RAPID EVALUATION OF BUILDING AND INFRASTRUCTURE TO ACCIDENTAL AND DELIBERATE AIRCRAFT IMPACT

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INTRODUCTION: MOTIVATION AND OBJECTIVES

Terrorist events involving the impact of large transport aircraft such as the Boeing 767 and 757 into the World Trade Center Towers and the Pentagon revealed the vulnerability of such structures to terrorist attack. They also elicited inquiries with regard to the effects of impacts of these aircraft types into other critical facilities including aboveground and below ground storage facilities, nuclear power plants, dams and other military and civilian installations. A significant capability to evaluate these threats has been developed during the past 17 years by Weidlinger Associates, Inc. (WAI) in Systems Safety Assessment studies. Small medium and large aircraft have been impacted into buried and aboveground reinforced concrete and light steel frame storage facilities. Both explicit aircraft models and Riera functions (a simplified aircraft impact loading function) have been used to generate an extensive data base of impact results. The local effects of aircraft engine impacts have also been studied. Both bare and buried structures have been considered. The software used to predict these effects (the FLEX nonlinear finite element code) has been validated against full scale C-141B longitudinal and lateral impact tests, and TF-30 engine impacts into bare and soil covered reinforced concrete walls.

This simulation technology is being applied to the development of a fast running assessment tool to evaluate the effects of impact into specific facilities for the aircraft involved in the above mentioned assessment studies. The objective is to develop a fast running tool to predict the level of damage to a variety of facilities- military, civilian, infrastructure- subjected to aircraft impact for incorporation into probabilistic studies or other applications to mitigate risk. In addition, it will provide first responders a tool to estimate structural integrity, to assess dispersal of fuel, extent of fire damage and threat of fire leading to collapse. It could also be used to provide a planning tool to estimate extent of human injury and/or release of hazardous materials. This information can be used to develop emergency response plans for dealing with aircraft impact incidents. Another intended use is to develop and evaluate mitigation concepts for various impact scenarios. The Rapid Assessment Aircraft Impact Tool (RAAIT) is currently in an initial stage of development.

DEVELOPMENT PLAN

The development plan for the RAAIT tool consists of the following steps. First, compile a data base of existing test data and accidental and intentional crash data. This allows defining impact parameters for a wide variety of aircraft impactors and provides a validation data base for both first principles computations and the fast running tool. Second, civilian structure construction types of interest will be surveyed for inclusion in the initial version of the tool. Third a computational data base of structural damage resulting from aircraft impacts will be developed that spans the impact environments of interest and includes representative types of building construction. This includes damage to structural components: columns, walls and slabs, etc. resulting from the impact of engine, wing and fuselage sections of aircraft. Fuel dispersal will also be investigated. Fourth, the data base of computations will be used to develop response surfaces or simplified models for classes of impacts. The final tool, illustrated in Figure 1, will provide information on projectiles, debris and fuel dispersal in addition to structural damage.

OUTPUT PROVIDED BY THE AIRCRAFT IMPACT TOOL

The RAAIT tool will display different types of results based upon survivability or vulnerability aspects of the problem being considered and the output requested by the user. The first piece of information provided is whether the aircraft penetrated the structure and the size and extent of the breech hole. The extent of damage to the structure might be needed for a fire and stability assessment. If the impacted structure is penetrated, then fragment and debris data in the form of fragment size and velocity will be provided for use in internal damage assessment and possible human injury determination. Finally fuel dispersal data will be generated based upon the location of the fuel tanks in relation to the breech hole. An example of the damage data displayed is presented in Figs. 2 and 3.

