the fuselage evaluated from this test is compared with those given by the researchers in Fig. 9. In the figure, the actual crushing load of the fuselage is seen to be about one half of that given in [7] and [8]. In the test, the aircraft was completely crushed to the end of the tail, while in the analysis, it was predicted that uncrushed portion remained at the tail of the aircraft.

3.3 Crushing Load Component in Impact Force

The impact force $F_m(t)$ consists of an inertial force, that corresponds to the crushing load (P_c) as mentioned above, and a force required to decelerate the mass of the impinging cross-section as shown in Eq.(6) and Fig. 10. The figure shows that the crushing load does not greatly affect the magnitude of the impact force. Preferably, a mass distribution and the coefficient α, which are significant, should be evaluated precisely for the evaluation of the impact force.

4 Conclusion

Valuable experimental data obtained from the full-scale aircraft impact test were analyzed to evaluate the impact force against a rigid target.
The analysis and evaluation gave an accurate impact force-time curve under the test conditions and confirmed that the existing "Riera approach" with slight modification is a practical way of evaluating the impact force.

REFERENCES

[1] Riera, J. D. (1968). On the Stress Analysis of Structures Subjected to Aircraft Impact Forces. Nuclear Engineering and Design 8, pp. 415- 426
[2] Kar, A. K. (1979). Impactive Effects of Tornado Missiles and Aircraft. Journal of the Structural Division, ASCE, Vol. 105, No. ST11, pp. 2243-2260
[3] Riera, J. D. (1980). A Critical Reappraisal of Nuclear Power Plant Safety against Accidental Aircraft Impact. Nuclear Engineering and Design 57, pp. 193-206
[4] Bahar, L. Y. and Rice, J. S. (1978). Simplified Derivation of the Reaction-Time History in Aircraft Impact on a Nuclear Power Plant. Nuclear Engineering and Design 49, pp. 263- 268
[5] von Riesemann, W. A. et al. (1989). Full-Scale Aircraft Impact Test for Evaluation of Impact Force, Part 1: Test Plan, Method and Results. Proc. 10th SMiRT.
[6] Gerard, G. (1958). The Crippling Strength of Compression Elements. Journal of the Aeronautical Sciences, January, pp. 37- 52
[7] Drittler, K. and Gruner, P. (1976). The Force Resulting from Impact of Fast-Flying Military Aircraft upon a Rigid Wall. Nuclear Engineering and Design 37, pp. 245-248
[8] Zorn, N. F., Schuëller, G. I. and Riera, R. D. (1981). A Probabilistic Approach for Evaluation of Load Time History of an Aircraft Impact. Proc. 6th SMiRT Conference, J6/10

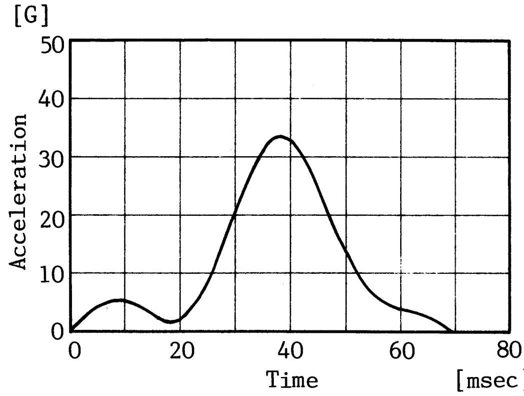

Fig. 1 Acceleration Response of Target (Filtered)

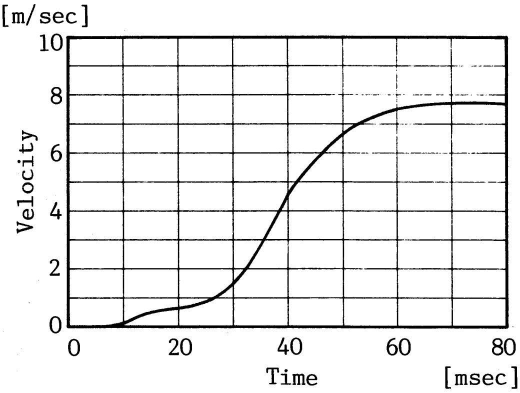

Fig. 2 Velocity Response of Target (Smoothed)

