Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division III, Applied Computation

LOAD ON STRUCTURES DUE TO LARGE AIRPLANE IMPACT

Alexander Kultsep [1] Mhamed Souli [2] and Ivan Volkodav [3]

[1] Principal Analyst, CKTI-Vibroseism Ltd., St.-Petersburg, Russia, (akultsep@cvs.spb.su)
[2] Professor, Université Lille1, Villeneuve, France, (mhamed.souli@univ-lille1.fr)
[3] Chief Engineer, Atomenergoproekt, St.-Petersburg, Russia, (i_volkodav@su.spbaep.ru)

ABSTRACT

Impact load for Boeing 747-400 commercial aircraft was obtained with adequate scaling of well-known dependencies of mass distribution (per unit length) and fuselage buckling load (per unit length) for Boeing 720 aircraft, which J.D.Riera received in 1968. The Boeing 747-400 impact load on a rigid barrier for different values of the impact velocity was found solving the body motion equations in quadratures using the obtained dependencies of Boeing-747-400 mass distribution and fuselage buckling load per length. Conclusive a simplified finite element model of airplane based on Arbitrary Lagrange Euler (ALE) formulation with mass, momentum and energy conservation was proposed for performing plane crash simulations on geometric complex rigid or flexible structures. The detailed description of proposed model is presented.

INTRODUCTION

Impact load due to large airplane crash is a design case for nuclear facilities. Design codes define the plane impact load as time dependent force during the plane impact against a rigid wall. The force curves are usually obtained by equations similar to J.D. Riera received (1968) based on dependencies of mass distribution and fuselage buckling load for middle size commercial aircrafts. The great advantage of this approach is simplicity of airplane data needed for calculation. However, Riera approach is one dimensional therefore its use for load calculation on geometric complex or flexible structures may be difficult. On the other hand, many attempts were made in order to create a realistic airplane model which could enable crash simulations with wide range of structures (see for example Siefert and Henkel (2011)). Realistic crash models use one or more failure criteria. The failed elements in many computer codes are deleted from further analysis, which leads to violation of momentum conservation and as consequence to reduction of resultant impact load. Furthermore the used failure criterion is usually dependent of finite element mesh size. Therefore such models need verification (see Byeong (2011)), which could be performed basically on the Riera calculation results. A crash model verification based on the experiments like in automotive industry is difficult to organize in the case of airplane crash. Only few such tests performed for small aircrafts are known (Sugano (1993)).

Meanwhile, there is public demand for safety guarantee against crash of large airplane like Boeing 747-400, which is defined only in few codes and papers. In this paper the impact load of Boeing 747-400 commercial aircraft crash against a rigid barrier was obtained with adequate scaling of well-known Riera mass and fuselage buckling load distribution dependencies for Boeing 720 aircraft.

Because the airplane finite element model anyway needs verification and failure criterion scaling, there is no reason to create detailed model, but create simplified bulk model with averaged buckling force and mass distribution data, which can represent the load curve given for scaling. Such model, based on ALE formulation with momentum conservation was proposed and tested for performing plane crash simulations on geometric complex structures.

REFERENCE AIRPLANE CRASH LOAD CALCULATION BY RIERA APPROACH

The load on target due to aircraft impact is calculated mainly according to equation proposed by Riera (1968). It is assumed, that the impact occurs at normal direction to a rigid target. The airplane fuselage is considered as a rigid-plastic bar with distributed mass $\mu(\xi)$ and ultimate crushing force (buckling load) $P(\xi)$ distributed over the length ξ. The load on target is calculated then as follows:

$$R(t) = P[\xi(t)] + \dot{\xi}^2(t)\mu[\xi(t)]. \qquad (1)$$

As shown by Birbraer (2009) an inverse function to the function $\xi(t)$ can be calculated as follows:

$$t(\xi) = \int_0^{\xi} \frac{d\eta}{\sqrt{v_0^2 - 2F(\eta)}}, \qquad (2)$$

where v_0 is the airplane initial impact speed;

$$F(\xi) = \int_0^{\xi} \frac{P(\eta)d\eta}{m_a - m_1(\eta)}, \qquad (3)$$

where m_a is the airplane total mass; $m_1(\xi)$ is the mass of crushed fuselage part:

$$m_1(\xi) = \int_0^{\xi} \mu(\xi)d\xi. \qquad (4)$$

Inversing $t(\xi)$, the function $\xi(t)$ can be found and then the dependencies $P[\xi(t)]$, $\mu[\xi(t)]$ and $m_1[\xi(t)]$. The velocity $\dot{\xi}(t)$ is calculated by differentiation of integral in equation 2:

$$\dot{\xi}(t) = \left(\frac{dt}{d\xi}\right)^{-1} = \sqrt{v_0^2 - 2F(\xi(t))}. \qquad (5)$$

Substitution the found functions in equation 1 yields the variation of the load R(t). For Boeing 720 aircraft Riera provides mass and crushing force distribution over the length of the fuselage considering fuel loss, engines and wing tips separation. Using this data the equations 2 – 5 are provide solution of equation 1 which matches well with the results obtained by Riera for Boeing 720 in (1968) (see figure 1).