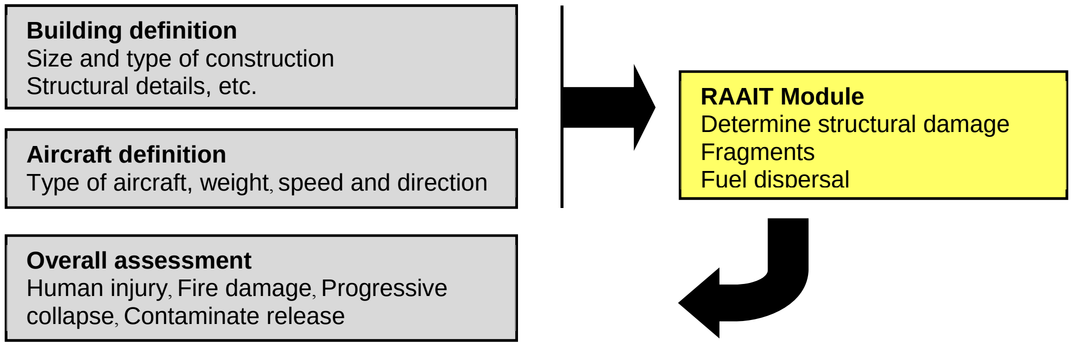


Fig. 1: Example RAAIT integration into vulnerability assessment environment

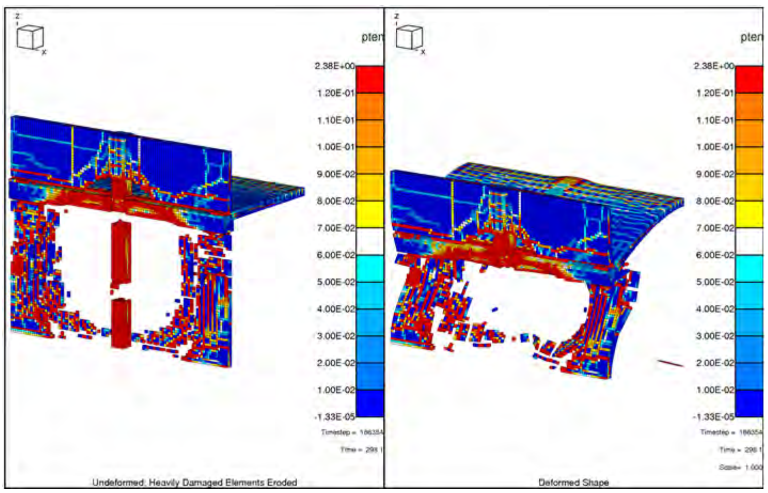


Fig. 2: FLEX analysis using Riera representation of aircraft impact concrete frame structure – post impact damage

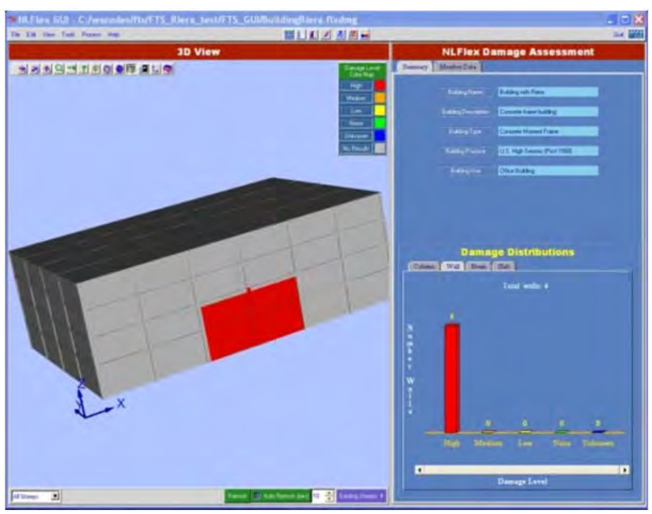


Fig. 3: Structural damage from Riera type aircraft impact analysis

DESCRIPTION OF DATA BASE AND MODELING APPROACHES

A wide range of aircraft types will be included in the tool data base. These range from light aircraft such as the Cessna 172 to business jets (Learjet and Gulfstream) and large commercial aircraft such as the Boeing 747, 757 and 767 plus an assortment of military aircraft (F-4, C-130, C-141B) (see Fig. 4.) Various impact representations of the aircraft have been developed ranging from simple "Riera-type" loading functions to detailed nonlinear finite element models that were used to generate the damage data bases. Explicit models of aircraft engines have also been developed including the J-79, T-56, TF-30/33, TF-34, F100, F117 (PW2000), F118 and CF-6. These two approaches will be used to develop RAAIT structural damage assessment modules. They are:

- Simulations of aircraft impact using Riera loading functions applied to a high fidelity model of structure
- Simulations of aircraft impact using high fidelity models for both aircraft and structure

Impact Modeling Approaches

The simpler type of modeling involves a combination of a Riera forcing function and finite element analysis. One of the first papers on aircraft impact force was written by Riera [1] who introduced certain assumptions which form the basis of the "Riera approach" for determination of forcing functions for aircraft impact on a rigid target. These assumptions are as follows:(1) Aircraft is separated into crushed and uncrushed regions, and crushing occurs only at the cross section in contact with the target; (2) Buckling of the cross-section decelerates the remaining uncrushed portion which behaves rigidly; (3)Material behavior of the fuselage is perfectly rigid-plastic.

