Presented at the Second Asian Conference on High Pressure Research (ACHPR-2), in Nara, Japan on November 1-5, 2004.

Numerical Simulation of Jumbo Jet Impacting on Thick Concrete Walls —— Effects of Reinforcement and Wall Thickness

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ABSTRACT

A three-dimensional computer simulation of the impact of a Boeing 747 passenger jet has been conducted using the AUTODYN®-3D computer program. The targets are reinforced or non-reinforced concrete wall with three different thicknesses.

The fuselage, the wings and the engines of the airplane are modeled by shell elements. The stringers are represented by beam elements, and the jet fuel by solid elements. As for the target wall the concrete is modeled by the solid elements, and the reinforcement by the beam elements. The impacts between these elements are examined thoroughly by an edge-to-edge contact capability together with a standard node-to-face one. The Johnson-Cook constitutive equations are applied to aluminum and steel, and a dynamic yield model with failure to the concrete.

The numerical results were discussed over not only the perforation or non-perforation of the concrete target, but also the damage such as the cratering or spalling estimated in the concrete and the crushing behavior of the B747. The numerical stability during the computation is also addressed to examine the validity of the numerical techniques adopted for this simulation.

Key words; AUTODYN®-3D, Boeing 747, Concrete, Impact, Spalling

Introduction

An accident previously considered hypothetical became real when the hijacked Boeing 767 passenger jet crashed into the North Tower of the New York World Trade Center on September 11, 2001. The possibilities of aircraft impacts against infrastructures have been investigated mainly in nuclear industries since 80's [1], [2]. However, the aircrafts discussed in these studies were not commercial jetliners but military jet fighters such as an F-4 Phantom.

In the present paper, three-dimensional computer simulations of the impact of a Boeing 747 passenger jet against five different concrete walls has been conducted using the AUTODYN®-3D computer program [3]. All the components of the jetliner of our numerical model, namely, the fuselage, the wings and the engines are modeled by shell elements. The five different types of targets are reinforced or non-reinforced concrete plates with three different thicknesses. The objective of this work is to numerically asses the damage of the wall caused by the impact of the B747 which is almost 15 times the weight of the F-4. The impacts between these elements are examined by a contact capability. An eroding slide-line capability is utilized to prevent mesh tangling. The

Johnson-Cook constitutive equations [4] are applied to aluminum, and the RHT model [5] to the concrete.

The numerical results were discussed over the crushing behavior of the B747, the impact force loaded on the wall. Recommendations for future studies are presented to improve the accuracy of the simulation.

Numerical Modeling

A three-dimensional multiple-solver hydrocode: AUTODYN®-3D was applied to this numerical analysis. In the present study shell elements are used for the jetliner, and hexahedral solid elements are used for modeling the concrete wall, and beam elements for the reinforcements.

Boeing 747 jetliner The geometry of the jetliner is created first by the general-purpose True*Grid* mesh generation computer program [6]. Then the obtained geometry is imported into the AUTODYN finite element model as shown in Fig.1. The overall length is 70.5 m and the wing span is 64.0 m. The thickness of the shell elements is adjusted so that the numerical model is consistent with the Boeing 747 data [7]. The total mass of the jetliner is thus 3.4×10^5 kg (340 t) including four engines and the fuel. Each engine masses 4.0×10^3 kg (4 t) and the fuel 1.0×10^5 kg (100 t). The impact velocity of the jetliner is assumed to be 83.3 m/s (300 km/h) which slightly exceeds the landing speed of about 77.8 m/s (280 km/h). Because of the intense impact loading condition a constitutive model for the material of the jetliner is required to take into consideration the strain hardening and the strain rate effects. The Johnson-Cook model is adopted and the material properties of the 2024-T351 aluminum are taken from a reference [4].

