International Journal of Engineering Research in Mechanical and Civil Engineering
(IJERMCE) Volume 1, Issue 2 , June 2016

Simulation of Crash Landing Of Aircraft Structures –A Review

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Abstract: **For the modern aircrafts which have been designed and built to greater level of sophistication also need to perform to the top notch in terms of crashworthiness and passenger/crew safety. For this the development and validation of reliable simulation tools is a very important criterion. Through efficient use of finite element simulation methods, development costs and certification tests can be reduced, to meet the new age aircraft safety and crashworthiness certifications. The present work is an overview of aircraft crash simulation.**

***Index Terms*—Crashworthiness, crash landing, material models, simulation, etc**

I. INTRODUCTION

In recent years, crashworthiness design and certification has been and will continue to be the main concern in aviation safety. Crash avoidance has been and will continue to be the main theme in aircraft safety. Since it has been observed that many crashes are potentially survivable, the design for crash survivability has become of increasing importance during the last decades. For these reasons aircraft crashworthiness and occupant safety are among the most important and challenging design considerations in the aircraft industry.

Crashworthiness evaluation is carried out by a combination of experimental tests and analytical methods - simulation. Several breakthroughs in computational capacity and more efficient explicit finite element methods has opened up tremendously the capability of the analytical methods and led to the possibility of detailed crashworthiness studies through complete aircraft crash simulations by finite element models. The modern simulation techniques can incorporate many structural complexities such as: geometrically accurate models; human occupant models; restraint systems and airbag models; and advanced material models to include nonlinear stress-strain behaviors, laminate composites and material failure. This simulation technology is being used by the automotive industry driven by safety legislation and consumer pressure for safety from quite a long time.

To cater to the new crashworthiness design requirements that will be established by the next generation of aircraft, the development and validation of reliable simulation tools is an important way of reducing development costs and certification tests, at the same time meeting aircraft safety and crashworthiness requirements.

The present work is an overview of aircraft crash simulation and, highlights selected topics of the finite element crash technology, review recent applications, and identify future challenges of the technology.

II. AIRCRAFT STRUCTURES CRASH SIMULATION

Occupant safety during crash is an important design factor for civil aircrafts. Part 25 – Air crashworthiness standards: transport category airplanes provide the guidelines [1] for emergency landing on ground and water. The impact dynamic research of aerospace structure by NASA could be traced back to the 1960s. As the customer demand for air mode of travel has increased with advantage in time of travel and due to technical requirements regulating the structural integrity of the aircraft structures during impact/crash,which has led to the recent attention to regulateand improve structural crashworthiness and reducing fatal injuries to the occupants. Addition to this, increased concern regarding fuel consumption which increases carbon footprint and sustainable environment is the main urge driving the need for lighter yet stronger aircraft structures.

Simulation (analysis) of aircraft structures for crashworthiness has evolved over the past years [2]. The pioneering analysis utilized lumped parameter models, also known as kinematic models, which employ a semi empirical modeling approach using lumped masses, beams and nonlinear springs to represent the airframe structure. The equations of motion are explicitly integrated to obtain the velocities, displacements and rotations of the lumped masses under the influence of external and internal forces. These models rely heavily on test data for definition of the spring properties to characterize the crushing behavior of the subfloor, landing gear, and other energy absorbing components.

Few of the tools used for crash simulation of the aircraft structures are discussed briefly in the following sections.

PAM-CRASH: It is an explicit finite element analysis tool (code). It uses a Lagrangian formulation with a finite element mesh fixed in the material and distorts with it. The equations of motion are integrated in time explicitly using central differences. Very small time steps are required for the method to have a stable solution, thus making it one of methods suitableto impact and crash simulations and less appropriate for equilibrium structural analyses.