Based on these assumptions and knowledge of the aircraft stiffness and mass distribution, the impact force, F, against a rigid target can be derived at any time from the momentum equation, as follows:

$$F = P_c + \alpha\mu V^2$$

where P_c is the load necessary to crush the fuselage at the impact interface, μ is the mass per unit length of the uncrushed portion, V is the velocity of the uncrushed portion and α is a constant included to obtain better correlation with data.

Small private planes Business jets Commercial air liners

Fig. 4: Range of aircraft considered

Using this approach, Riera and others developed the force-time impact relationship for aircraft such as the Boeing 707, F-4 Phantom, B-52, A-10, etc [2]. Others [3] introduced a constant in front of the velocity squared term to better correlate with data. The area over which the force is applied corresponds to the effective fuselage impact region. The impacts of engines and the wings are considered separately. This approach has been approved by the International Atomic Energy Agency (IAEA) for determining the response of nuclear reactors to aircraft impact. This approach results in an overestimate of the load applied to the structure because the interactive effects of the two impacting structures are neglected. It does provide a reasonable upper bound on the damage produced by the fuselage impact as long as a good knowledge of the aircraft stiffness and mass distribution is known and represented.

The function presented above is valid for normal impact of the structure. Riera also proposed a means for developing forcing functions for non-normal incidence with a specified surface friction angle [1]. For these cases bending failure of the fuselage was not considered. The adequacy of this methodology for determining the impact force was confirmed by Sugano et al in a paper published in 1993 [4]. A full-scale aircraft impact test of an F-4 Phantom into a massive reinforced concrete target was conducted by Sandia National Laboratories. The plane was impacted head-on at 215 mps with the primary purpose of determining the impact force as a function of time. Secondary objectives included determining the crushing behavior of the aircraft, whether the engines broke away during impact and what their impact velocities would be if this occurred and to record the dispersal of fuel after impact. Water was used as the fuel surrogate. The impact force-time curve from the analysis and test are shown in Fig. 5 as presented in Sugano [4].

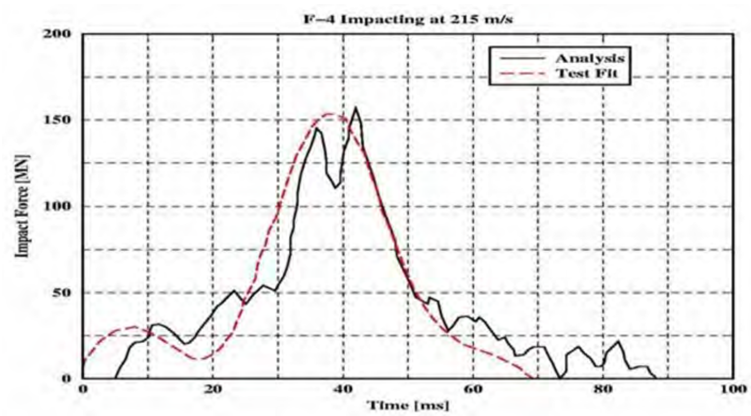


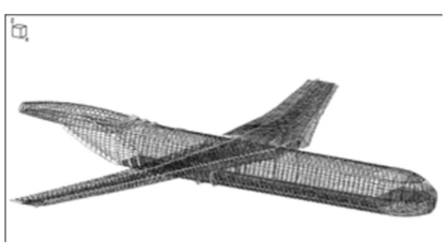
Fig. 5: Impact force vs. time curve (Sugano et al, 1993, p. 373).

Coupled aircraft/structure loading

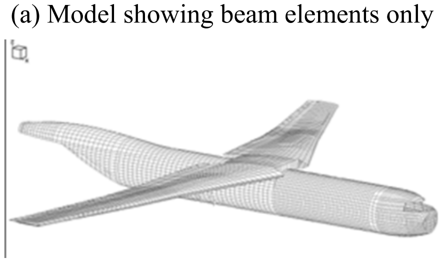
In this more accurate but much more computationally intensive approach an explicit model of an aircraft is combined with the target building model. The aircraft is given an initial velocity at the start of the dynamic phase, and a contact algorithm simulates the impact of the aircraft and fuel into the target building. Material nonlinearities, geometric nonlinearities, rate effects and structural details are included in the analysis. The FLEX explicit, large deformation nonlinear transient analysis code is used in the following analyses [5].