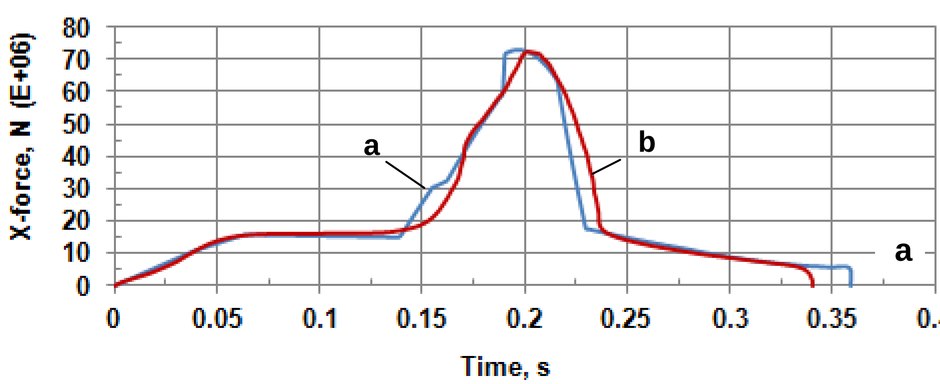


Figure 1. Boeing 720 impact force: a – calculated by proposed method, b - Riera solution (1968)

In order to get impact load for Boeing 747-400 the initial Boeing 720 data was scaled using coefficients obtained from Boeing 720 and 747-400 dimensions comparison: k_l = 1,73 for length and crushing force scaling; k_m = 3,82 for scaling of distributed mass $\mu(\xi)$. The resulting force curves for initial impact velocity 100 m/s and 150 m/s are presented in figure 6 (curves "Riera 100 m/s" and "Riera 150 m/s") compared with proposed below FEM solution. Also the resulting maximum force values for initial impact velocity 200 m/s matches well with force curve peaks shown in Blandford (2009).

ALE METHOD FOR AIRPLANE CRASH MODELING

Method description

Arbitrary Lagrange Euler (ALE) method, developed with the collaboration of the authors in the LS-DYNA software, and described in detail in Souli et al (2012), uses numerical scheme with analysis divided into two phases for each time step. First a Lagrangian phase is performed, in which the mesh moves with the material, in this phase the changes in velocity due to the internal and external forces are calculated. During the second phase advection step is performed, in which the mesh moves back to initial position and material moves through mesh cells. The method is very robust for computation of large structural deformations like fluid motion or bullet crumple.

The LS-DYNA material model #26 (see LSTC (2012), honeycomb and foam material) was used for aircraft crash behavior simulation. The calculation was performed in multi-material ALE formulation with different honeycomb materials used for airplane modeling and material #3 (null material) used for surrounding air simulation. The material #26 is controlled by load curve which describes material compression behavior. The load curve shape used in this analysis has tree specific values σ_y , σ_c and ε_{vc} presented in figure 2.

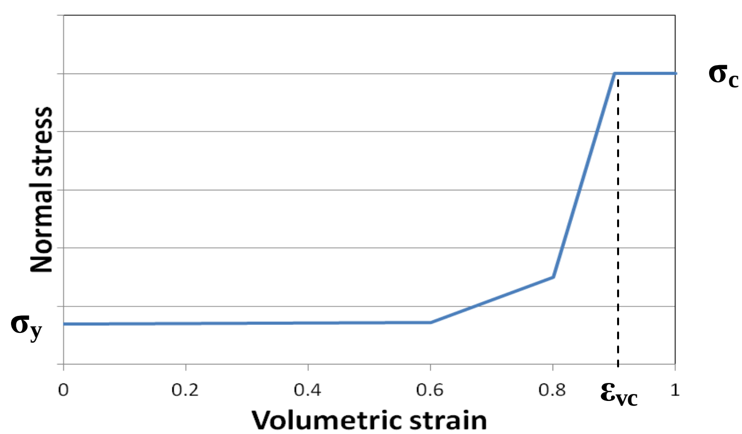


Figure 2. Load curve for material #26

The value of σ_y can be found from equation $\sigma_y = P_C / A$ where P_C is fuselage crushing force, A is fuselage cross section area. The parameter ε_{vc} is volumetric strain for fully compressed material which value can be obtained from volume of all uncompressible fuselage parts like metal sheets, beams and solid plastic parts divided by the total fuselage volume. The variable of σ_c is yield stress for fully compacted material which value was obtained by test calculations.