KRASH**:** Under contract to the U.S. Army at the onset of the 1970's, the computer code KRASH was developed by the Lockheed California Company to provide an analytical capability to determine helicopter structural dynamic responses to multidirectional crash impact forces [3]. Analytical capability was required to support crashworthiness design trade-off studies. Subsequent to the U.S. Army's sponsored efforts, KRASH was upgraded under an FAA contract and its capability was directed toward the analysis of light fixed wing aircraft subjected to crash impact conditions [4]. The upgraded version is called KRASH79 and contains many new features while retaining its original concept. The completion of the FAA sponsored research in 1985 [5] has resulted in the version, denoted KRASH85, which is capable of simulating crash scenarios of transport category aircraft.

The computer code KRASH [6] can be used to perform a nonlinear transient response analysis to simulate the crash impact behavior of any arbitrary three-dimensional structure. The analysis includes both geometric and material nonlinear structural behavior capability. KRASH is often referred to as a "hybrid" analysis method because it generally requires input data derived from other analyses or tests since the structure is represented in a rather coarse manner using nonlinear beam and spring structural elements and lumped masses. The code integrates the Euler equations of motion of the lumped masses connected together by the beam members, each with six degrees of freedom, and computes the time histories of accelerations, velocities, and displacements. In addition, using small deflection linear analysis or large deflection plastic analysis, the internal beam forces, shears, moments and torsions are computed. The loads and deflections of the external springs used to simulate those portions of the aircraft coming into contact with the ground are also determined.

For the design of crashworthiness structures, the appropriate KRASH code is often used in conjunction with a conventional finite element program such as NASTRAN. For example, in the design of the composite cabin sections in Reference 7, KRASH85 was used for the dynamic analysis of the cabin drop test conditions and NASTRAN was used for determining internal loads required for strength analysis.

ABAQUS [7]**:** It is a general purpose FEM program that can solve a variety of problems. ABAQUS is used in the automotive, aerospace, and industrial products industries. The product is popular due to the wide material modeling capability, and the program's ability to be customized. ABAQUS also provides a good collection of multiphysics capabilities; ABAQUS software used for finite element analysis (FEA) consists of three products - ABAQUS/Standard, ABAQUS/CAE and ABAQUS/Explicit, which can be used to run a variety of simulations. It allows users to configure the materials using a variety of models. The user also has very fine control over the meshing and the element types used in the model. Perhaps the biggest advantage of ABAQUS is seen as that it allows modeling at a high level of detail. The user is able to setup a very detailed model describing various kinds of behavior, as well as a “bare-bones” model that provides general information.

ABAQUS/Standard is used to solve implicit finite element analyses, such as dynamics, statics and thermal with different types of contact and material nonlinearity options. ABAQUS/Explicit is used for transient dynamics and also quasi-static analyses by using an explicit approach which is suitable for cases like drop test, crushing and manufacturing processes. ABAQUS/CAE is mainly used for modeling and visualization for ABAQUS analysis products. It gives access to CAD models, visualization and advanced meshing.

III. EXPLICIT AND IMPLICIT ANALYSIS

An explicit FEM analysis does the incremental procedure and at the end of each increment updates the stiffness matrix based on geometry change (if applicable) and material changes (if applicable). Then a new stiffness matrix is constructed and next increment of load or displacement is applied to the system. Explicit solution takes account of the finite propagation speed (at the speed of sound) of dynamic effects through the material. For this a mesh which is fine enough to represent the spatial effects (e.g. a stress wave propagating through the structure), and time steps of the same order of magnitude as the transit time of sound waves from each element to its neighbors. If the time steps exceed that size, the response will usually be unstable and the analysis will fail after a few time steps. The time step size is limited by the smallest element in the model, not by the average size.

Implicit solution methods smear out those local effects. The propagation of dynamic effects around the structure is controlled by the inertia of the structure, not by the speed of sound. This method assumes the speed of sound as infinite or that any applied load affects all of the structure instantaneously. The mesh for this solution only needs to be fine enough to capture the overall deformation of the structure, and the time steps only need to be small enough capture the frequency spectrum of the response that you are interested in. An implicit FEM analysis is the same as Explicit with the addition that after each increment the analysis does Newton-Raphson iterations to enforce equilibrium of the internal structure forces with externally applied loads. The equilibrium is usually enforced to some user specified tolerances.

