To be presented at the First International Symposium on Explosion, Shock Wave and Hypervelocity Phenomena, March 15-17, 2004, Kumamoto University, Japan.

Computer Simulation of a Boeing 747 Passenger Jet Crashing into a Reinforced Concrete Wall

Masaharu Itoh[1,a], Masahide Katayama[1,b], Robert Rainsberger[2,c]

[1] CRC Solutions Corp., 2-7-5 Minamisuna, Koto-Ku, Tokyo 136-8581, Japan

[2]XYZ Scientific Applications Inc., 1324 Concannon Blvd. Livermore, CA 94550, USA

[a]mashi@crc.co.jp, [b]m-kata@crc.co.jp, [c]info@truegrid.com

Keywords: Boeing 747, crash, reinforced concrete, damage, finite element analysis, Johnson-Cook constitutive model, RHT concrete model, contact capability, eroding slideline, AUTODYN

Abstract. The purpose of this study is aimed at assessing the capabilities to numerically simulate the dynamic phenomenon of a Boeing 747 jetliner impacting against a reinforced concrete wall. The geometry of the numerical model of the jetliner is adjusted to fit the Boeing data which are available publicly. The thickness of the wall is 3 meters and the impact velocity is 300 km/h. Because of the highly nonlinear characteristics of the phenomenon the strain hardening and the strain rate effects are considered for the constitutive models of the jetliner and the concrete. The simulation shows that the concrete wall exhibits no severe damage by the impact under the conditions assumed in the study.

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, a three-dimensional computer simulation of the impact of a Boeing 747 passenger jet against a reinforced concrete wall has been conducted using the AUTODYN®-3D computer program [3]. The B747 is almost 15 times as heavy as the F-4. All the components of the jetliner of our numerical model, namely, the fuselage, the wings and the engines are modeled by shell elements. The concrete is modeled by solid elements and the reinforcement by beam elements. The impacts between these elements are examined by a contact capability. An eroding slideline 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.

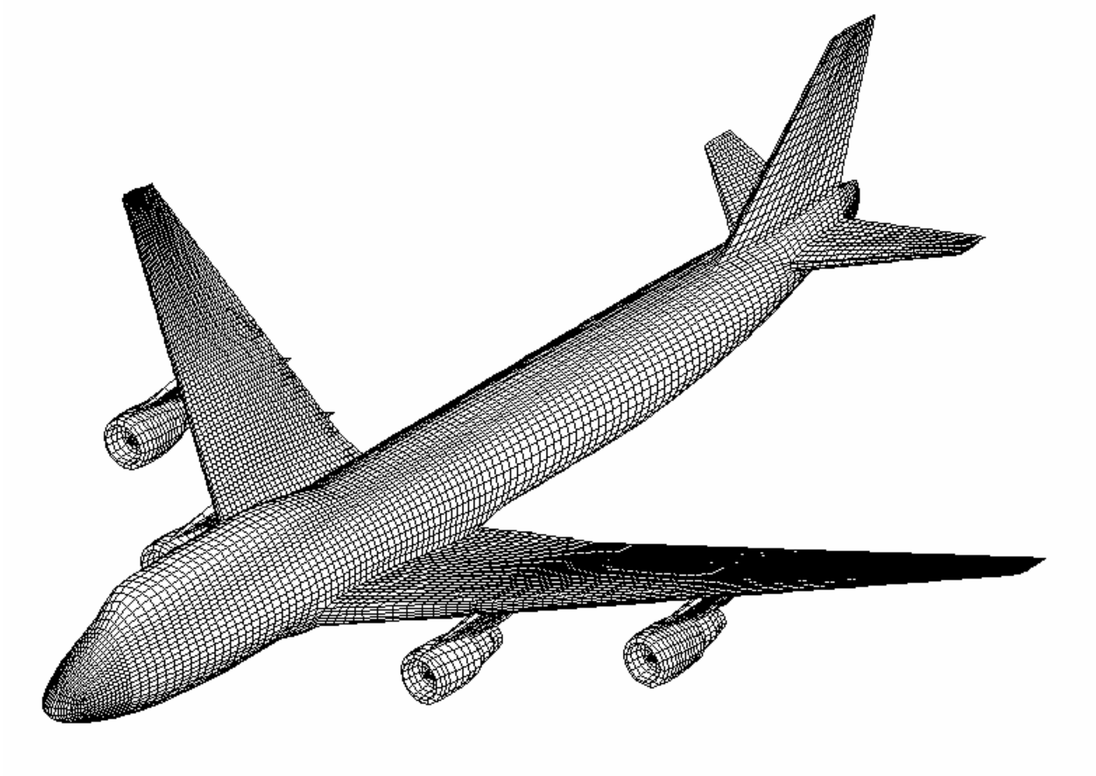
The numerical results were discussed over the crushing behavior of the B747, the impact force loaded on the wall. Recommendations for future studies are presented to improve the accuracy of the simulation.