Method verification with test model

In order to test proposed approach an example on crushed cylindrical bar was prepared. The test bar has the following properties: diameter 7.2 m, length 60 m, averaged density 50 kg/m^3, bar crushing stress 0.6 MPa, initial impact velocity 100 m/s. The FE model material data is presented in table 1 and the corresponding load curve for description of crushing force is given in table 2. All other material data was set by LS-DYNA as default.

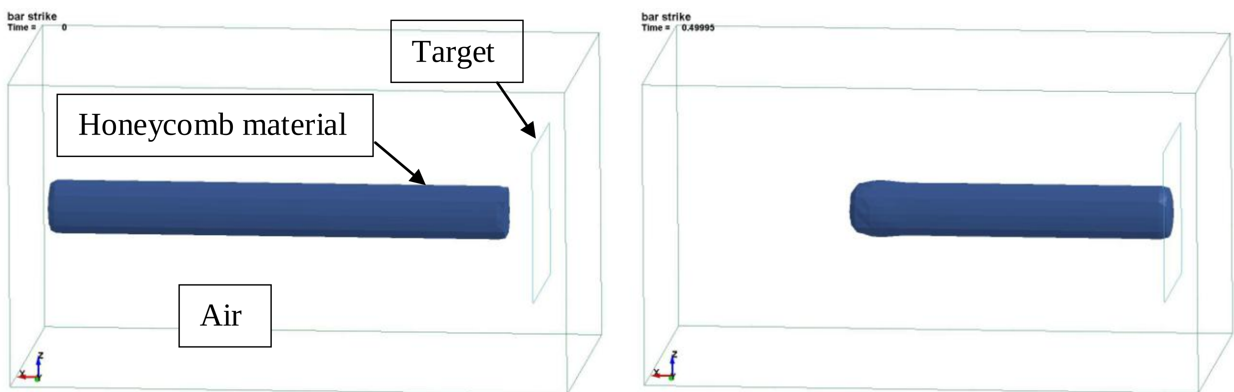
Table 1: Material data for test example

Parameter	RO	E	PR	SIGY	VF
Unit	kg/m^3	MPa	-	MPa	-
Value	50	1000.	0.4	2.0	0.02

Table 2: Load curve definition

Volumetric strain	Stress (MPa)
0.00	0.60
0.90	0.62
0.95	0.90
1.00	2.00

The FE model has volumetric mesh containing 116800 cubic elements of 1 m edge size. The picture of generated volume fraction filled with honeycomb material is shown in figure 3. Remain part of volume is filled with material modeled surrounding air.



Initial position   Position by the end of impact, time 0.5 s

Figure 3. ALE model of crushed test bar, volume filled with honeycomb material

During the calculation the material is compressed nearby the impact zone. Therefore the bar becomes shorter (figure 3 right) and the material density is increased (figure 4). The performed calculation matches well with results obtained by Riera approach. Remained after impact bar length obtained by Riera approach counts 39.6 m, the final bar length calculated with proposed ALE model is 42.5 m. Obviously, the difference is caused by finite depth (approx. 2 m, figure 4) of compressed material volume, which is neglected in Riera approach. However, the calculated impact force is similar for both calculations (figure 5). The initial distance between the bar and the target in model is 4.5 m, so the true impact will begin at 0.045 s calculation time. It is interesting, that according ALE computation the impact force arises before that time. This is result of aerodynamic forces acting on the target due to airflow induced by the moving bar.

