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Expansion of the Riera Approach for Predicting Aircraft Impact Damage to Steel and Concrete Buildings
Part 2 –Simplified Analysis Methodology

Steven W. Kirkpatrick and Robert T. Bocchieri

Applied Research Associates, Inc.
2672 Bayshore Parkway, Suite 1035, Mountain View, CA 94043, USA
e-mail: skirkpatrick@ara.com

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1. ABSTRACT

The Riera model (1968, 1980) for applying aircraft impact loads is typically used to evaluate the response of a relatively rigid, non-responding uniform structure, such as strongly reinforced nuclear reactor containment buildings. More recently, for more complex geometrical structures that sequentially fail during impact, modern finite element codes have been used to model both the aircraft and building, such as was done in the Federal Building and Fire Safety Investigation of the World Trade Center Disaster (Kirkpatrick, et al., 2005, 2006). This detailed modelling approach provides the ability to analyze these complex events, but at a high computational cost. In order to conduct studies with a broad scope, considering a range of building types and aircraft impact scenarios, a fast-running computational tool is needed.

Here the Riera approach is expanded to consider impacts on weaker and more general building designs, such as those of typical steel and concrete frame construction. With this approach, loads from multiple segments of an aircraft are applied to a complex geometrical structure through use of ray tracing algorithms. Penetration of the aircraft segments through a failing structure, and through non-structural mass inside of these structures, is included.

2. INTRODUCTION

Impacts of aircraft on nuclear power plant (NPP) facilities have long been a safety consideration. Since September 11, 2001 this concern was heightened with increased awareness that an aircraft could be used in an intentional attack on a NPP. This resulted in a recent decision by the U.S. Nuclear Regulatory Commission (NRC) that applicants for new power reactors must assess the ability of their NPP facilities to avoid or mitigate the effects of a large commercial aircraft impact (U.S. NRC, 2009).

The impact of a large commercial aircraft on a structure involves many different physical mechanisms. The aircraft applies loads on the structure both through the inertial loading from the deceleration of the aircraft mass and the effects of the structural strength as the aircraft crushes against the building structures. Depending on the strength of the impacted structure, there will be failures of the building exterior components and the remaining aircraft structures and debris will propagate into the building interior resulting in subsequent impacts with interior structures.

Historical analyses of the effects of an aircraft impact required methods to approximate the impact loads applied on the structure. The most common approach to assess aircraft impact loads is to use the Riera model (1968, 1980). This model calculated the total force of an impacting soft object on a rigid target, as shown in Figure 1. In this model, the projectile behaves as a rigid object outside a small deformation zone at the interface with the rigid structure. Riera derived an equation for the total reaction force on the target,

$$F_x(t) = P_c[x(t)] + \mu[x(t)]V^2(t) \tag{1}$$

where P_c is the crush strength of the projectile and μ is the mass density of the projectile per unit length and V is the velocity of the remaining uncrushed portion of the aircraft. Thus, the load is the combination of the crushing forces and the inertial loading against the rigid target.

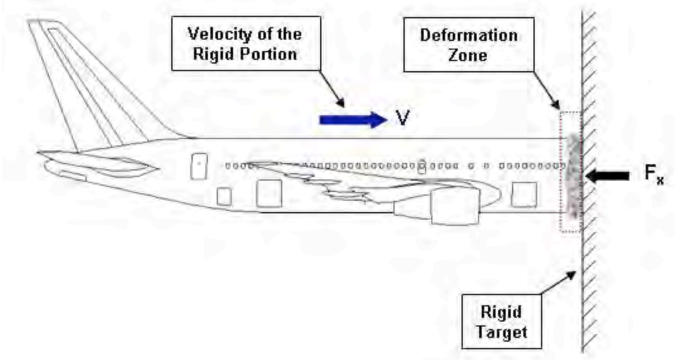


Figure 1. Model of an impinging soft projectile and target reaction forces.

Full scale impact testing has shown that the Riera model provides a good estimate of the overall loading against a rigid structure (von Riesemann et al., 1989; Muto et al., 1989). The test impacted an F-4 Phantom fighter jet against an essentially rigid block of concrete at a speed of 215 m/s. Analysis of the tests demonstrate that for this type of high speed impact the inertial term in Equation 1 dominates the impact load and is roughly an order of magnitude larger than the contribution from the crush strength.

Typical applications of the Riera model have been to assess the capacity of the containment structures or other heavy NPP structures to withstand an aircraft impact loading (e.g. Riera et al., 2003; Kukreja et al., 2003; Dundulid et al., 2005). For these applications, the structures being impacted have relatively simple geometries and can be approximated as semi-rigid, making the use of the Riera model appropriate. The primary effects that will be missed by this analysis methodology are the detailed local impact effects of individual heavy or strong objects such as the engine, landing gear, and wing spar components. However, if the impacted structure is sufficiently strong and thick to withstand these localized impacts the overall distributed loading will be captured.

More recently, advances in computers and finite element codes have progressed to the point where the detailed aircraft impact response can be accurately simulated. This approach can be used for a much greater range of aircraft impact scenarios and buildings and is explored in a companion paper (Kirkpatrick and Bocchieri, 2009). This methodology provides the highest level of fidelity for assessing aircraft impact damage when properly applied. However, the necessary model development procedures and analyses can also be relatively expensive and time consuming. Thus, for many applications, a more efficient engineering level analysis methodology is needed.

