ANALYSES OF CRITICAL STRUCTURES AND CONTAINED EQUIPMENT FOR AIRCRAFT IMPACT LOADINGS

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SUMMARY

The evaluation of critical structures and contained equipment for aircraft impact loading involves a complex interaction of numerous parameters including the types of aircraft and their loading functions, critical impact locations, nonlinear behavior of materials and structures, energy absorbing characteristics of elements and systems, modeling techniques and analysis procedures, soil parameters, and dynamic modes of failure and damage. Furthermore, for an accurate determination of the response of a structure and its contained equipment, it is extremely important to consider the nonlinear behavior of the local impacted area as well as the overall behavior of the remainder of the structure. The forces transmitted through the local area into the remainder of the overall structure are usually significantly lower than the applied load, and the corresponding frequencies tend to shift to a lower frequency range.

The paper presents a discussion of the above major considerations associated with aircraft impact analyses. The paper emphasizes three major topics: (1) characterization of the loading, (2) nonlinear behavior of the local impacted area, and (3) special modeling and analytical techniques required for aircraft impact analyses.

The above discussion is based on the results of the analyses of two reactor buildings, a boiling water type and a pressurized water type, and their contained equipment and piping systems. A summary of applicable results is presented for the pressurized water type of building.

The paper concludes with a critique of the existing techniques and procedures currently in use for the evaluation of critical structures and systems for aircraft impact effects. Recommendations are made for improved procedures for hazard analysis, modified modeling techniques for analyses, and needed research and developmental work.

1. Introduction

The paper presents a discussion of the major considerations in the analyses of critical structures and contained equipment for aircraft impact loadings. Such analyses involve a complex interaction of numerous parameters including the types of aircraft and their loading functions, critical impact locations, energy absorbing characteristics of elements and systems, nonlinear behavior of materials and structures, modeling techniques and analysis procedures, soil behavior, and dynamic modes of failure and damage. The emphasis of the discussion is on three main topics: characterization of the loading, nonlinear behavior of local impacted area, and special modeling and analytical techniques required for aircraft impact analyses. The discussion is based on the analyses of two reactor buildings, namely, a boiling water type and a pressurized water type. A summary of applicable results is presented for the pressurized water type of reactor building.

2. Characterization of Loading

Before any aircraft impact analyses can be initiated, it is necessary to select one (or more) aircraft and develop the corresponding loading functions. The first major step in the selection of an aircraft is the development of a general probabilistic model of the aircraft hazard. The model should describe the events associated with the aircraft crashes of interest and should contain basic parameters for all types and sizes of aircraft. The model should also contain the evolutionary nature of safety features in a form that they can be easily updated. For the particular nuclear power plant under consideration, the crash event should be modeled in detail and should consider the location and characteristics of the site with respect to airports, the phenomenon of the crash itself, and the type and time of occurrence of the emergency event. Each important parameter should then be assigned a probability distribution and the concept of multidimensional sample space should then be used to establish the criteria loadings. A single aircraft (or a series of aircraft) and its size, velocity, and configuration should then be selected on the basis of the results of the probabilistic hazard analysis described above.

A loading function should then be derived to represent the loads applied to the structure by the aircraft selected above. This is a critical step in any aircraft impact investigation because the response of the structure and the contained equipment is directly affected by the selected loading function. The present methods of calculating loading functions are based on parameters such as an assumed velocity profile along the aircraft and the fuselage buckling strength, etc. The aircraft is usually represented by stepped axially symmetric cross-sectional elements. An elastic or elastic-plastic force-deformation relationship is assumed for the aircraft. In some cases, a fracture model is also used in conjunction with the force-deformation relationship. The impacted structure is usually assumed to be rigid for simplicity and due to lack of test data. However, it is possible (although complex) to model the nonlinear behavior of the impacted area for a realistic determination of the aircraft impact loading function. The loading function is usually developed using the finite element or the finite difference approach, with the appropriate boundary conditions. If detachment of fragments is considered, the total force acting on the structure can be obtained by adding the forces exerted by the body of the aircraft and its fragments such as engines.

Figure 1 presents a survey of the aircraft impact loading functions proposed by various investigators during the last decade. It should be noticed that these functions differ not only with respect to their load-time characteristics but also their durations. These differences in the loading functions can have a significant influence on the response of the structure and the contained equipment.

The methods of calculation of the aircraft impact loading functions described above need considerable additional investigative and developmental work.