AIRCRAFT AND STRUCTURAL MODELING

First a detailed finite element model of the aircraft structure is built based upon the aircraft drawings and material property specifications. Two examples for a C-141 and C-130 aircraft are shown in Figs. 6 and 7. Shell and beam elements model the skin and stiffeners respectively. The individual body rings, longerons, bulkheads, cargo deck members and, in particular, detailed members in the nose of the aircraft, wings and around the landing gear areas were included in the models. The aircraft mass distribution is obtained from the weight reports. This is used to generate the location of nonstructural masses. The fuel may be modeled simply as properly distributed nodal masses or explicitly include through the use of continuum elements. Mindlin-type, single integration quadrilateral plate elements with transverse shear deformations were used to represent the shell components of the structure. Timoshenko beam elements with transverse shear deformations were used to model the aircraft stiffeners. The C-141B model employed over 9,000 nonlinear beam elements and over 6,000 nonlinear shell elements. The C-130 model used over 16,000 nonlinear beam elements and over 18,000 nonlinear shell elements.



(a) Model showing beam elements only



(b) Model showing shell elements only

Fig. 6: Structural elements in a refined FLEX finite element model of C-141B

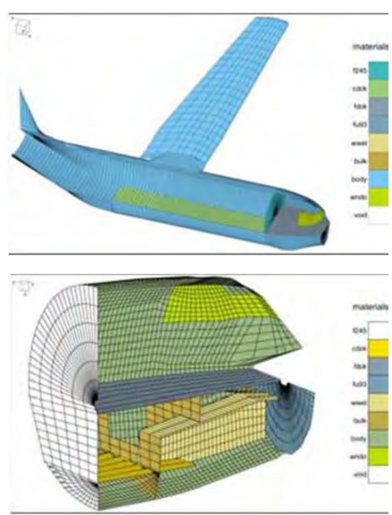


Fig. 7: Overview of the C-130 finite element model; half of model has been removed to show interior.

The combination of the mass and stiffness of the aircraft engines makes them likely candidates to penetrate the impacted structure. In order to properly model the engine penetration, this aspect of the problem may be handled separately or detailed models of the engines can be included in the aircraft model. Figs. 8 and 9 illustrate relatively detailed models of the TF-30 turbojet engine and T-56 turboprop engine used in recent impact analyses. A picture of a Boeing 767 finite element model with refined models of their GE CF-6 engines is presented in Fig. 10a. This model was used recently in an analysis of the World Trade Center.