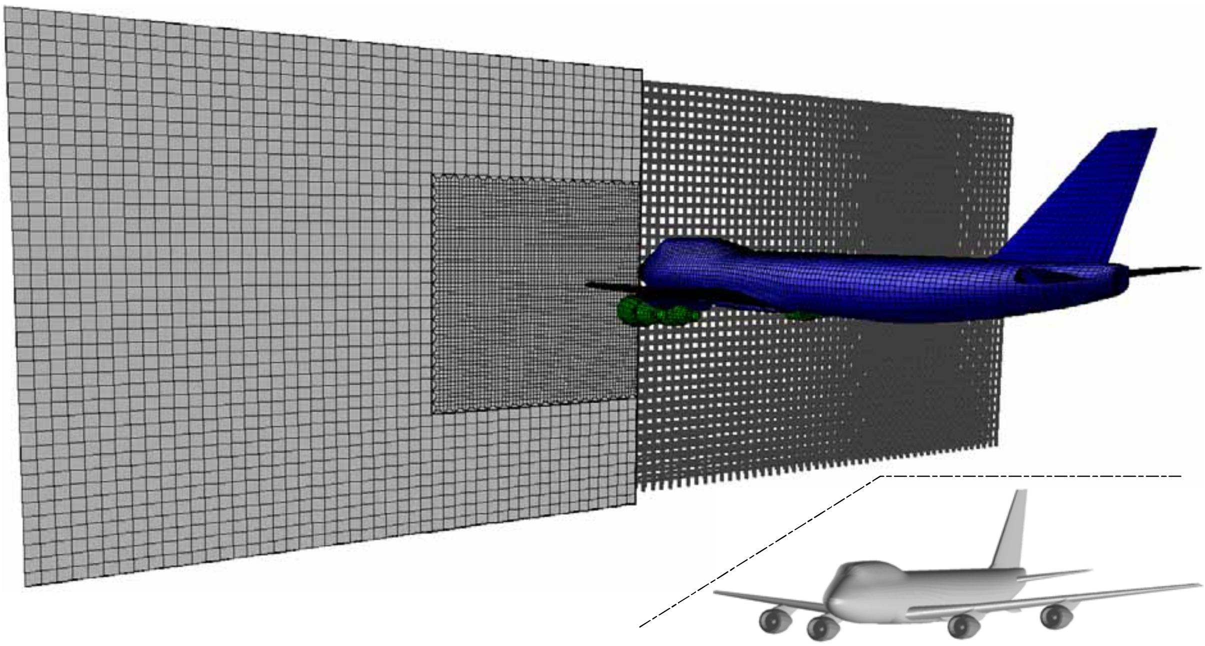


Figure 1. Finite element model of a Boeing 747 and 3 m reinforced concrete wall, the right-hand side concrete is transparent as to see the reinforcement arrangement. The jet: 26,092 elements, the total mass of 3.4×10^5 (340 t) [the fuselage 2.16×10^5 (216 t), the fuel 1.0×10^5 (100 t), the engines 1.6×10^4 (16 t)], 83.3 m/s (300 km/h). The RC wall: the concrete consists of fine meshes and coarse ones, totally 186,000 solid elements, 150 m width × 60 m height; 99 longitudinal and 39 lateral bars; 0.4 m pich; double-reinforced.

Target Wall Five cases of numerical analyses were carried out for different types of targets as shown in Table 1. All the concrete targets have rectangular shapes with the same 150 m width and 60 m height. As indicated in the left-hand side of Fig. 1. for the CASE−4, fine meshes are assigned to the central region where the impact loading is concentrated while coarse meshes are used for the surrounding region. The former region has a face of 60 m × 30 m and a thickness of 3 m which consists of 120 × 60 × 15 meshes. The size of one solid element is then 0.5 m × 0.5 m × 0.2 m. The surrounding region is divided uniformly into rectangular solid elements. Each element has a size of 1.5 m × 1.5 m × 0.2 m. The concrete wall contains 186,000 elements totally.

Table 1. Performed numerical analysis cases.