This paper describes the development of an engineering aircraft impact analysis methodology as well as its implementation in a computer code and coupling to the computer code BAM (Building Analysis Module). This methodology uses the approach developed by Riera for applying impact loads, but expanded to consider impacts from multiple segments of the aircraft on a complex structure as well as penetration through the failing structure and non-structural mass inside of buildings. Finally, validation studies of the simplified aircraft impact methodology are described.

3. SIMPLIFIED AIRCRAFT IMPACT ANALYSIS METHODOLOGY

The Riera approach for applying aircraft impact loads is commonly used to evaluate the response of a relatively rigid, non-responding uniform structure, such as strongly reinforced nuclear reactor containment buildings. However, the analysis methodology is not well suited to complex building geometries or impact scenarios where the building exterior is penetrated and the subsequent extent of damage propagating into the building interior is of interest. Here the Riera approach is expanded to consider impacts on weaker and more general building designs, such as those of typical steel and concrete frame construction. With this approach, loads from multiple segments of an aircraft are applied to a complex geometrical structure through use of ray tracing algorithms. Penetration of the aircraft segments through a failing structure, and through non-structural mass inside of these structures, is included.

The analysis methodology developed resulted in the programming of an aircraft impact module (AIM) that applies aircraft impact loads to the computer code BAM (Building Analysis Module). BAM is an accredited engineering tool developed to evaluate conventional weapon effects on buildings due to internal and external detonations (JTCG/ME 2006). The resulting computational tool (AIM/BAM) provides a means for performing rapid assessments of impact damage for a wide variety of impact scenarios and standard building types. A methodology was also developed to quickly generate the input parameters for a wide array of aircraft based on geometrical simplification of the aircraft structure and knowledge of similar aircraft weight distributions.

Several modifications were made to BAM to account for different building component failure modes unique to aircraft impacts. The changes added specific component failure modes anticipated for aircraft impact loads that have not been considered in blast response. The additional failure modes added to BAM were: (1) shear failure modes for localized loading on structural columns and beams of framed structures; and (2) breach of columns, beams, walls and floors of framed structures. In addition, a feature was added to track the effects of the non-structural building components (e.g. office furnishings). The non-structural mass has been shown to have a significant effect on the distance that an aircraft can penetrate into a building and produce impact damage.

To define the attributes of a given aircraft in the Aircraft Impact Module (AIM), a simplified aircraft geometry as well as the strength and mass of the primary aircraft parts are defined. The approach used to define the geometry of an aircraft is shown in Figure 2. The fuselage, nacelles, and engines are approximated as cylinders or tubes. The engines are solid cylinders, while the nacelles and fuselage are tubes. Contents for the fuselage are modelled as a solid cylinder inside the fuselage. The wings, fuel and empennage are treated as general trapezoids. Each of the primary aircraft components is given both a mass density and strength. The mass density and strength could in reality vary along the length of a given component (e.g., more mass in the front of the fuselage than in the aft section), but here it has been modelled as being uniformly distributed in each component.

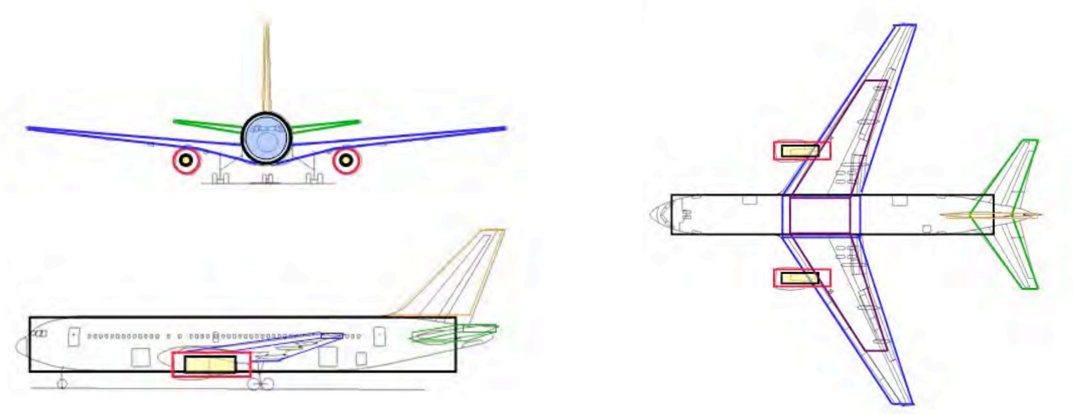


Figure 2. Aircraft component geometry definition.

After the characteristics of the aircraft and the impact trajectory are defined, a ray-tracing algorithm is used to discretize the aircraft components into segments and determine which segments strike which building components. The potential path for each segment is traced through the building to identify building components that may be impacted. This methodology is demonstrated in Figure 3.

When aircraft segments impact building structural members they are crushable while the building structural components are considered as rigid, until they fail. The Riera model for an impacting soft object on a rigid target is used to define this impact response. The total reaction force on the target, derived by Riera, was provided in Equation 1. This equation for the impact forces is used here, but applied separately for each segment of the aircraft.

For aircraft segments impacting the non-structural mass in the building, the amount of penetration through this mass, as well as the amount of crush and the loads on each segment, need to be calculated. These were approximated in AIM through the use of the so called “fluid jet model” for long-rod penetration (Zukas, 1990).