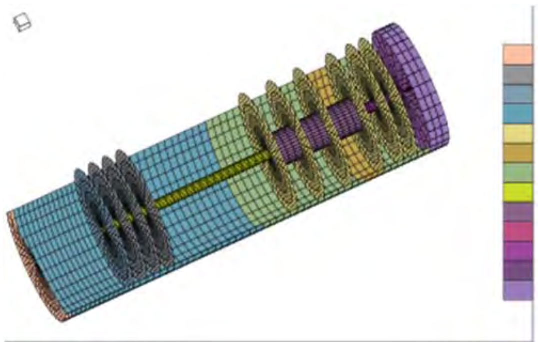


Fig. 8: TF30 engine model and details

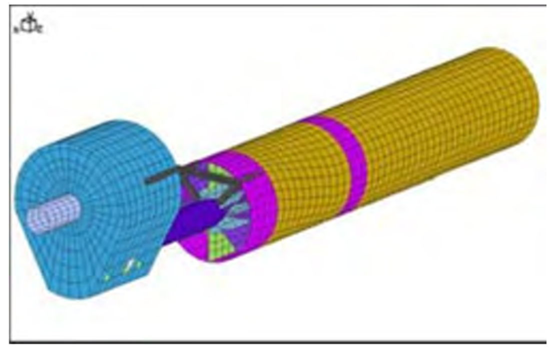
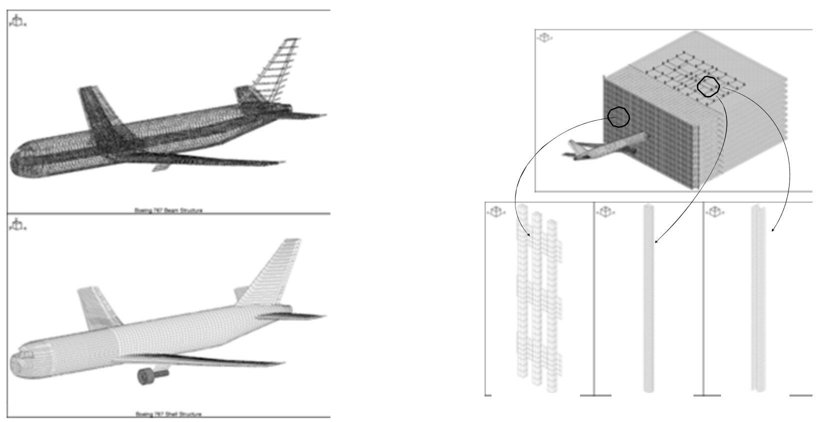


Fig. 9: T-56 engine model



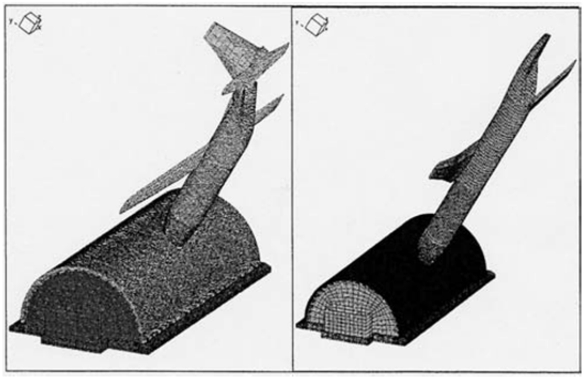
(a) Boeing 767 with CF-6 engine model (b) Boeing 767 model impacting WTC1

Fig. 10: Boeing 767 and WTC 1 model

Detailed models of the structure must also be developed. Models of an aircraft shelter and a reinforced concrete multi-bay, multistory structure are shown in Figs. 11 and 12. The aircraft shelter model has over 418,000 hexahedral elements, 45,000 beam elements and 89,000 shell elements. Hexahedral elements are used for the concrete and soil elements, beam elements were used to represent the rebar explicitly and shell elements modeled the corrugated liner for the aircraft shelter model. For the reinforced concrete multi-bay multi-story structure, over 433,046 hexahedral elements, 153,601 beam and bar elements and 6221 shell elements were included in the model. For the World Trade Center Models over 649,052 elements were used including beams, shells, springs, and membranes (Fig. 10b).

To properly represent the crushup and failure of the aircraft, sophisticated nonlinear material models including strain hardening, softening and rate effects must be used. Care must also be taken to ensure the material models are robust and converge. A three invariant, viscoplastic concrete model was used in the analyses presented here [6,7]. It is based upon a kinematic softening plasticity theory with an isotropic softening parameter and non-associated flow. The model consists of a perfectly plastic three-invariant failure surface with a three-invariant strain hardening cap. Damage and erosion criteria were based upon eroding elements based upon principle tensile strains, the damage parameter and the positive volumetric plastic strain. Interpretation of these criteria in terms of concrete, rock removal and failure mechanisms led to the series of successful predictions. The aluminum/metal model employed in the calculations was the simple von Mises isotropic, elasto-plastic strain hardening model. The beam and shell constitutive model representations for failure of metals are based upon an isotropic ductile fracture model.

After reaching ultimate strain, localized behavior is assumed to occur at each integration point [8]. Stress versus displacement across the band or crack is monitored and the expended fraction of total fracture energy capacity is calculated. Because the softening is based on displacement, rather than on strain, the response is insensitive to model discretization. With this model, elements can be eroded when the expended fracture energy exceeds a specific fraction of the total available fracture energy. Rate dependence can be included if the material data warrants its inclusion.