Case Name	Wall Thickness	Reinforcement
CASE−1	1 m	0. 8 %
CASE−2	2 m	0.8 %
CASE−3	2 m	None
CASE−4	3 m	0.8 %
CASE−5	3 m	None

In order to represent the material nonlinearity of the concrete we adopted the RHT [5] model which has the following specific features like pressure hardening, strain hardening, strain rate hardening and damage with tensile crack softening. The material properties calibrated with the compressive strength of 35 MPa are taken from the material library of AUTODYN.

The bottom of the wall is rigidly fixed, while no boundary condition is applied to the other five surfaces.

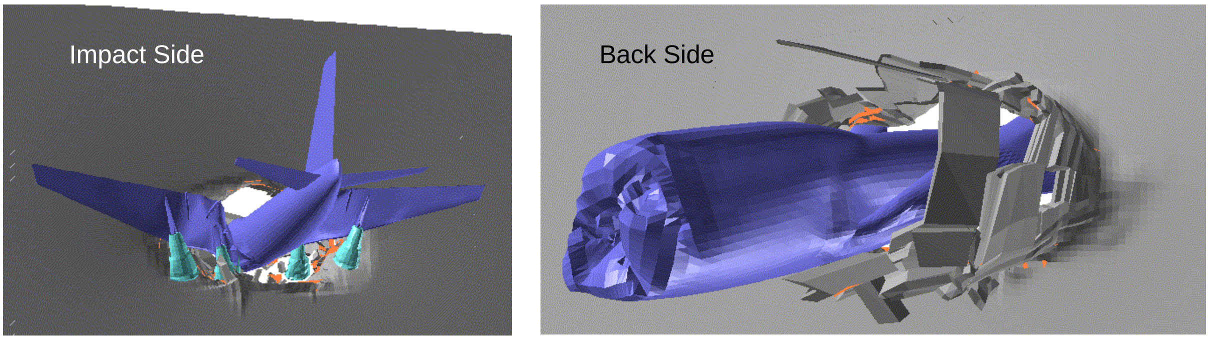
Reinforcement The right-hand side of Fig.1 depicts the double-reinforced arrangement. The number of longitudinal bars is 99 and that of lateral ones is 39. They are placed 0.4 meter inside the front surface of the wall. The same number of bars is put along the back surface. The ration of the reinforcement is 0.8 percent. As for the material the SD345 steel is used. The following material properties are used: density of 7.8×10^3 kg/m^3: bulk modulus of 1.71×10^5 MPa: shear modulus of 7.88×10^5 MPa: yield stress of 2.15×10^2 MPa: fracture strain of 0.19.

Numerical Results

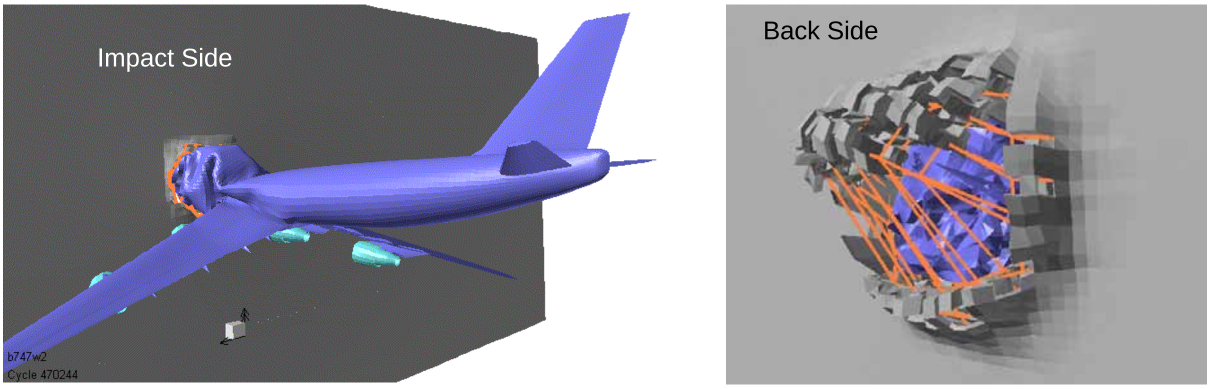
Figure 2. and 3. summarize the overview on the numerical results of the present study for five different target walls, while each assumption for the impactor is the same. All the calculations were carried out up to 1 s. The figures of (a) through (c) depict the deformations or damages estimated to the Jumbo jets and the concrete walls in the impact side and the back side at 1 s, for the CASE−1 through CASE−3 respectively, as well as the figures of (d) and (e) do in the impact side and from the upper viewpoint at 1 s, for the CASE−4 and CASE−5 respectively. The graphs of (a) through (e) indicates the energy balance histories by each material for the CASE−1 through CASE−5 respectively. “Body” means all the material of the Jumbo jet except for engines; “Eng.” does all the material in the four engines; “Con.” does all the concrete material; “R-F” does all the reinforcement steel. On the other hand, “Int.” stands for the internal (distortional) energy and “Kin.” does the kinetic energy.