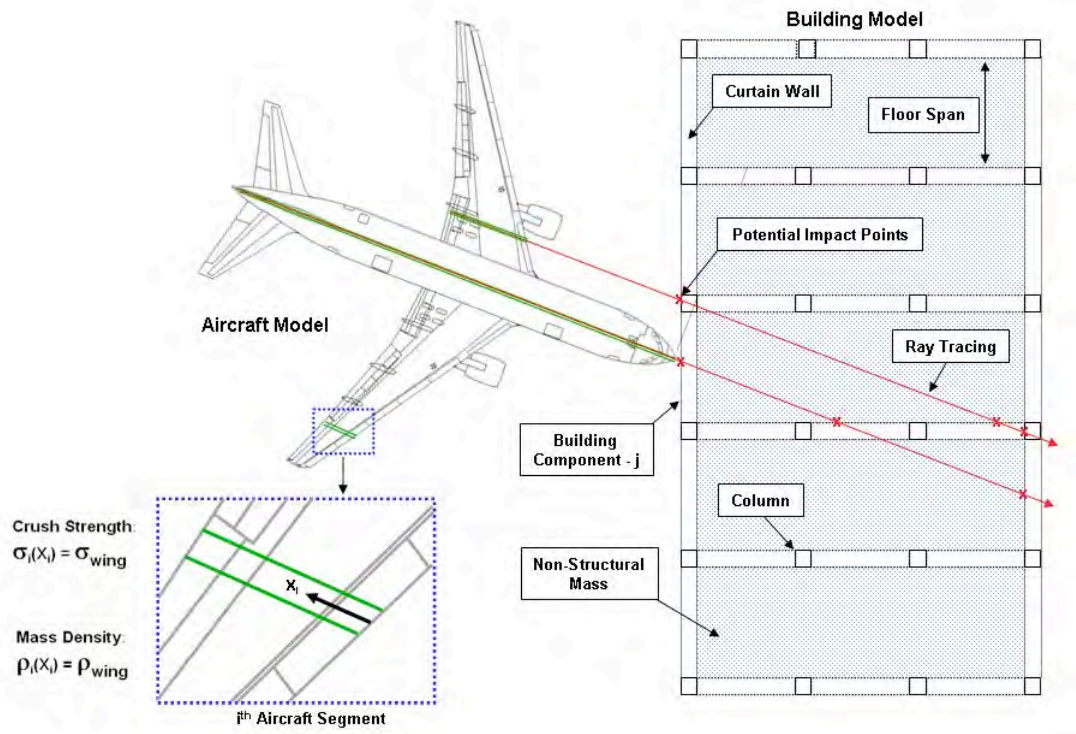


Figure 3. Discritizing the Aircraft into Segments Impacting Building Elements.

When aircraft segments are penetrating the non-structural mass in the building, both the force exerted on the segment and the speed of penetration are needed to calculate the total forces on the aircraft and its degree of penetration in the building. As the aircraft is being eroded, it is being decelerated. The so called “fluid jet model” for long-rod penetration of a homogeneous material at high velocity derives the flow pressure at the stagnation point between the two materials from Bernoulli’s theorem. The pressure can be defined as

$$P(t) = \frac{1}{2}\rho_p\left[V(t) - U(t)\right]^2 = \frac{1}{2}\rho_t U^2(t) \qquad (2)$$

where V is the rod speed, U is the speed of penetration, and ρ_p and ρ_t are the densities of the rod and target, respectively. The speed of penetration is then

$$U(t) = \frac{V(t)}{1 + \sqrt{\rho_t/\rho_p}} = \frac{V(t)}{1 + \mu} \qquad (3)$$

where $\mu = \sqrt{\rho_t/\rho_p}$.

Equations (2) and (3) neglect the strengths of the impacting rod and target materials. This approximation has been found to be accurate for conditions with either high velocities or low strength materials. From Equation (2), the force exerted by the rod on the target is

$$F(t) = a_p\left(\frac{1}{2}\rho_p\left[V(t) - U(t)\right]^2\right) \qquad (4)$$

where a_p is the cross-section area of the rod.

Equations (3) and (4) are now applied for each segment of the aircraft. One reason to neglect the crush strength of a segment and the building contents in calculating the speed of penetration is that the interior contents have an associated crush strength that may be comparable to that of the aircraft structures. Also, in the case of fuel segments, the segment is obviously a fluid and has no strength.

The above Equations 1 through 4 govern the mechanics of the aircraft impact and penetration behaviour implemented in AIM/BAM. The aircraft is divided into local segments, as shown in Figure 3, and the total impact response is solved incrementally using small time steps. When an aircraft segment is impacting a building structure, the aircraft segment is crushed at the current speed of the aircraft. When passing through the non-structural mass, the speed at which the segment is eroded is the difference between the speed of penetration, $U(t)$, and the speed of the aircraft, $V(t)$.

The total reaction force on the aircraft is a sum of all the individual impacts of the aircraft segments. When impacting a building component the reaction force is governed by the segment crush strength. When passing through the non-structural mass, the reaction force is the lesser of the crush strength and the interface pressure defined by Equation (3). The total combined force in each time step can be used to determine the deceleration of the aircraft based on the remaining mass of the uncrushed structures.