Finite Element Model

The AUTODYN®-3D utilizes various numerical solvers such as finite element, finite difference, finite volume and smooth particle hydrodynamics (SPH) methods. In the present study shell elements are used for the jetliner. 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 meters and the wing span is 64.0 meters. The thickness of the shell elements is adjusted so that the numerical model is consistent with the Boeing 747 data [7]. The total weight of the jetliner is thus 340 tons including four engines and the fuel. Each engine weighs 4 tons and the fuel 100 tons. The impact velocity of the jetliner is assumed to be 300 km/h which slightly exceeds the landing speed of about 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 [4].

Fig.1 Finite element model of a Boeing 747, a total of 26,092 elements, the total weight of 340



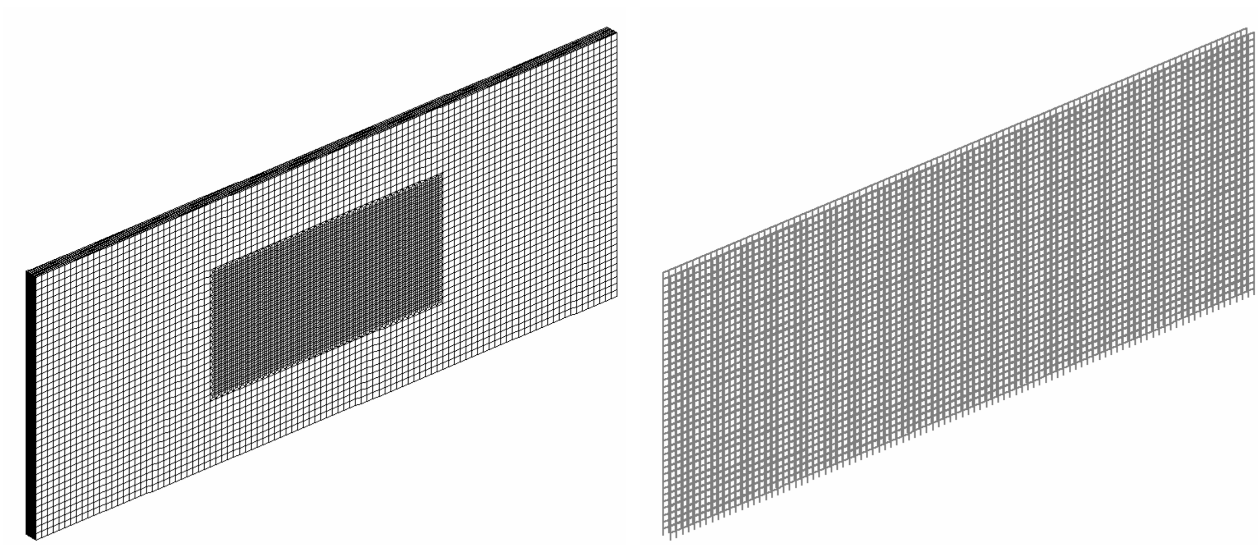


Fig.2 Initial mesh configurations of the concrete wall (left) and the reinforcement (right), the concrete wall consists of fine meshes and coarse ones, totally 186,000 solid elements are used.