Crash Behavior of the Jetliner In every case the buckling occurs in the nose of the jet, and it is subjected to serious deformation. However, outstanding crashes on four engines are observed only in the CASE−1 (1 m thickness; with the reinforcement). On the contrary, every jet except for CASE−1 drops its main wings in the tip, like birds do when they flap. No significant deformations can be observed behind the main wings in every case.

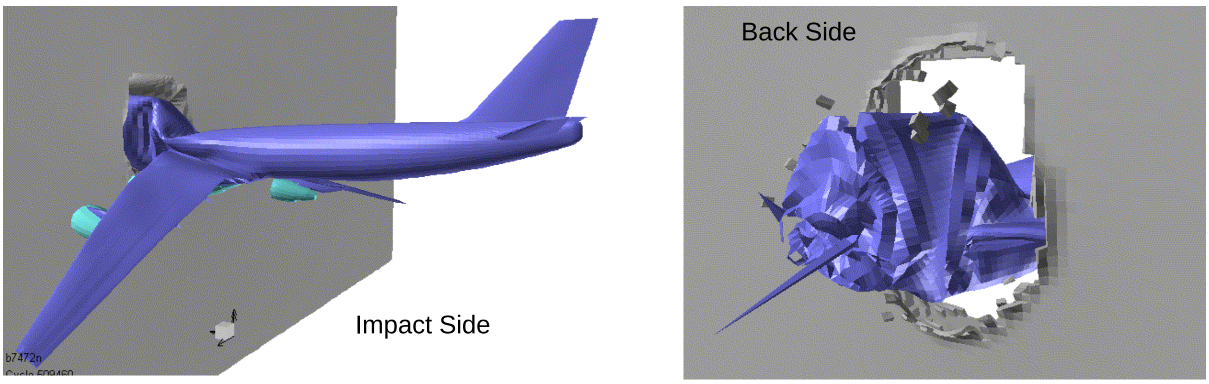
Damage on the Concrete Wall From Fig. 2.(a) through (e), we can know that the concrete wall are perforated completely in the cases of CASE−1 and CASE−3 (2 m thickness; without the rein forcement). Especially, in the case of CASE−1, the both front and rear reinforcements are broken and cut in the vicinity of the impact surface. The rear reinforcements of CASE−2 seem to survive,



(a) CASE-1 (Thickness: 1 m, with RF), Time: 1 s.