Initially this methodology applies to the entire aircraft when it is intact. As the aircraft is ultimately broken into separate components, the individual reaction forces and velocities are calculated for the fuselage/empennage, port and starboard wings, port and starboard fuel, and port and starboard engines/nacelles. Simple methods were used to ‘breakup’ the aircraft components. This is important so that the aircraft decelerates properly and so components (such as fuel and engines) are free to propagate into the building. Upon first impact of the fuselage with a building element, the entire aircraft is decelerated uniformly. When the wings, engines, nacelles, and fuel impact building elements, they are ‘released’ from the other components and are decelerated separately. To ‘release’ a component means that it is no longer decelerating with the remaining aircraft mass. The deceleration force is the sum of the crush strength of the aircraft segments impacting and crushing against building components.

In general for any segment, one could specify any piecewise function for the crush strength as a function of the crush distance. However, in the current development of AIM a constant value was assumed for all segments of each component of the aircraft. The crush strengths for the aircraft components were estimated based on the crush forces seen in rail vehicles as well as results from the high-fidelity analysis of the Boeing 767 impacts with the WTC towers. Some passenger rail vehicles have an internal frame construction with a riveted outer skin similar to that of the fuselage in many aircraft. A recent study performed crash tests of this type of rail vehicle against a rigid wall and measured the crush force at approximately 500,000 lbf (2224 kN) (Kirkpatrick, and MacNeill, 2002). If one considers this structure as roughly analogous to that of the fuselage of a large commercial aircraft, such as a Boeing 767 (MTOW of 345,000 pounds or 156.5 Mg), this force would provide an initial deceleration to the aircraft of approximately 1.5g.

Results from the dynamic finite element modelling of the Boeing 767 impacting the WTC towers were also used to provide some estimate of aircraft component crush strength (Kirkpatrick, et al. 2005). In this analysis, the aft end of the aircraft decelerated at approximately 3 to 3.5g while the fuselage forward of the wings is impacting the building.

Based on these data, the aircraft fuselage models in AIM were given two crush strengths. A lower bound that decelerates the initial MTOW of a given aircraft at 2g was selected, and an upper bound providing 4g of deceleration. The wings, which are a fairly strong component of an aircraft and have approximately the same structural weight as the fuselage for most aircraft types (Roskam, 1989), were given crush strengths that would also provide 2g and 4g decelerations of the MTOW. The empennage, a much lighter-weight structure than the wings although of similar construction, were given crush strengths of half that of the wings. Engines, which are much stronger structures, were given crush strengths roughly two orders of magnitude higher than that of the fuselage and wings.

To assess whether a building structural component failed at the end of a time step, the forces from all aircraft segments impacting that component were summed and used in the component failure algorithms existing in the Building Analysis Module (BAM). Once the impacted building structural components have accumulated sufficient loading to fail, they are removed from the analysis and the residual aircraft segments can propagate further into the building interior to load subsequent components.

When not impacting a structural component, all aircraft segments within the building are penetrating through the non-structural mass, and are consequently eroded by this mass, which simultaneously slows down the aircraft. Non-structural contents are all of the contents of the building that have very little strength compared to the primary building structure. Examples of these items include interior office partitions, HVAC and fire fighting systems, and general building contents such as workstations, file cabinets, and archives. The inertial effects of this mass, although it has little strength, can have a significant effect on slowing down the aircraft as it passes through the building. There is surely a significant variation in these contents and their distribution throughout a building. For simplicity, and in conformity with the generic nature of the building models developed for BAM, it was decided to represent these building contents as being uniformly distributed from floor to ceiling and from front to back wall throughout a building.

A limitation of the current AIM algorithms is that they do not account for any redirection of aircraft segments. This assumption can introduce errors if there are significant dive angles where redirection of aircraft debris can occur due to the floor structures of the building. Although loading for the initial impact on the floors should be reasonably accurate, the loading on subsequent structures would be incorrect. As a result, the application of AIM to date has been primarily using level flight conditions.

4. AIM VALIDATION

Validating AIM is complicated by the limited data available on aircraft impacts with buildings of steel frame and reinforced concrete construction similar to that used in this study. A considerable amount is known about the aircraft impacts with the World Trade Center (WTC) Towers. Several other collisions have occurred between aircraft and buildings but none of these have been as carefully analyzed and documented. Although the WTC Towers had a unique steel-framed building construction, the event provides the most suitable general aircraft impact and penetration event for validation of AIM. The ability of the model to predict the correct penetration of an aircraft into a building is important to assess the total damage for the progressive collapse potential and can be necessary for safety assessments if there are critical components in the building interior.

An approximate model of ten floors of WTC 1 was constructed using a customized version of the Smart Target Model Generator (STMG). This is the tool used to construct the generic building models for BAM. A model of a Boeing 767-200ER, with the appropriate amount of fuel and cargo as the aircraft which impacted the towers on September 11, 2001, were constructed using AIM and impacted with the building model. Results from the detailed aircraft impact analysis conducted as part of the Federal Building and Fire Safety Investigation of the World Trade Center Disaster were used for comparison (Kirkpatrick et al. 2005).