(a) C-130 (b) C-141B

Fig. 11: Finite-element simulation of aircraft-shelter impact, C-130 and C-141 impacting a shelter

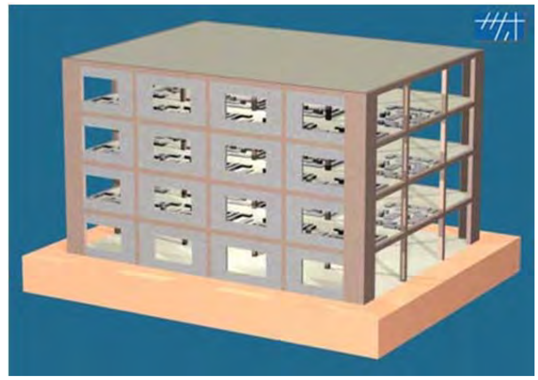


Fig. 12: Finite element model of multi-story building with infill walls

RAAIT DEVELOPMENT METHODOLOGY

The RAITT tool is being developed using technology and models developed under various System Safety Assessment Studies. New structural types including various types of aboveground building construction will be added to the current model set. Complete reinforced concrete structures, steel framed structures, bare flat slabs with thickness ranging from 0.30 to 0.91 m and heavy reinforcement; reinforced arches with thicknesses of 0.15 to .91 m, weak steel framed structures, buried reinforced concrete slabs with soil cover will be considered. Other structures such as dams, bridges, etc. can also be added in the future.

Impact velocity scenarios will include the credible threat range of each type of aircraft with multiple impact locations. This includes takeoff, landing, cruise speed and maximum flight envelope velocity ranges.

Fuel dispersal is explicitly modeled in some cases to evaluate and determine the fuel spray pattern inside and external to the impact structure. This information will be used to enhance an empirical data base for fuel dispersal based upon prior testing and events.

Riera loading functions will be used to develop data base and trends, and then explicit simulations of full aircraft and aircraft components such as wings and engines will be performed for peg points and selective validation of the simplified loading approach. Explicit aircraft simulations will also be used for impact regimes where the Riera loading is not applicable or less accurate. These included non-normal incidence, highly compliant structures and for fuel dispersal studies.

Verification and Validation of Finite Element Method

FLEX has been extensively benchmarked against other nonlinear codes such as DYNA-3D as well as precision test programs conducted by DTRA, the U.S. Air Force, and U.S. Army Corps of Engineers. Sophisticated models must be compared with test data to validate that the degree of refinement and material models reproduce the physics necessary to predict the response of structures subjected to impact. Computations of J-79 engines impacting walls that simulated small and medium scale tests reported by Sugano [9, 10] were carried out to understand the necessary degree of model refinement for this class of computations (Fig 13). Pretest predictions of C-141B lateral and normal impact tests validated the capability to predict fuselage crushup and tearing [11, 12a,b]. An example of these comparisons for a longitudinal impact test at 43 mps is shown in Fig. 14. These comparisons demonstrated the need to include material softening to obtain reasonable correlation with the test data. Predictions of TF-30 impacts at 109 and 152 mps into bare and soil covered reinforced concrete walls, respectively [13,14],demonstrated the ability to accurately predict engine and reinforced concrete damage and penetration. Fig. 15 compares the measured and predicted damage to the engine and the response of the wall for the bare wall impact.

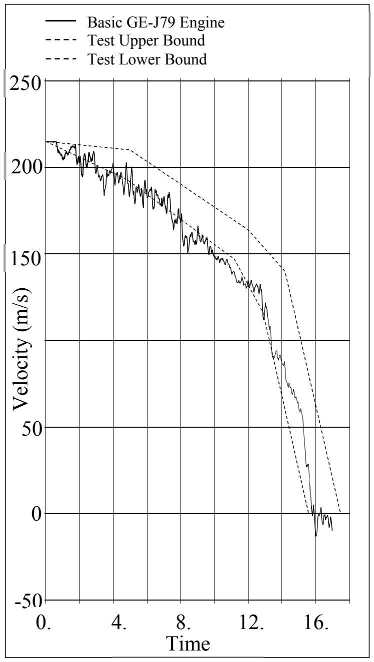


Fig. 13: J79 engine crash into concrete wall (215 m/s), back of turbine frame [13]