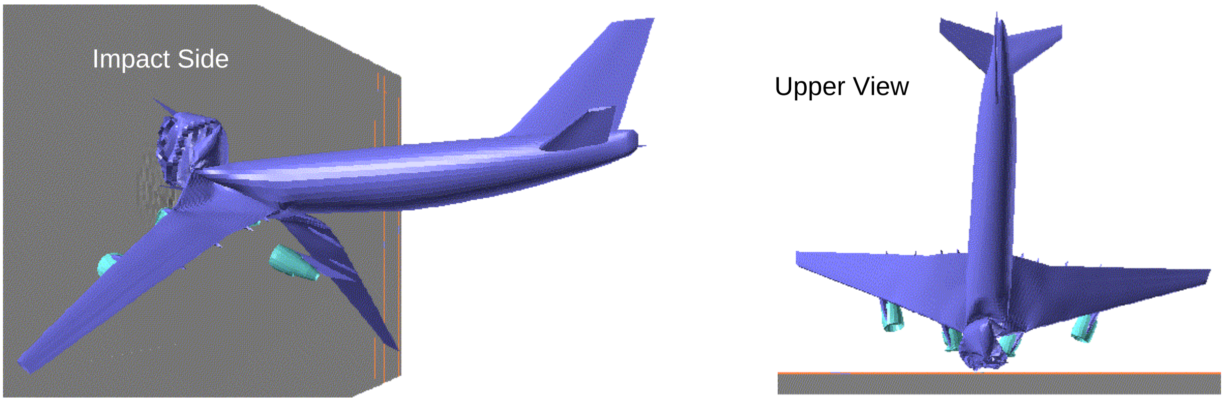


(b) CASE-2 (Thickness: 2 m, with RF), Time: 1 s.

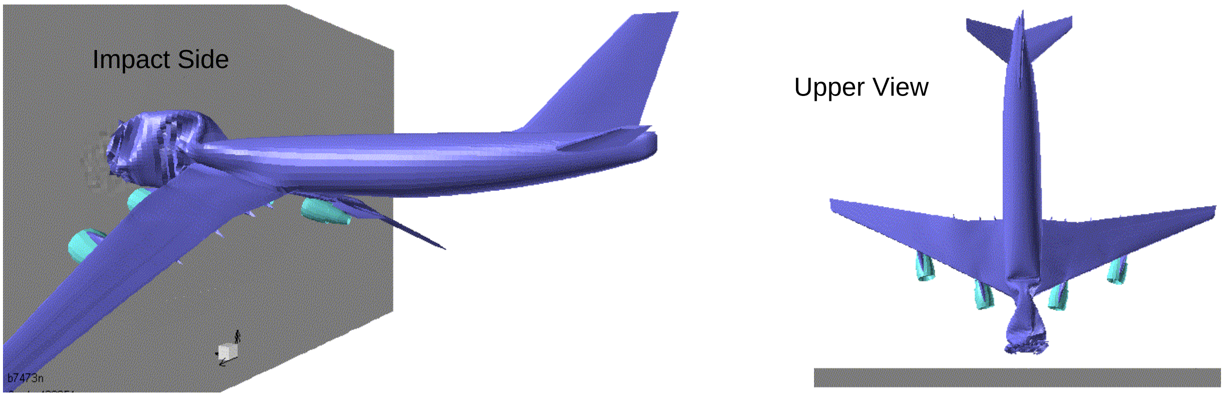


(c) CASE-3 (Thickness: 2 m, without RF), Time: 1 s.

Figure 2. Overview of the deformations and damages on the Jumbo jets and concrete walls. (1/2)



(d) CASE-4 (Thickness: 3 m, with RF), Time: 1 s.



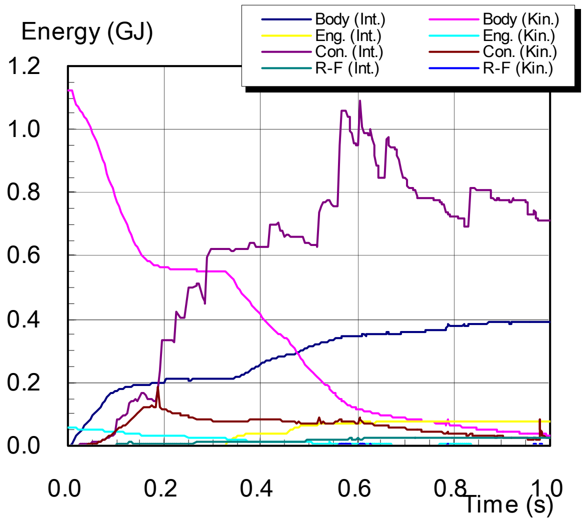
(e) CASE-5 (Thickness: 3 m, without RF), Time: 1 s.