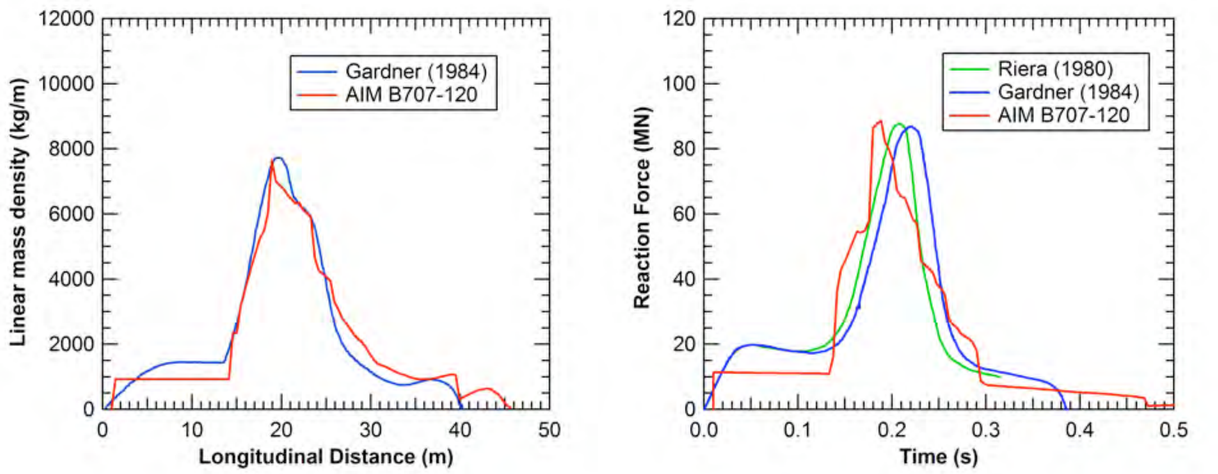
Before conducting these aircraft impact analyses, it is important to first verify that AIM can reproduce the aircraft impact loading traditionally used in evaluating Nuclear Power Plant Safety. The loading from a Boeing 707 as derived by Riera (1980) and Gardner (1984) is used for this validation.

Impact Load from a Boeing 707 on a Rigid Structure

AIM was first validated by comparing the aircraft loading of a Boeing 707 predicted with AIM against models traditionally used for assessing the safety of nuclear power plant structures. A model of a Boeing 707 was generated in AIM and impacted against a rigid wall. The linear mass density of the AIM aircraft model is compared to the linear mass density of a Boeing 707 as cited by Gardner (1984) in Figure 4(a). The correct linear mass density is important because the loading of an aircraft on a structure is dominated by the inertia of this mass, especially at high speeds. The comparison of the calculated reaction forces of the B707 impacting a rigid structure is shown in Figure 4(b). Overall, the peak reaction force and load duration are in good agreement. The primary differences are attributable to the assumed linear mass distribution used in AIM. The distribution of mass cited by Gardner places more mass in the forward fuselage than is represented in AIM. The reaction force predicted by AIM is therefore lower at short times for this specific aircraft.

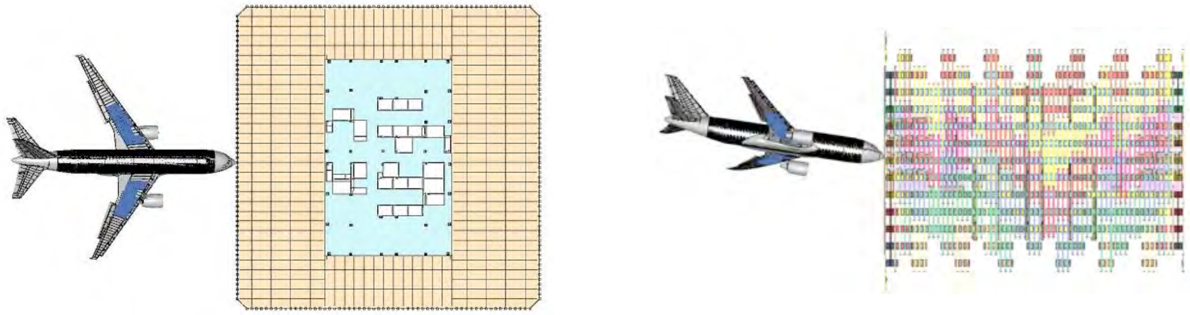
Boeing 767-200 Impact with the WTC Towers

The high-fidelity LS-DYNA model of the WTC Towers and the Boeing 767 used in the Federal Building and Fire Safety Investigation of the World Trade Center Disaster is shown in Figure 5. The position and orientation of the aircraft are shown just prior to impact. The aircraft that impacted WTC 1 and 2 had a nominal dive angle of 10.6 and 6 degrees, respectively. This dive angle complicates the analysis of these events using AIM/BAM because the current implementation of the AIM algorithm does not account for redirection of aircraft components by the floor slab, as happens in a dive. AIM should therefore under-predict the level of aircraft penetration as compared to that predicted from the high-fidelity modelling.

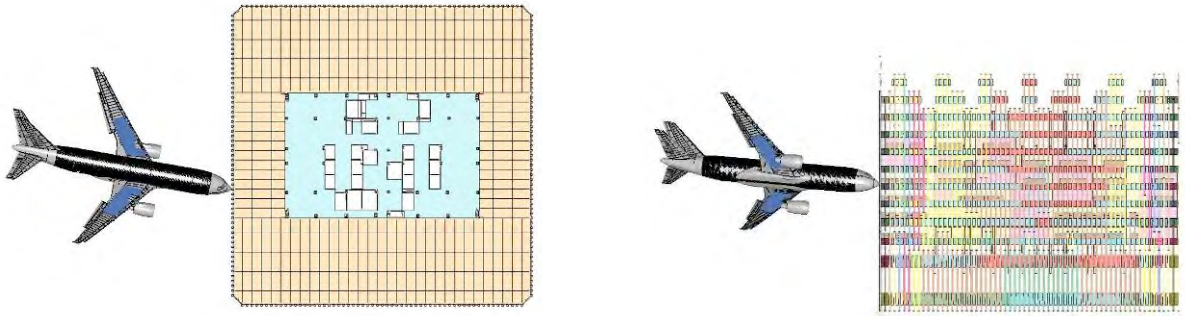


(a) Linear mass density approximations **(b) Impact reaction forces**

Figure 4. Comparison of Boeing 707 impact forces from AIM, Riera (1980), and Gardner (1984).