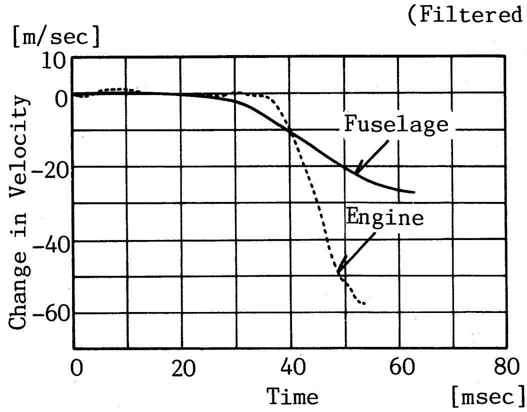

Fig. 3 Velocity Reduction Curve on Test

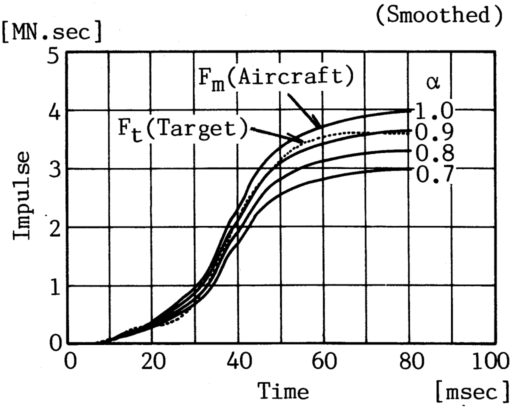

Fig. 5 Impulse of F_t and F_m

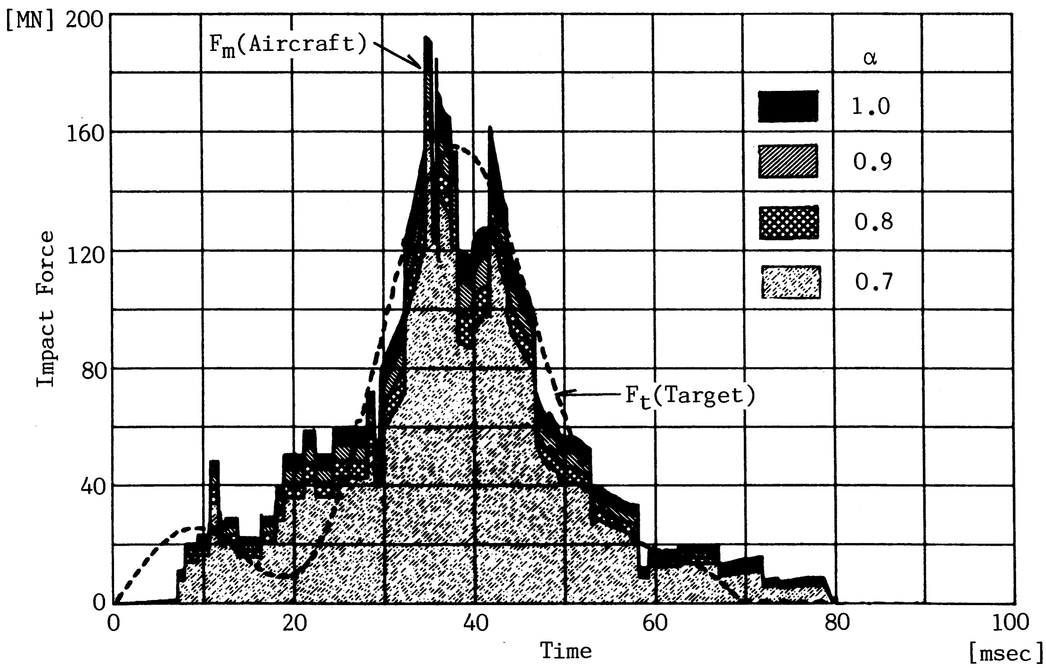

Fig. 4 Impact Force (F_t and F_m) versus Time Curve

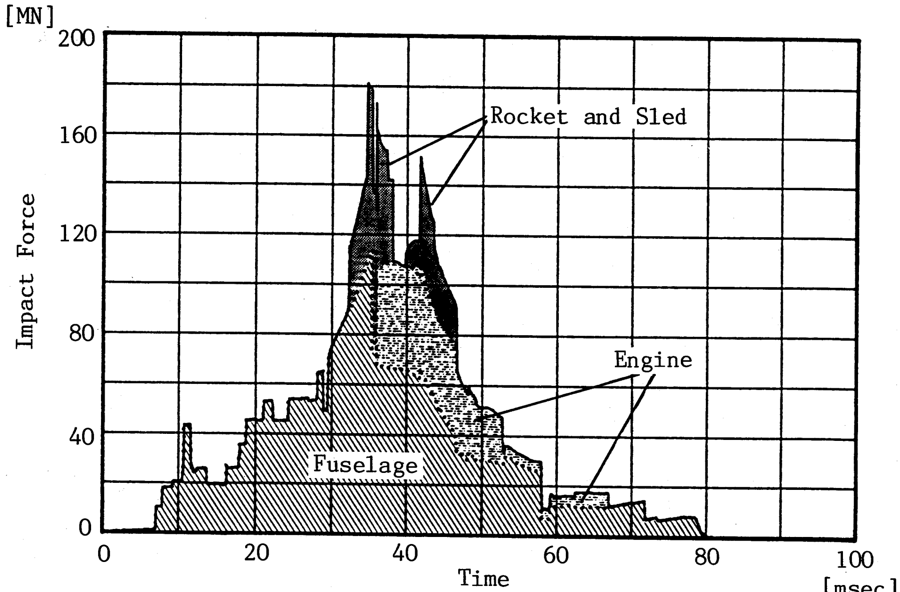

Fig. 6 Impact Force of Each Component (α=0.9)