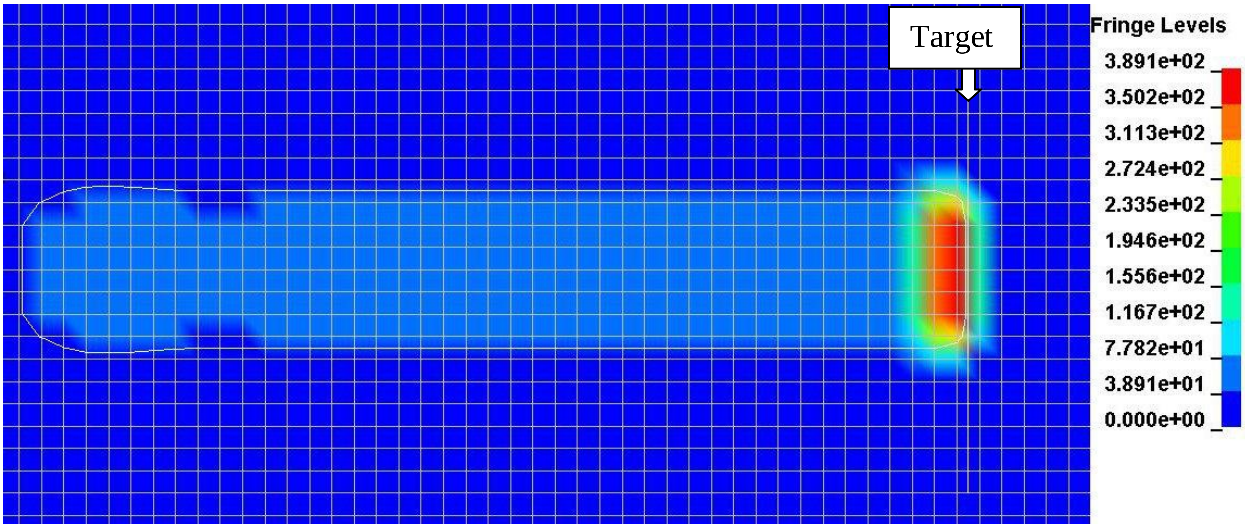


Figure 4. Test bar material density distribution (kg/m^3) by the end of impact, time 0.5 s

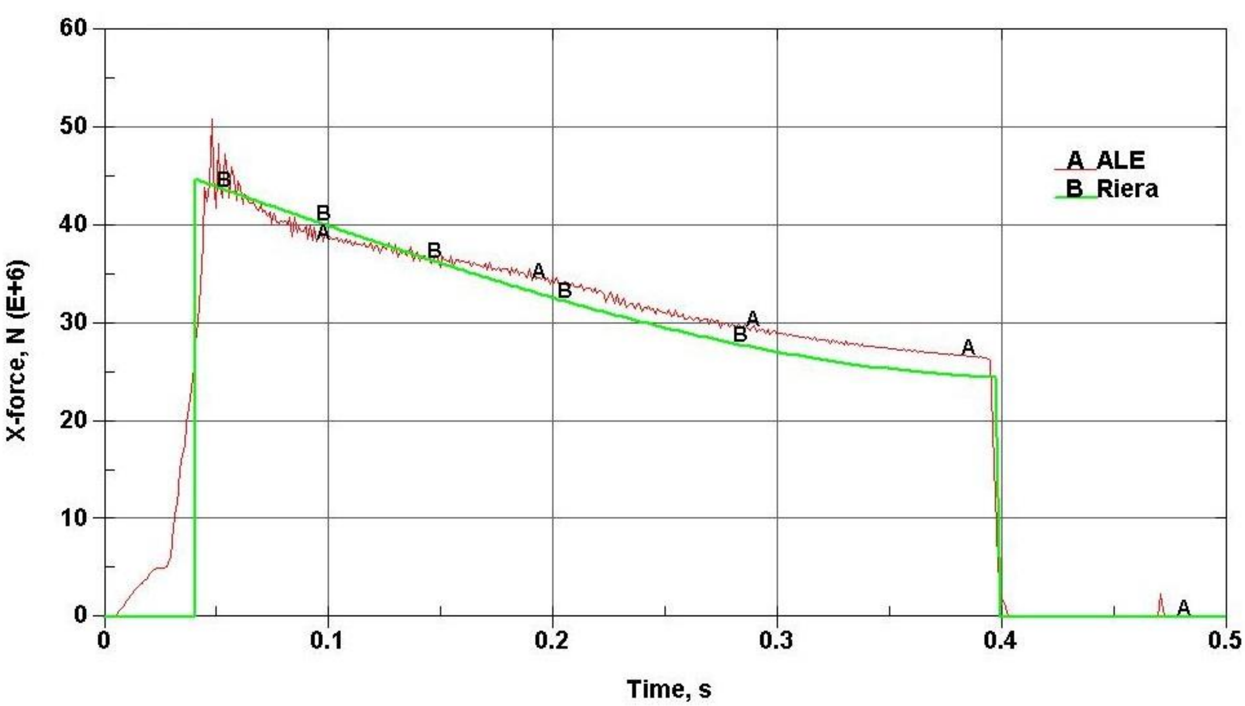


Figure 5. Impact force (N) for crushed test bar

AIRPLANE CRASH MODEL

Model description

Described above modeling technique was used for airplane crash simulation. Similar to the Riera approach it is assumed that the engines and wing tips will be separated and are not considered in the calculation. The main dimensions of the simplified airplane geometry are shown in figure 6.