Figure 2. Overview of the deformations and damages on the Jumbo jets and concrete walls. (2/2)

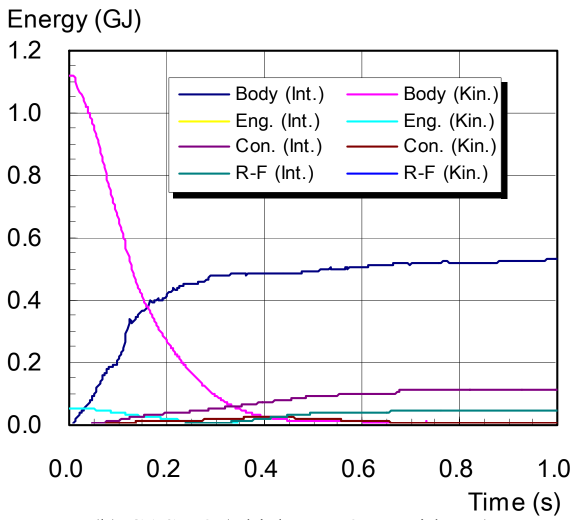
but they are not supportable in any sense, actually some of them are known to be fractured by an additional output separately done. And outstanding scabbing (spalling) can be observed in the back side of the concrete wall of CASE−2. Slight dents or multiple shallow craters are formed around the impact area on the front side, whereas no significant deformations can be observed on the back side, for both the CASE−4 and CASE−5 that have the same thickness of 3 m.

Energy Balance History Through the comparison among five graphs in Fig. 3., the history of the kinetic energy of the Jumbo jet of CASE−1, “Body (Kin.)”, is apparently different from the other cases: it indicates two-step decrease curve. This history tells us that the nose of the jet perforated the concrete wall at about 0.15 s, and that the four engines impacted on the wall again in order after about 0.3 s. And, it takes over 0.8 s for the jet of CASE−1 to be decelerated sufficiently, while the jets of other cases are stopped or rebounded within 0.5 s. However, since the internal energy of the concrete of the CASE−1 shows extraordinary increase, the calculated fact that the increase of the internal energy of the jet (“Body”) is less than the other cases can be recognized to be caused by some numerical energy error. That the total energy of the system decreases less than the initial amount (the kinetic energies of “Body” and “Eng.”) in the CASE−2 through the CASE−5 can be explained by the numerical erosion of the elements.

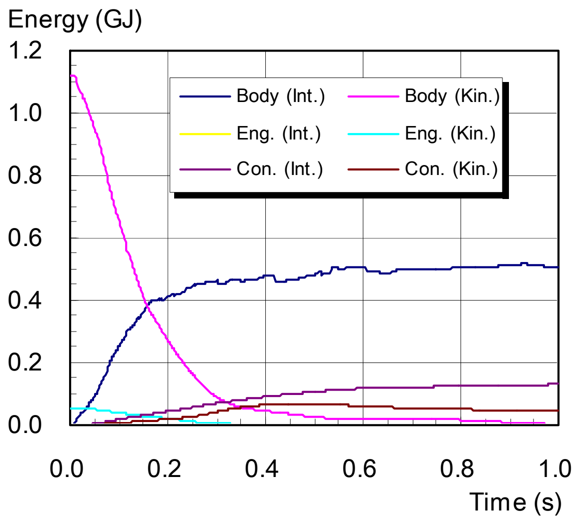
From the comparisons between the CASE−2 and the CASE−3, and between the CASE−4 and the CASE−5, any significant differences cannot be found, and this fact is coincident with the former comparisons of the deformations and damages investigated by using Fig. 2. Although the histories of the energies for the CASE−4 and the CASE−5 differ from each other a little, there seem not to be any convictive reasons, and it might be amplified by the asymmetry of the jets caused by a minute numerical error.