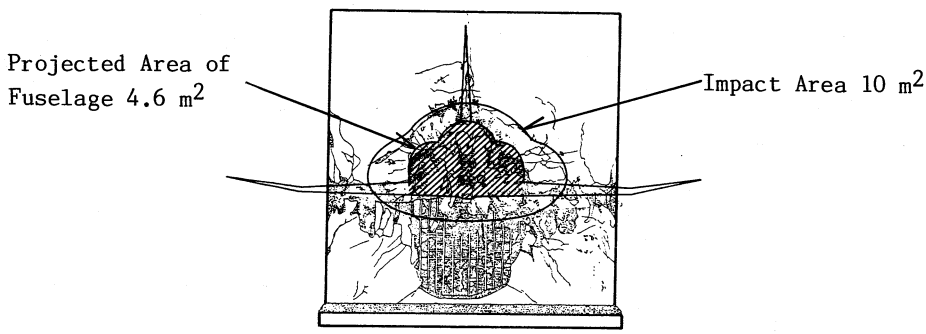

Fig. 7 Impact Force Acted Area

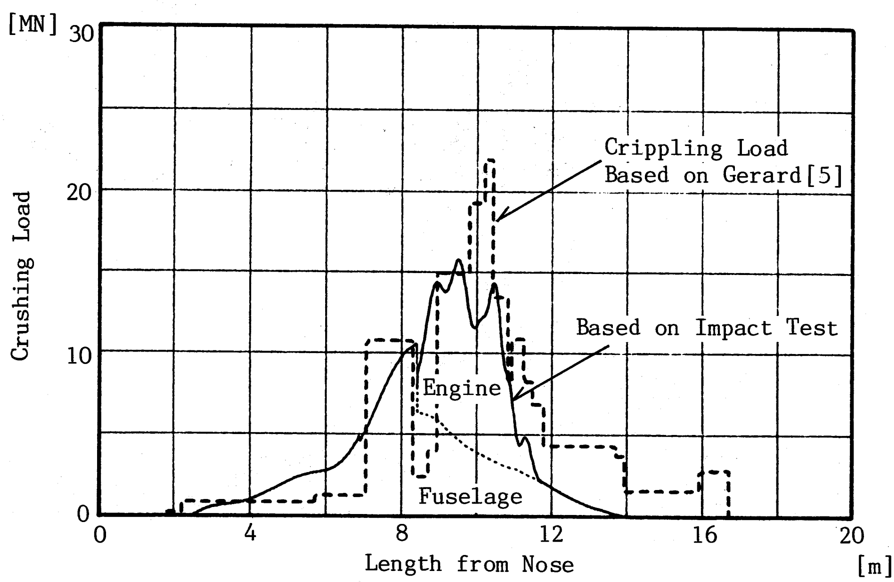

Fig. 8 Crushing Load of Aircraft