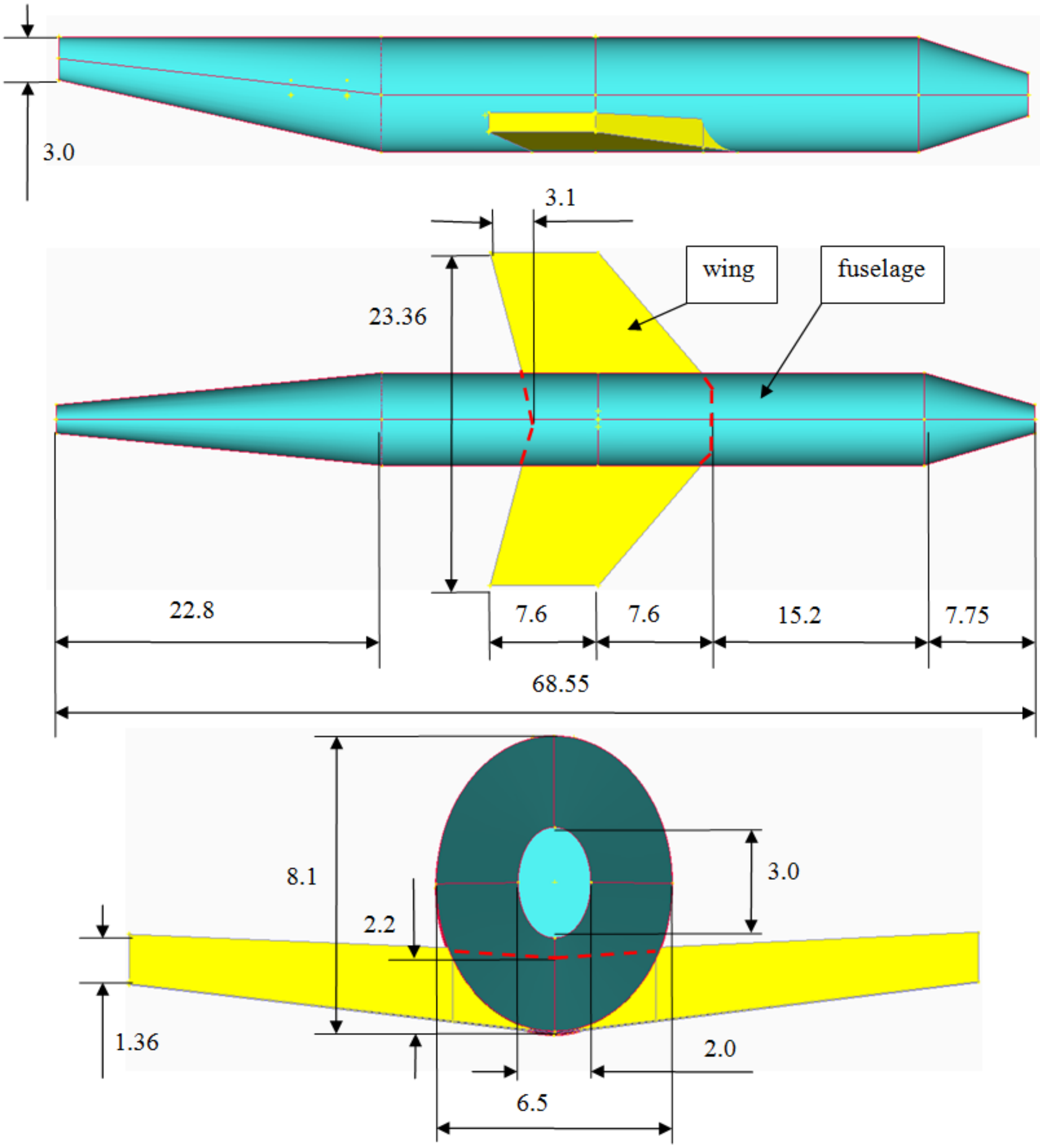


Figure 6. Dimensions of large airplane simplified model, m

The calculation domain consists of 132800 cubic elements. The aircraft fuselage and middle part of the wing are presented by separate materials. The 'wing' part contains many heave and strong parts (e.g. fuel tanks and gears) therefore material data for 'wing' has heavier density and crushing stress as shown in table 3.