(a) WTC 1 plan view **(b) WTC 1 side view**

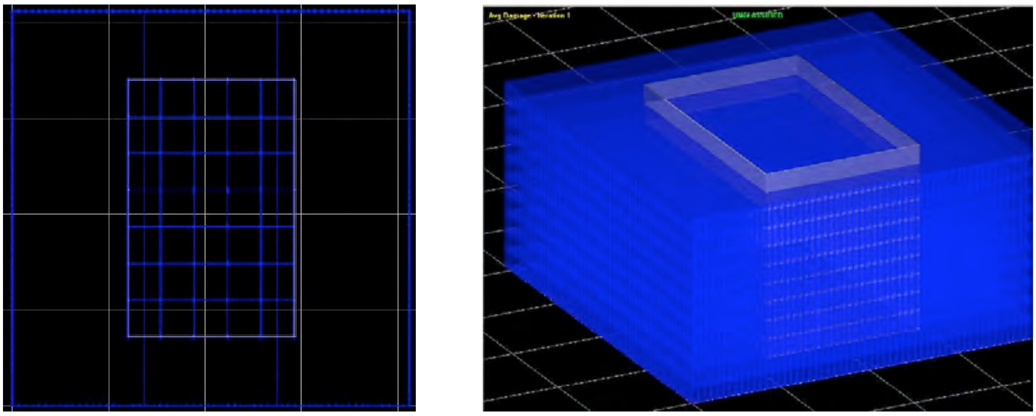


(c) WTC 2 plan view **(d) WTC 2 side view**

Figure 5. WTC tower and aircraft models showing the aircraft just prior to impact.

Ten floors of the unique steel-framed building construction representative of the WTC Towers were generated using the manual version of STMG. Average properties of the exterior and interior columns, floor beams and spandrels were used from the impact area of WTC 1 in constructing the model. The model geometry is shown in Figure 6. The model includes exterior box columns with the actual spacing used in the WTC Towers, interior core columns with the average spacing used, core floor beams between columns, barrier walls around the core, and a concrete slab spanning an entire floor. A uniformly distributed non-structural mass equal to the total non-structural mass in the high-fidelity analyses was included in the model.

Four impact analyses were performed on WTC 1 and 2, two with the actual dive angle and two with no dive. The aircraft model was run with the nominal crush strength (2g) and with a crush strength of twice this value (4g). All of the impact conditions analyzed with the high-fidelity modelling had a nonzero dive angle. However, the case with no dive angle is still useful to analyze since these impact conditions should be an upper bound on the actual penetration.



(a) Plan view **(b) Side view**

Figure 6. Model of a WTC Tower generated using STMG.

The normalized momentum of the aircraft that impacted the WTC towers were used to evaluate the impact and penetration results from the four approximate analyses. The comparison of the normalized aircraft momentum curves to the high-fidelity LS-DYNA results for the nominal WTC 1 impact conditions are shown in Figure 7. The figure shows that the LS-DYNA simulation shows the aircraft having no significant momentum after 0.6 s. In neither WTC tower impact did a significant portion of the aircraft exit the building.

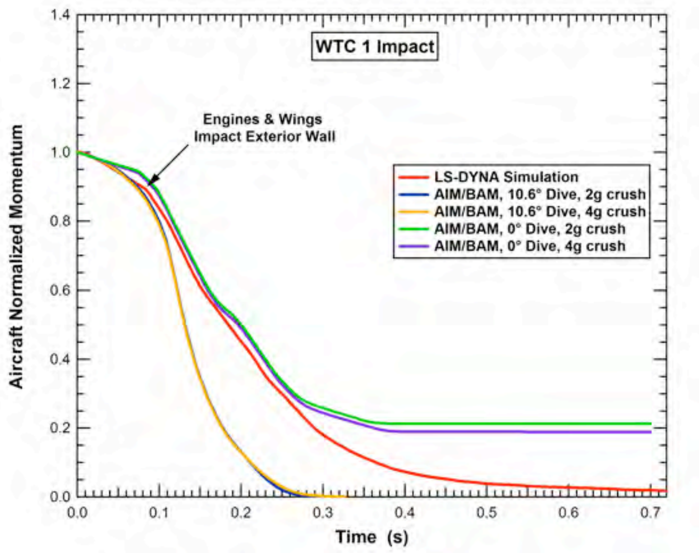
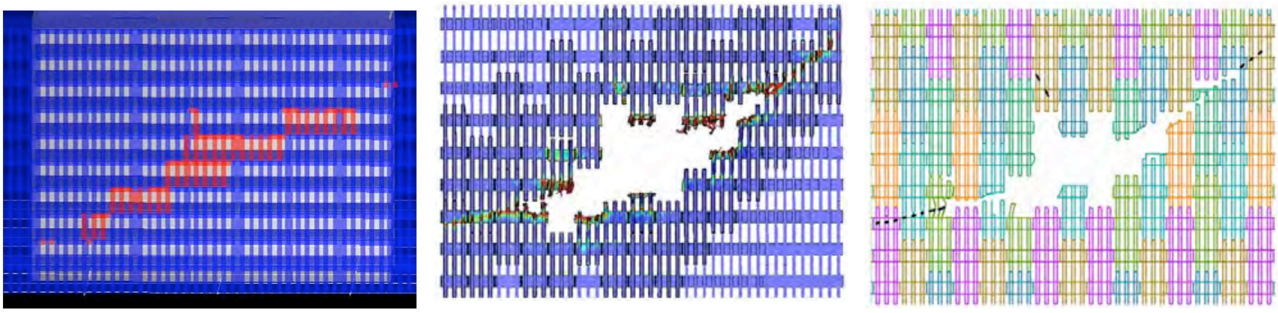