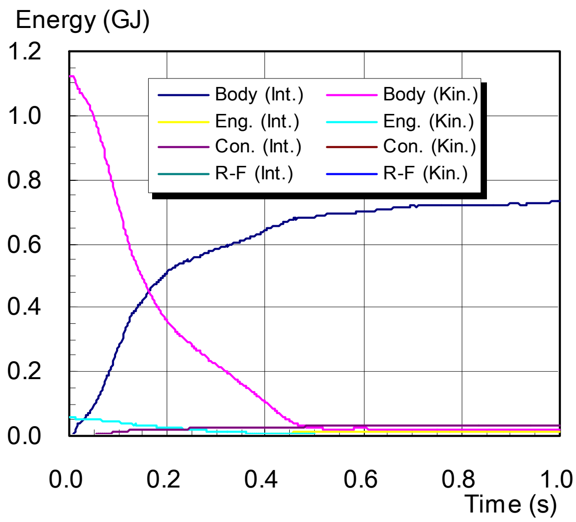
(a) CASE-1 (Thickness: 1 m, with RF)



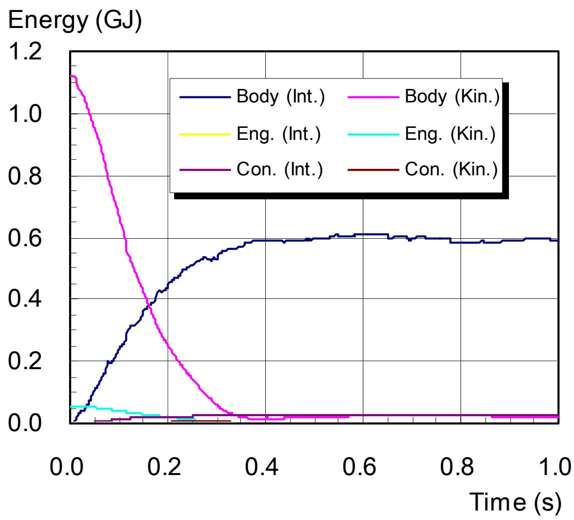
(b) CASE-2 (Thickness: 2 m, with RF)



(c) CASE-3 (Thickness: 2 m, without RF)



(d) CASE-4 (Thickness: 3 m, with RF)



(e) CASE-5 (Thickness: 3 m, without RF)

Figure 3. Calculated energy balance histories by every material.

Conclusions

The present numerical simulation has successfully demonstrated that the numerical models adopted in this study are effective and efficient in order to predict the response of the concrete wall impacted by the Boeing 747 jetliner, moreover in order to comprehend the dynamic behavior and deformation mechanism of both the impactor and target materials. We may conclude that the reinforced concrete of 3 m thickness is not severely damaged when it is impacted by the Boeing B747 with the velocity of 83.3 m/s (300 km/h), and the usual reinforcement is less effective than the concrete thickness in the current problem. However, in order to improve the accuracy of the simulation the assumptions adopted in the present study need to be reviewed for future studies. For example, the weight of the fuel is distributed uniformly to all the elements of the jetliner because of the lack of information about its exact location. The fuel needs to be modeled by solid elements and placed inside the wings and the fuselage.

Finally, it requires about one-month of computer time to complete the simulation using a 3 GHz of Windows® PC.

Acknowledgements

The authors gratefully acknowledge Mr. T. Ohta of CRC Solutions Corp. for his help to generate the geometric model of the Jumbo jet. They also thank to Mr. B. I. Gerber of Century Dynamics Inc. for his arrangement between CRC Solutions Corp. and XYZ Scientific Applications Inc. to perform this work.

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