Concrete wall The concrete target is a rectangular wall 150 meter long, 60 meter high and 3 meter thick. As shown in Fig.2 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 meter $\times$ 30 meter and a thickness of 3 meters which consists of $120\times60\times15$ meshes. The size of one solid element is then 0.5 meter $\times$ 0.5 meter $\times$ 0.2 meter. The surrounding region is divided uniformly into rectangular solid elements. Each element has a size of 1.5 meter $\times$ 1.5 meter $\times$ 0.2 meter. The concrete wall contains 186,000 elements totally.

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 Fig.2 shows the reinforcing bars. 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 Result

Crashing behavior of the jetliner Each engine changes its direction toward the center of the fuselage as shown in Fig.3. Accordingly, the two inside engines tend to impact near the region where the nose of the fuselage hits the wall. See also Fig.5. The nose section bends backward because of the distinct bulge at the cockpit as shown in Fig.4. We continue the simulation until 500 ms. At this stage the momentum of the jetliner decreases to 4 percents of the initial amount as shown in Fig.6. The velocity transients at the nose and at the tail are shown in Fig.7.

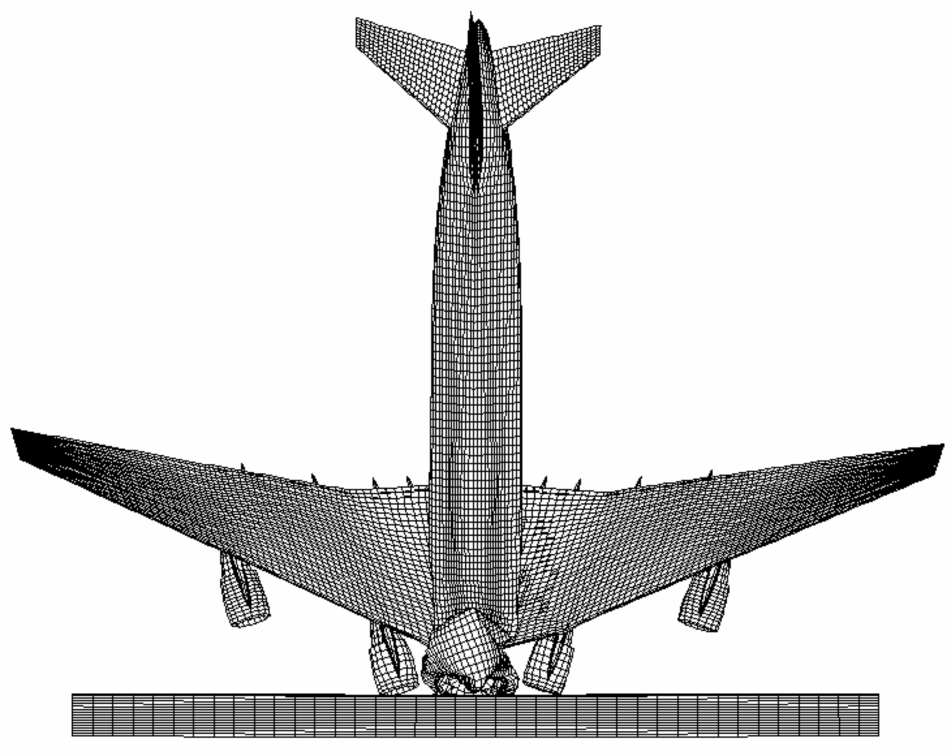


Fig.3 Deformed configuration at 400 ms when the two engines hit the central part of the wall.

Damage to the concrete wall When an concrete slab is impacted by a high speed projectile with a blunt nose, a region near the rear surface of the slab is damaged because of hydrostatic tension waves. This fracture phenomenon is called spalling or scabbing which leads to the fragmentation of the material. In our simulation the ejection of concrete is not observed as shown in Fig.5. A slight dent is formed at around the impact area.