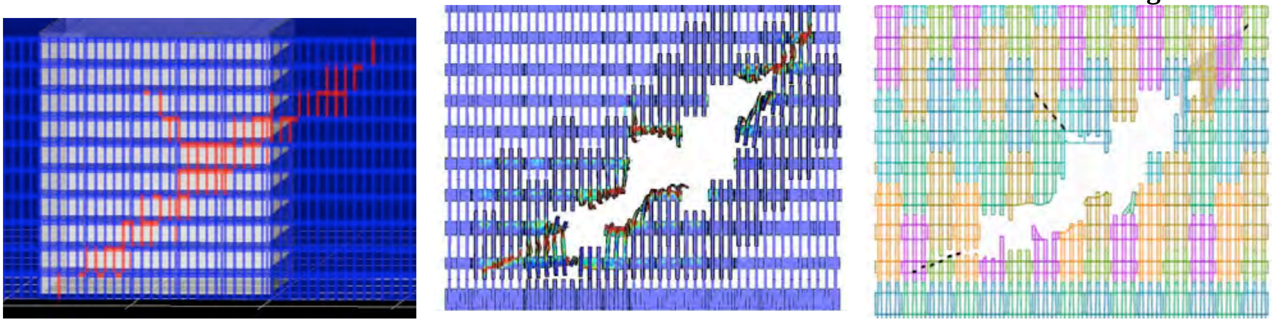
Figure 7. WTC 1 comparison of aircraft momentum.

As expected, the AIM/BAM analysis underestimates the degree of penetration for the actual dive angles, once again highlighting this limitation with the current loading methodology. This was expected since the penetration distance is largely determined by the geometry of the building and the angle of dive. The slices of each aircraft component will be brought to a halt once impacting a floor laterally, unless the floor fails. With no dive angle, the AIM/BAM analysis predicts greater penetration resulting in a significant portion of the fuselage exiting the back side of the building. Both analyses bound the LS-DYNA simulation result. That some of the fuselage should exit the building with no dive angle is also consistent with further results from LS-DYNA simulations where the dive angle was reduced by a few degrees and more of the fuselage debris exited the building (Kirkpatrick, et al. 2005).

Damage predicted to the impact face of the WTC towers is shown in Figure 8. For the AIM/BAM analysis, components in red indicate failure. The damage pattern predicted by AIM/BAM is compared in this figure with that from the high-fidelity LS-DYNA numerical simulations and that documented by high-resolution photography. The agreement is good, but not as accurate as the LS-DYNA simulation. The largest differences are due to the bolted joints on every third floor of the building columns, that were not included in the AIM/BAM analysis due to limitation in STMG. These joints resulted in entire three-story, three-column-wide panels to be removed from the exterior, as seen in the figure.



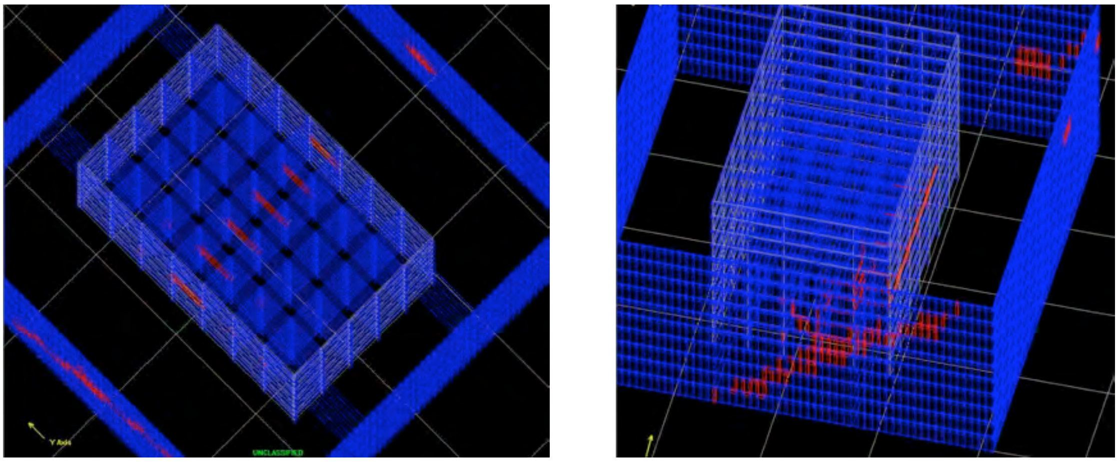
WTC 1 - AIM/BAM **WTC 1 – LS-DYNA** **WTC 1 Damage**



WTC 2 - AIM/BAM **WTC 2 – LS-DYNA** **WTC 2 Damage**

Figure 8. Damage to the impact faces of the WTC Towers.