In an implicit dynamic analysis the code is solving the equation

$$[M]\{a\}+ [C]\{v\}+ [K]\{u\}=\{F\}$$

and updating the displacement and velocity, where M - mass, C – co-efficient of damping, K – co-efficient of stiffness, a – acceleration, v – velocity, u – displacement and F – force. This is stable and accurate for relatively large time steps. In an explicit dynamic analysis the code is just solving

$$\{a\}= [M]^{-1}\{F\}$$

and updating the velocity assuming acceleration is constant over the time step. This method is only stable for very small time steps and it is practical to use explicit dynamic procedures when the phenomenon being simulated is very short in duration like an impact event. Implicit dynamic methods are used for simulating longer duration events like vibration of a structure following an impulse load.

Implicit solution calculates current quantities in one time step are based on the quantities calculated in the previous time step. It follows Euler time integration scheme. In this scheme even if large time steps are taken, the solution remains stable. This is also called an unconditionally stable scheme. But there is a disadvantage, and it is that this algorithm requires the calculation of inverse of stiffness matrix and calculation of an inverse is a computationally intensive step. This is especially so when non linearities are present, as the Stiffness matrix itself will become a function of u. Another advantage of explicit analysis is that it requires much less disk s pace and memory than implicit for the same simulation. For problems in which the computational cost of the two programs may be comparable, the substantial disk space and memory savings of explicit analysis make it attractive.

The above mentioned linear or non-linear behavior – both explicit and implicit methods can be either linear or nonlinear. But in real world applications, there are usually quicker ways to model the high speed linear dynamics response of a structure, so the models analyzed with ABAQUS explicit are usually nonlinear.

IV. MATERIAL MODELS

ABAQUS has an extensive material library which can be used to model many engineering materials, including metals, rubbers, concrete, damage and failure, fabrics, and hydrodynamics. ABAQUS also provides the facilities to create and use a user-defined material model for the purpose of finite element simulation. Few of these material models [8] are discussed briefly in following steps.

Elasticity: Linear relationship between stress and strains is considered for most of the materials usually called elastic response and described by linear elasticity theory. Elastic properties can be specified as isotropic or anisotropic. Elastic properties may be dependent on temperature and/or predefined field variables.

Plasticity: Plastic deformations are non-recoverable deformations. Plasticity theories are developed to model the material's response under ductile non recoverable deformation.

Isotropic Metal Plasticity: In ABAQUS, Mises yield surface is used to model isotropic metal plasticity. The plasticity data are defined as true stress vs. logarithmic strain. ABAQUS assumes that no work hardening continues beyond the last entry point.

***Anisotropic Metal Plasticity*:** ABAQUS uses Hill's yield potential (an extension of the Mises yield function) to model anisotropic metal plasticity. In this material model a reference yield stress (σ_0) is need to be defined. Anisotropy is introduced through the definition of stress ratios.

Hardening: ABAQUS offers the following options for the modeling of hardening:

Isotropic hardening: uniform stress-plastic strain response in all directions,

***Linear kinematic hardening*:** used in the cases where simulation of Bauschinger effect is relevant. Applications include low cycle fatigue studies involving small amounts of plastic flow and stress reversal.

Combined nonlinear isotropic/kinematic hardening**:** more general than linear model. Johnson-Cook hardening: suitable for high-strain-rate deformation of many materials including most metals.

V. APPLICATIONS OF THE CRASH SIMULATION

A few of the studies in the field of aircraft structures crashworthiness are discussed in brief in following sub-sections,

Liu Xiaochuan et al [9] made an effort to study the crashworthiness of a civil airplane by both simulation and experimental test. The vertical drop test of the fuselage section was conducted on a 2.93 m long fuselage section consisting of 7 frames. It also included passenger seats, overhead bins and artificial test dummies. Vertical drop test was carried out with actual impact velocity of 6.85m/s. Deformations of the structure and accelerations at typical locations were measured and used to validate the modeling method and numerical method of impact simulation. Numerical simulation of the drop test was performed by using the LS-DYNA code. The finite element model of main fuselage structure was developed and validated by modal test, and the error between the calculated frequencies and the test ones of the first four modes were less than 5%.