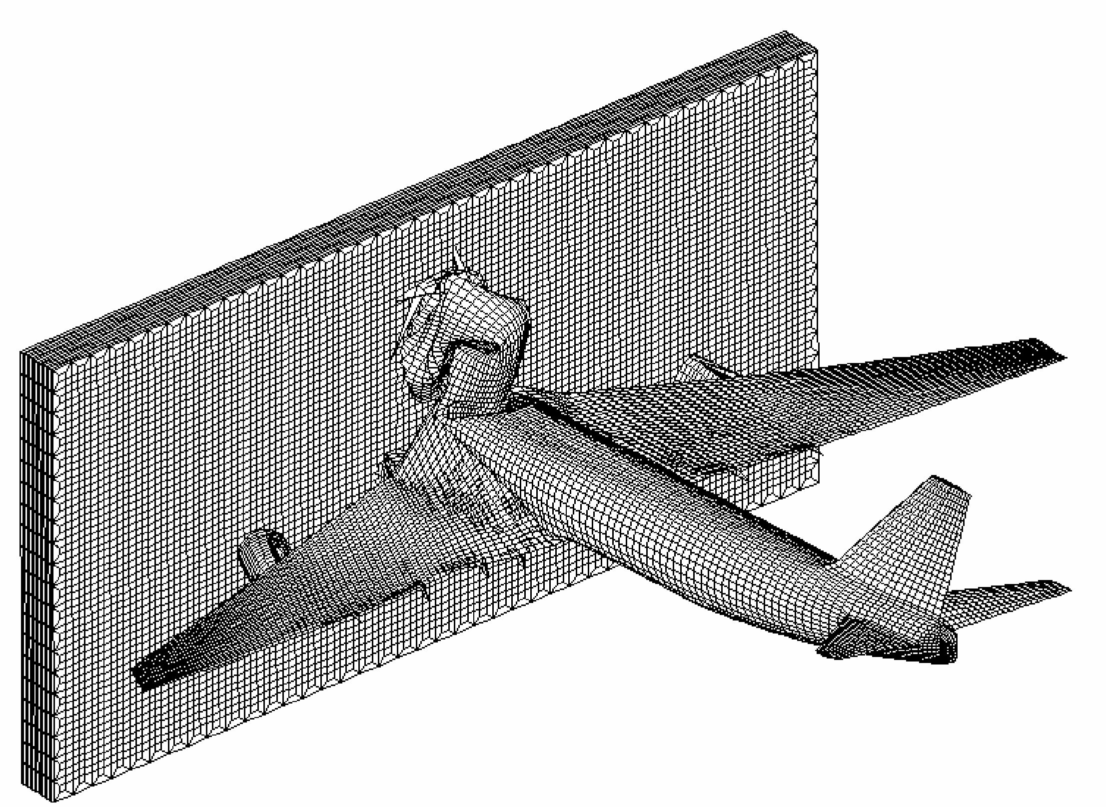


Fig.4 Mesh configuration at 500 ms after impact; the nose of the jetliner is severely damaged.