Table 3: Material data for airplane crash model

Parameter	RO	E	PR	SIGY	VF	LCA	MU	Eu	Gu
Unit	kg/m^3	MPa	-	MPa	-	-	-	MPa	MPa
material data for fuselage	70	200	0.4	2.0	0.025	1	0.01	778	500
material data for wing	270	200	0.4	2.0	0.050	2	0.01	1000	500

The corresponding material curves (LCA) for both materials are presented in table 4. The total mass of the airplane model calculated by cells filled with honeycomb material is 248 t.

Table 4: Load curves definition for airplane crash model

LCA=1		LCA=2	
Volumetric strain	Stress (MPa)	Volumetric strain	Stress (MPa)
0.00	0.07	0.00	7.50
0.60	0.072	0.01	7.50
0.8	0.20	0.05	0.80
0.92	0.50	0.60	0.82
0.945	1.00	0.8	0.90
0.975	2.00	0.9	3.00
1.00	2.00	0.948	6.00
		0.95	8.00
		1.00	8.00

Calculation results

The calculations were performed for the airplane impact against rigid target for three initial speeds 100 m/s, 150 m/s and 200 m/s. The calculated resultant impact force is presented in figure 7 (curves A, C and E) compared with results obtained by Riera approach described above (curves B, D and F).

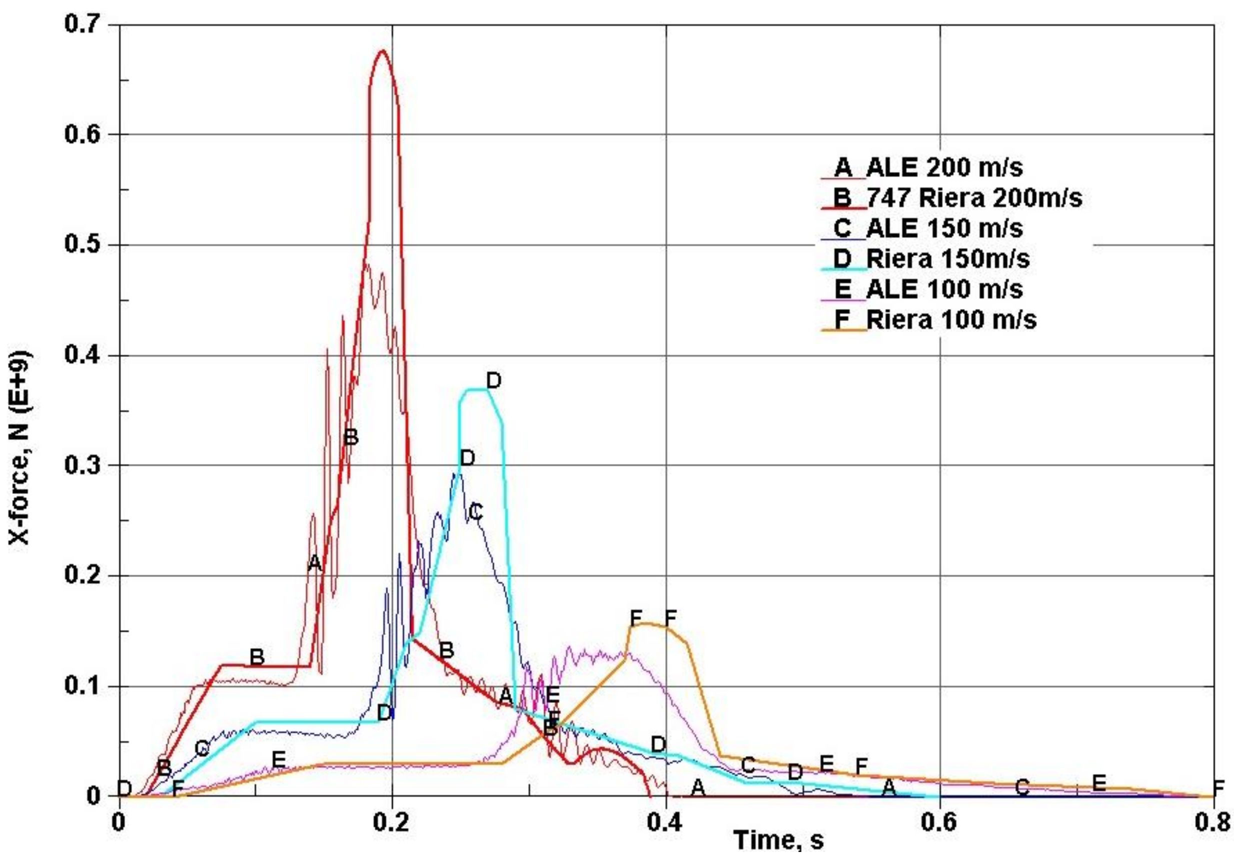


Figure 7. Calculated impact force

Figure 8 presents development of airplane crushing for initial speed of 150 m/s. Honeycomb material becomes compressed during the analysis, the final value of maximum density arrives 2086 kg/m^3, i.e. the density is close to the density of fully compacted aluminium alloy (figure 9).