Mou Haolei [10] et al studied the influences of composite skin on fuselage section crashworthiness, viz., effects of composite ply number and effects of composite ply angle on crashworthiness of composite fuselage section.

A finite element model of fuselage section with a double elliptical section consisting of the cabin and cargo was developed. This model consisted of materials namely aluminum alloys and unidirectional composite materials. Aluminum is used to model frames, stringers and plates. Composite material used to model only fuselage skin. Mass of seats and dummies were accounted as concentrated masses located at the junctions between seats and floor. The vertical crash direction of the model was parallel to the normal direction of rigid surface, and the vertical impact velocity of 6.67 m/s was considered to evaluate the crashworthiness of composite fuselage section without considering aerodynamic forces.

A.R. Rahai et al [11] investigated fiber reinforced polymer (FRP) bonding for Steel plate shear wall (SPSW) as an innovative method for enhancing behavior of thin steel plate subjected to in-plane shear. A finite element analysis research program was conducted and a steel plate shear wall model was designed. To investigate the effect of the proposed strengthening scheme on a common SPSW, a one-story model was produced. The accuracy of the simulation and the calculations has been carefully validated with some of the most renowned laboratory tests available in the literature.

R.C. Batra et al [12] have studied deformations of the laminate composite materials/structures under low energy impact by employing a hybrid technique which consists of micromechanics approach for deducing effective properties of a ply with continuum damage mechanics (CDM) approach to study the damage and failure at the ply level has been carried out.

A Adams et al [13] have studied the vertical drop test of a section of fuselage consisting of a conformable auxiliary fuel tank located below the passenger floor. A drop test with vertical velocity of 9 m/s (30 ft/s) was conducted to evaluate the structural integrity of the fuel tank. The objective was to find the interaction between fuselage, particularly floor structure and the auxiliary fuel tank under severe but survivable impact conditions. Structural response data from impact were obtained by instrumentation installed on the fuselage, floor and fuel tank. The test data were compared with finite element simulation to get a better understanding of the impact event by analytical correlation. FE code LS-DYNA was used to develop 3-D full scale fuselage section.

F. X. Meng et al [14] have presented a study to improve the crashworthiness behavior of aircraft fuselage by using simplified structural models. They considered two simplified cylindrical fuselage structures of commercial aircraft under the passenger floor. One was a traditional fuselage section which is prone to break down its global integrity due to large deformation of cargo floor. Second one was newly suggested fuselage section without sacrificing the cargo volume. Here an energy absorption device with hexagonal honey-comb structure is introduced between the cargo floor and the lower clip-plate. Drop tests were conducted for both models. Dynamic response of Results showed that newly suggested fuselage with honeycomb energy absorption device can maintain a more integral cabin structure and acceleration levels acted on passengers is decreased significantly than the traditional one.

In addition to above mentioned references, few more of them [15 – 31] will provide more insight to the reader.

VI. CONCLUSION

Advancement in the computational capability of tools used in the analysis of crashworthiness of aircraft structures has come a long way since their inception. Above discussed finite element simulation methods have found wide acceptance not only in the aircrafts but also in the automotive industry for vehicle crash scenarios. Correlation between simulation and experimental results has built the confidence in finite element simulations. Simulation tools will be very essential in the crash analysis studies since they reduce the cost by a big margin when compared with experimental tests. Tools also help in development of optimum designs and optimization of structures by reducing the overall weight, improving energy absorption characteristics, etc.

FUTURE SCOPE OF WORK

Analysis validation: Validation of the crash modeling with the experimental data is a major deficiency in the simulation. Lack of sufficient experimental data due to high cost of experiments is the cause.

Composite material modeling: New age flights are increasingly designed with several composite materials. These materials failure mechanisms, complex interactions like damage initiation and evolution make the problem very difficult.

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