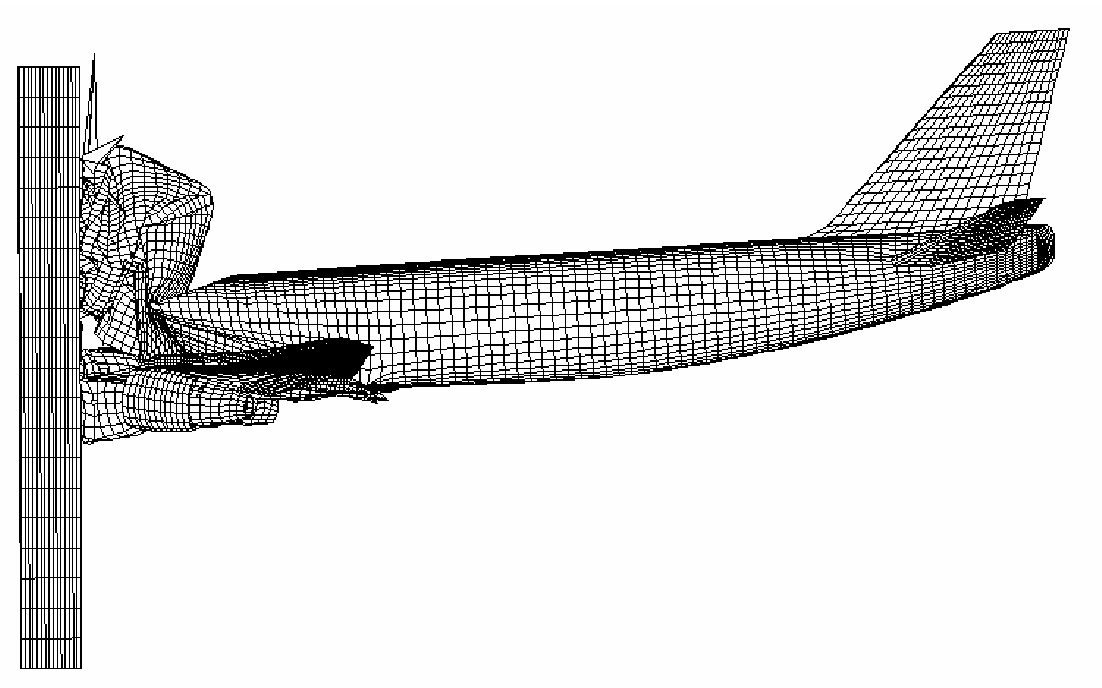


Fig.5 Side view at 500 ms, no scabbing from the rear surface of the concrete wall observed (the surrounding coarse meshes of the wall not shown).

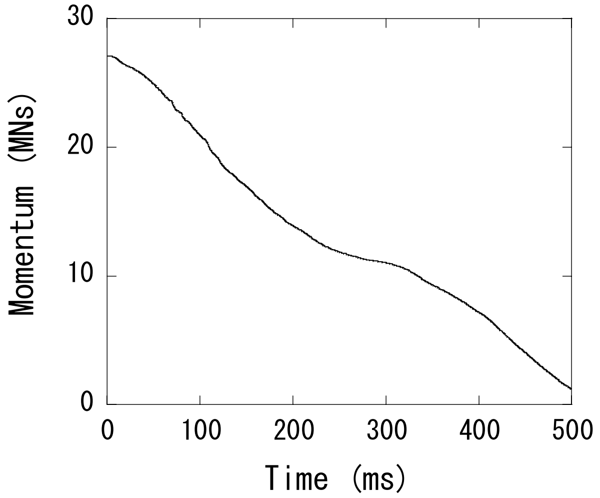


Fig.6 Momentum response of the fuselage.

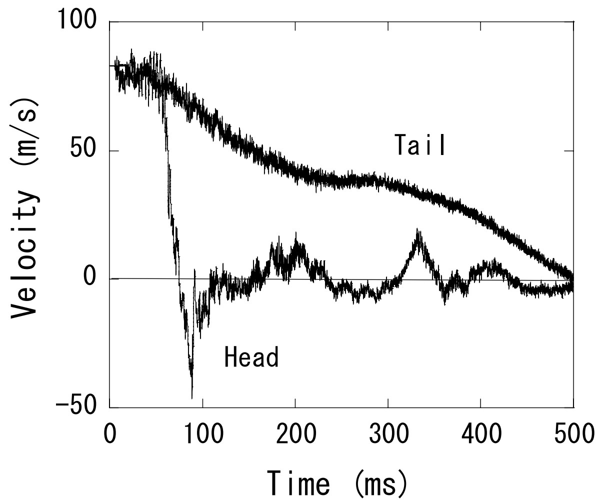


Fig.7 Velocity transients at the head and the tail of the fuselage.