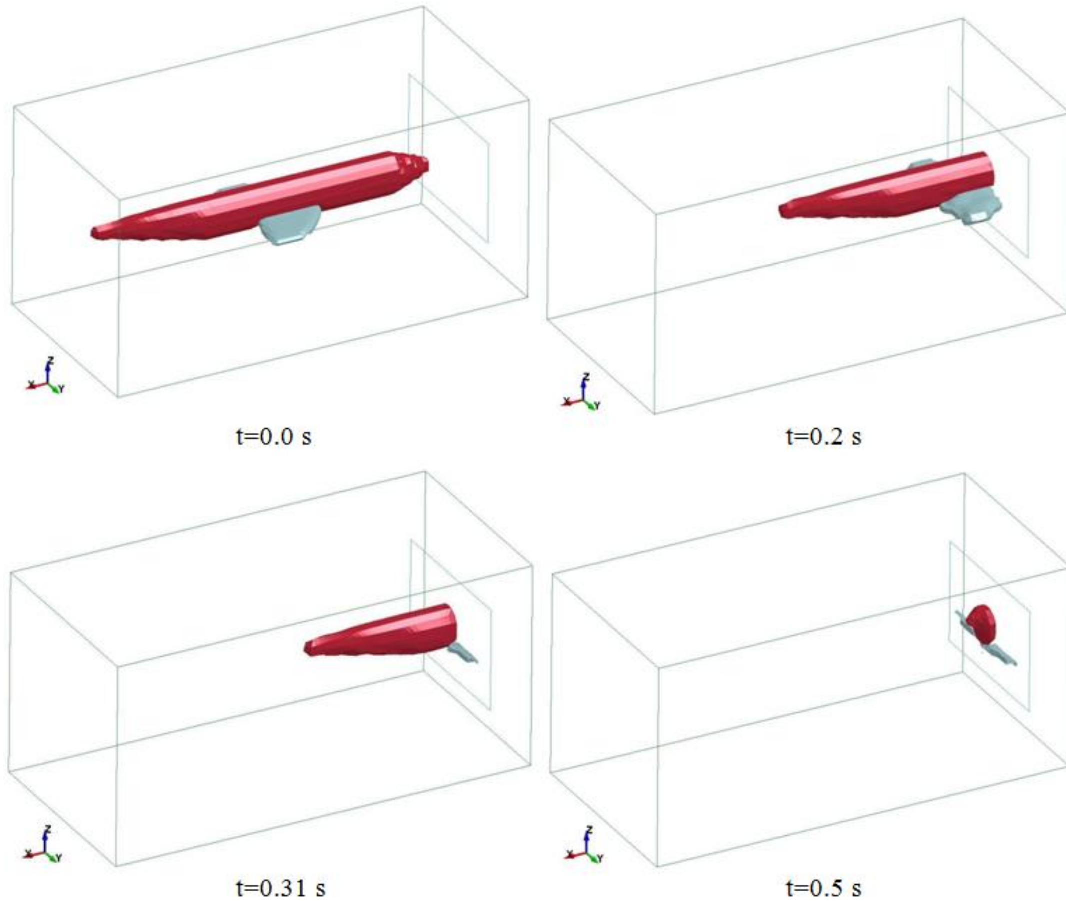


Figure 8. Airplane model shape at different calculation time, initial velocity 150 m/s.