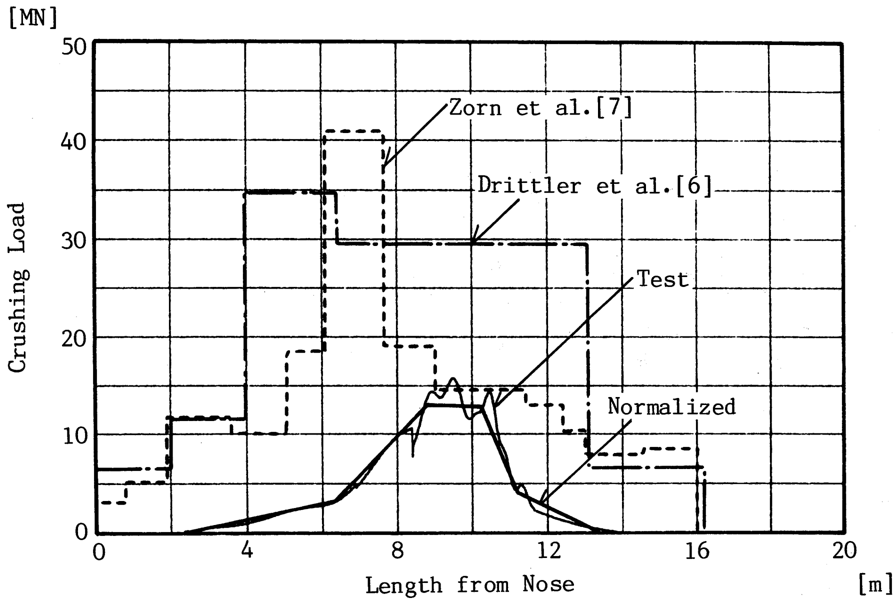

Fig. 9 Comparison of Crushing Loads

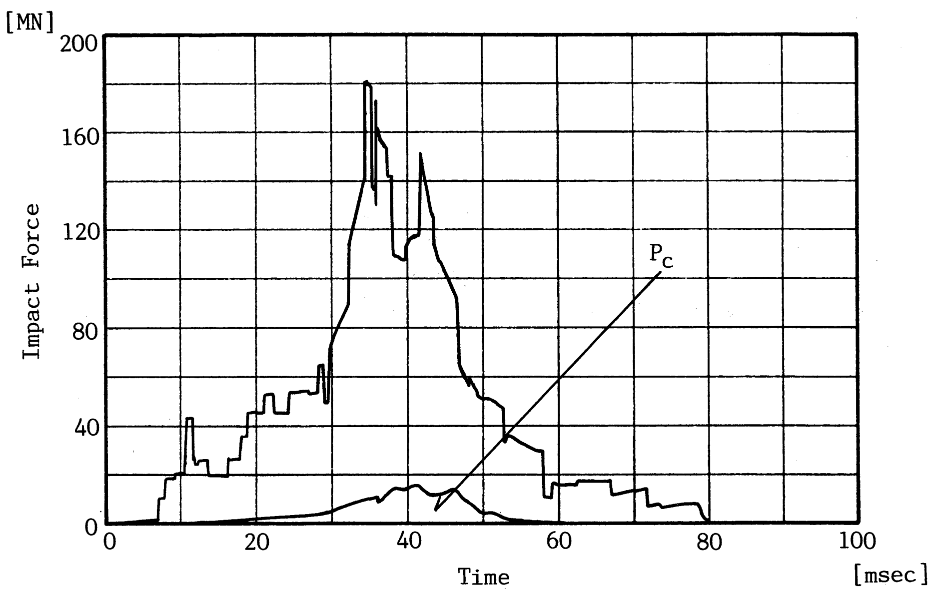

Fig. 10 Crushing Load P_c Component in Total Impact Force (α=0.9)