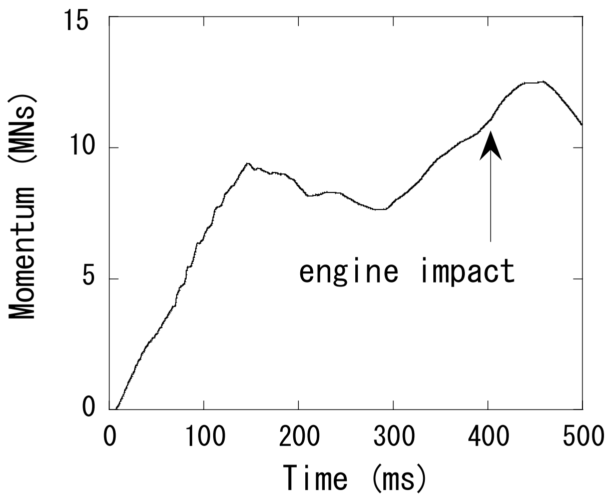


Fig.8 Momentum response of the wall.

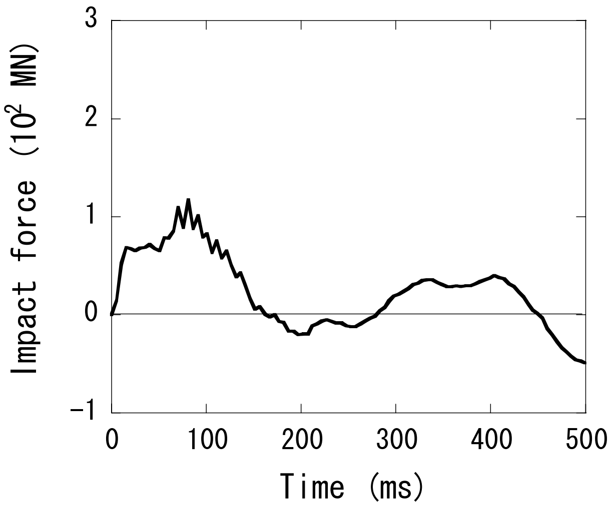


Fig.9 Impact force (smoothed).

Impact force The momentum of the concrete wall increases almost linearly until it reaches the first peak *A* as shown in Fig.8. At this time the velocity at the nose of the fuselage reduces to the zero level and oscillates around it afterward (Fig.7). The second peak *B* is recorded shortly after the engines impact the wall. The transient of impact force is obtained by differentiating the momentum response of Fig.8 by time. Fig.9 shows the impact force after a smoothing is applied. Distinct feature of this curve as compared with the impact force by the F-4 Phantom test [2] is the two separate peaks. The latter one exhibits one peak. This difference is attributed to the impact velocity. Because of the higher velocity of the F-4 the force peak by the fuselage and the one by the engine are superimposed.

Conclusions

The simulation shows that the numerical models adopted in this study are useful to predict the response of the concrete wall impacted by the jetliner. We may conclude that the reinforced concrete of 3 meter thickness is not severely damaged when it is impacted by the Boeing B747 with the velocity of 300 km/h. 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 three weeks of computer time to complete the simulation using a 3 GHz of Windows® PC.

References

[1] N. F. Zorn, et al., A probabilistic approach for evaluation of load time history of an aircraft impact, Proc. 6th SMiRT Conference, Paris, Aug. (1981), p.1

[2] T. Sugano, et al., Full-scale aircraft impact test for evaluation of impact force, Nuclear Engineering and Design 140 (1993), p373.

[3] Century Dynamics, *AUTODYN Theory Manual*, Sep. (2001).

[4] G. R. Johnson and W. H. Cook, A constitutive model and data for materials subjected to large strains, high strain rates, and high temperatures, Proc. 7th Int. Sympo. Ballistics, (1983), p.541.

[5] W. Reidel, K. Thoma., S. Hiermaier and E. Schmolinske, Penetration of reinforced concrete by BETA-B-500, numerical analysis using a new macroscopic concrete model for hydrocodes, 9th Int. Sympo., Interaction of the Effects of Motions with Structures, May (1999).

[6] XYZ Scientific Applications, Inc., *TrueGrid User Manual*, Version 2.1, (2001).

[7] Boeing 747 Family: Technical, http://www.boeing.com/commercial/747family/technical.html.