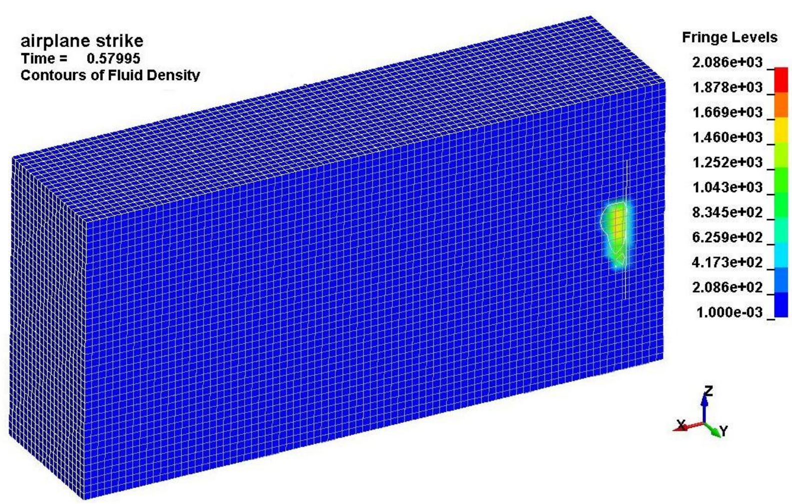


Figure 9. Material density distribution by the end of impact.

The calculation was performed for rigid target, but the proposed method allows running coupled calculation for airplane crushing and building structure response.

Since the ultimate objective is the design of structure resisting high impact, numerical simulations can be included in shape design optimization with shape optimal design techniques Souli et *al* (1993), Zuhal et *al* and material optimization Erchiqui et *al* (2007). Once simulations are validated by test results, it can be used as design tool for the improvement of the system structure being involved.

CONCLUSION

Load on the structure caused by the large airplane crash can be simulated with the proposed modeling method. Thereby the airplane structure is modeled with ALE finite element formulation with a honeycomb material. The proposed method gives results close to the analytic Riera approach considering airplane fuselage crushing force and momentum induced force using the same simple airplane data which is necessary for Riera calculation. However the advantage of proposed method is that the load calculation can be simply performed for geometric complex buildings and for different crushing scenarios.

REFERENCES

Birbraer A.N., Roleder A.J. (2009). "Extreme Actions on Structures," - *Publishing House of the Saint Petersburg Politechnical University*, pp. 219-222

Birbraer A.N., Volkodav I.A. (2008). "Loads on Structures due to Crashing Missiles Impact," *Earthquake engeneering. Safety of structures*, №2, pp. 53-57

Blandford E., etc. (2009). "Advanced seismic base isolation methods for modular reactors", UCBTH-09-004, *Departments of Civil and Environmental Engineering and Nuclear Engineering University of California, Berkeley, California*, p. 43

Byeong Moo Jin, Yun Seok Lee, Se Jin Jeon, Young Jin Kim, Yong Ho Lee (2011). "Development Of Finite Element Model Of Large Civil Aircraft Engine And Application To The Localized Damage Evaluation Of Concrete Wall Crashed By Large Civil Aircraft", - *Transactions SMiRT 21, Div-V: Paper ID# 862*

Erchiqui F., Souli M., Ben Yedder R. (2007). "Non isothermal finite-element analysis of thermoforming of polyethylene terephthalate sheet: Incomplete effect of the forming stage" - *Polymer Engineering and Science*, *Volume 47 Issue 12* , pp. 2129-2144.

LSTC (2012). "LS-DYNA® Keyword User's Manual. Volume II, Material Models", *Livermore Software Technology Corporation*, pp. 144-151

Ozdemir, Z., Souli, M., Fahjan, Y. M. (2010). "Application of nonlinear fluid-structureinteraction methods to seismic analysis of anchored and unanchored tanks", - *Engineering Structures, Volume: 32 Issue: 2,* pp: 409-423

Riera J.D. (1968). "On the Stress Analysis of Structures Subjected to Aircraft Impact Forces", - *Nuclear Engineering and Design, Vol.8,* pp. 415-426

Siefert A., Henkel F.-O. (2011). "Nonlinear Analysis Of Commercial Aircraft Impact On A Reactor Building – Comparison Between Integral And Decoupled Crash Simulation", - *Transactions SMiRT 21, Div-III: Paper ID# 144*

Souli, Mhamed; Gabrys, Jonathan. (2012). "Fluid Structure Interaction for Bird Impact problem, Experimental and Numerical Investigation", - *Computer Methods in Engineering and Sciences, CMES, Vol 85 Issue: 2,* pp. 177-192

Souli M., Zolesio J.P. (1993). "Shape Derivative of Discretized Problems" - *Computer Methods in Applied Mechanics and Engineering 108,* pp. 187–199

Sugano, T., H. Tsubota, Y. Kasai, N. Koshika, S. Orui, W.A. von Riesemann, D.C. Bickel, M.B. Parks.(1993) "Full-Scale Aircraft Impact Test for Evaluation of Impact Force." - *Nuclear Engineering and Design. Vol. 140.* pp. 373–385