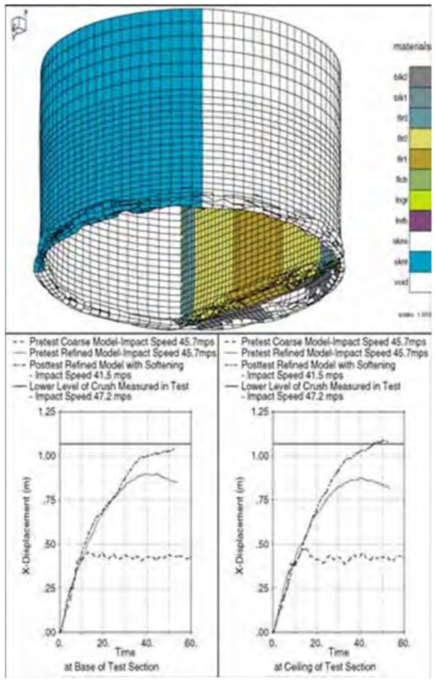


Fig. 14: Predicted axial shortening of test section at two locations vs measured crush; C-141B longitudinal impact test, 43 mps [12]

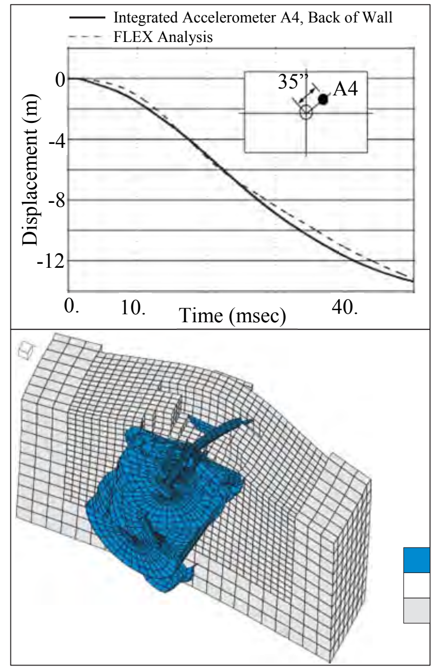


Fig. 15: Deformed TF-30 engine and comparison of displacement-time history with integrated accelerometer [13]

FLEX Modeling Tools Supporting RAAIT

In order to quickly generate FLEX models of buildings with Riera loadings, the Flex Template System (FTS) is being used. This allows models of buildings and other types of structures to be generated using a minimal amount of input. First the analyst defines the aircraft type, weight, impact speed, impact direction vector and impact-center location. Then he provides the building definition (Fig. 16). Tools then automate the application of Riera function pressure loading to impacted structural components (shown in red). An example of an impact into a reinforced concrete frame structure is given in Figs. 2 and 3.

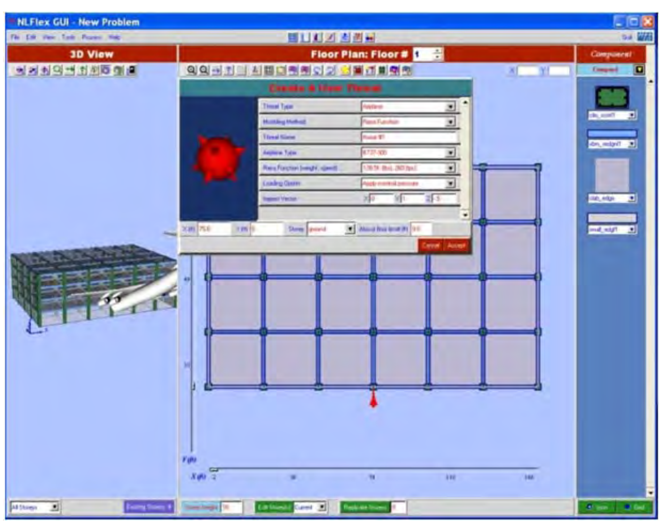


Fig. 16: FLEX modeling tools supporting RAAIT Riera function aircraft impact modeling

SUMMARY

The RAAIT Module is being developed to provide rapid assessment of damage to civilian structures caused by aircraft impact – either intentional or accidental. The tool is in its initial stages of development. The threat potential from aircraft impact must be considered by force protection and security planners – the target user base of several rapidly executing vulnerability and assessment tools. The tools can be enhanced to include aircraft crash threat scenario through incorporating RAAIT within their framework. The results from RAAIT (structural damage, fragments and fuel dispersal) could be utilized within other vulnerability assessment tools to predict casualties, potential for progressive collapse, fire spread, etc.

RAAIT will provide a convenient software environment for planners who must consider the entire range of potential threats including aircraft impact. Expanded functionality could be added to RAAIT by supporting a wider range of structures including buried structures, military structures, dams, nuclear power plants, other infrastructure and including modules to improve damage assessment due to primary and secondary fragments and evaluating fuel dispersal and related thermal effects.

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