Damage predicted form the AIM/BAM analysis to the interior of the Towers is shown in Figure 9. This damage provides a rough visualization of the penetration path through the building. In WTC 1, the fuselage and wings penetrated through the exterior. Little of the wings/fuel caused significant damage to the core, and only the fuselage penetrated deep into the core. This is consistent with the LS-DYNA simulation. Here, with no dive, the fuselage passed through the core and exited the back side of the building. The penetration through WTC 2 is similar except that the path was at an angle, passing through only the corner of the building core.



(a) WTC 1 – top view **(b) WTC 2 – top view**

Figure 9. Interior damage predicted for an impact with no dive angle.

5. CONCLUSION

A new Aircraft Impact Module (AIM) that calculates the loading applied on relatively rigid structures was developed and coupled with the Building Analysis Module (BAM) computer code. The resulting computational tool (AIM/BAM) provides a means for performing rapid assessments of impact damage for a wide variety of impact scenarios and standard building types. Validation of this code against existing engineering models and for the WTC Tower impacts yielded good agreement for these events.

6. REFERENCES

Dundulid, D., Kulak, R.F., Marchertas, A., Karalevicius, R., and Uspuras, E. 2005. Structural Integrity Analysis of an INPP Building Under External Loading. Transactions of the 18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18), Beijing, China.

Gardner, J.W. 1984. Calculation of the Forces Acting Upon a Rigid Structure from an Aircraft Impact. Int. J. of Impact Engineering, Vol. 2, No. 4, pp. 345-356.

JTCG/ME 2006. Joint Munitions Effectiveness Manual (JMEM) Weaponeering System (JWS) v1.1. Joint Technical Coordination Group for Munitions Effectiveness (JTCG/ME), 2006.

Kirkpatrick, S.W. and MacNeill, R.A. 2002. Development of a Computer Model for Prediction of Collision Response of a Railroad Passenger Car. Proceedings of the 2002 ASME/IEEE Joint Rail Conference, Washington, D.C. USA.

Kirkpatrick, S. W., Bocchieri, R. T., Sadek, F., MacNeill, R. A., Holmes, B. S., Peterson, B. D., Cilke, R. W., and Navarro, C. 2005. Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Analysis of Aircraft Impacts into the World Trade Center Towers, NIST NCSTAR 1-2B. National Institute of Standards and Technology, Gaithersburg, MD.

Kirkpatrick, S. W., Bocchieri, R. T., MacNeill, R.A., Peterson, B.D., and Sadek, F. 2006. Modeling Methodologies for Assessment of Aircraft Impact Damage to the World Trade Center Towers. Proceedings of the 9th International LS-DYNA Users Conference, pp. 9-53 through 67, Dearborn MI, USA.

Kirkpatrick, S. W., and Bocchieri, R. T. 2009. Expansion of the Riera Approach for Predicting Aircraft Impact Damage to Steel and Concrete Buildings: Part 1 – Detailed Numerical Impact Simulations. Proceedings of the 20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20), Espoo, Finland.

Kukreja, M., Singh, R.K., Vaze, K.K., and Kushwaha, H.S. 2003. Damage Evaluation of 500 MWe Indian Pressurized Heavy Water Reactor Nuclear Containment for Air Craft Impact. Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17), Prague, Czech Republic.

K. Muto, T. Sugano, H. Tsubota, Y. Kasai, N. Koshika, M. Suzuki, S. Ohrui, W.A. von Riesemann, D.C. Bickel, and R.L. Parrish 1989. Full-Scale Aircraft Impact Test for Evaluation of Impact Force - Part 2: Analysis of the Results. Transactions of the 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Anaheim, CA, USA.

Riera, J.D. 1968. On the stress analysis of structures subjected to aircraft impact forces. Nuclear Engineering.

Riera, J.D. 1980. A Critical Reappraisal of Nuclear Power Plant Safety Against Accidental Aircraft Impact. Nuclear Engineering and Design, Vol. 57, pp. 193-206.

Riera, J.D., Rios, R., and Iturrioz, I. 2003. Determination of the Load-carrying Capacity of a Reinforced Concrete Shell Subjected to Impact Loading. Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17), Prague, Czech Republic.

Roskam, J. 1989. Airplane Design, Part V: Component Weight Estimation. Roskam Aviation and Engineering Corporation, Ottawa, Kansas, USA.

U.S. Nuclear Regulatory Commission, 2009. SECY-08-0152 - Final Rule - 10 CFR Parts 50 and 52, Consideration of Aircraft Impacts for New Nuclear Power Reactors, February 17, 2009.

von Riesemann, W.A., Parrish, R.L. , Bickel, D.C., Heffelfinger, S.R., Muto, K., Sugano, T., Tsubota, H., Koshika, N., Suzuki, M., and Ohrui, S. 1989. Full-Scale Aircraft Impact Test for Evaluation of Impact Force - Part 1: Test Plan, Test Method, and Test Results. Transactions of the 10th International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Anaheim, CA, USA.

Zukas, J. A. 1990. High Velocity Impact Dynamics, New York, John Wiley and Sons, Inc.