3. Behavior of Local Impacted Area

The behavior of the local impacted area is usually nonlinear because of the high magnitude of the load and the small area of contact between the impacting aircraft and the impacted surface. The forces transmitted through this nonlinearly behaving local area into the remainder of the overall structure are generally lower than the applied load because of the large amount of energy dissipation in the local impacted area which has to undergo large nonlinear deformations. The peaks of the floor response spectra therefore also tend to be lower in magnitude and shift into the lower frequency range if the local nonlinear behavior is considered. It was shown in Reference 3 that when the local nonlinear behavior was taken into consideration, the peak values of the floor response spectra were reduced by about 30 to 50 percent and the frequencies at which these peaks occurred were shifted into the lower frequency range by about 10 percent or more. It was also shown that the forces in the structure were reduced by about 50 percent.

The above discussion clearly points towards the significance of performing nonlinear analyses of the local impacted area for obtaining economical and safer designs of structures and contained equipment. However, performing such nonlinear analyses involves utilization of very sophisticated analytical techniques to model the highly complex nonlinear behavior of the reinforced concrete structures. The potential cracking as well as crushing of concrete, along with yielding of reinforcing steel, have to be tracked step-by-step for the duration of the aircraft impact. Especially difficult is the problem of modeling unloading of cracked concrete in conjunction with yielded reinforcing steel. There are only limited test data available on the loading and unloading of reinforced concrete cross-sections of the heavily reinforced type such as those used in nuclear containments under very short duration and high magnitude loadings.

The modeling of reinforced concrete cross-sections becomes especially complex because the distribution of reinforcement and the properties of the composite material are not isotropic. It is therefore necessary to develop special anisotropic models, based on appropriate assumptions and limited data, by means of which the diverse failure possibilities can be described and converted into mathematical formulations. Appropriate flow rules and failure surfaces have to be assumed. A finite element or finite difference approach is then used to obtain the response of the structure.

An attractive approach for local nonlinear analyses consists of using "segment" elements. This approach is different from the 'standard' finite element approach in that the behavior of a reinforced concrete cross-section is modeled by a single segment, rather than two (or more) elements representing concrete and steel separately. The single segment represents the behavior of the reinforced concrete cross-section as modeled by several layers, each representing a layer of reinforcement or cracked or uncracked concrete.

The cracking of concrete and the yielding of steel is thus realistically modeled and monitored throughout the application of loading. Only the few degrees of freedom corresponding to the single segment are required, and the overall forces acting over the complete segmental cross-section are utilized in place of stresses and strains. The loading and unloading of the different segments, with the resulting cracking and crushing of concrete and the yielding of steel, is tracked in a simpler manner. A step-by-step nonlinear analysis is performed. Such an approach, which is considerably more realistic and simpler and cheaper to use than many available approaches, is in the process of being developed.

4. Modeling and Analytical Techniques

The idealization of the overall structure and the modeling and analytical techniques employed for an aircraft impact analysis depend on the objectives of the analysis and the information required. For example, in many cases the selection of nodal points is determined not only by the range of frequencies that need to be included in the analysis but also by the number of locations at which the information is required. The idealization should also take into consideration the distribution and orientation of walls in the vicinity of the impacted area which may transmit the load to the remainder of the structure.

The first major decision is usually the selection of the type of model to be used, e.g., lumped mass cantiliever or finite element type. If the objective is to develop floor response spectra at different levels of the structure only, it is sometimes sufficient to use a lumped mass cantilever type model if it appears that the overall structural behavior warrants such idealization and the path of the impact load through the walls in the local impacted area is such that the load can be directly and adequately transmitted to the lumped mass cantilever. The lumped mass models must, however, be used with caution because of the possibility of elimination of higher frequencies of interest. If the objective of the analysis is to generate forces and streses, however, a finite element model must be employed. In such cases it may be desirable to use an axisymmetric model, if the structural configuration permits such an idealization. (If small portions of the structure are nonaxisymmetric, such as appurtenances etc., a three dimensional finite element model can be developed for the local areas only in conjunction with the overall axisymmetric model.) For three dimensional finite element models, the size of the structure and the resulting number of degrees of freedom could impose computational tasks on computers beyond their capacity. It has been observed that because of the large thickness of the walls of a nuclear containment structure, the element size is occasionally governed by the aspect ratios, especially if thin plate or shell type elements are used.

The soil can be modeled using the continuum approach (frequency-independent soil springs or frequency-dependent impedance functions) or the finite element approach, as discussed by the authors in Ref. 7.

5. Sample Results

Figure 2 shows an axisymmetric model employed for the analysis of a pressurized water type of reactor building. The analyses were performed for the loading function shown in Figure 3. A typical envelope spectrum in the radial direction at the top of the structure, for the load applied radially at Node Point 42, is shown in Figure 4.

6. Use of Results For Design Of Equipment and Piping Systems

For the design of equipment and piping systems for an aircraft impact loading, the analyses are usually performed for aircraft impacts at several critical points and the response spectra obtained at support locations are then enveloped to produce a single spectrum at each support point (in each global direction). It should be evident that such enveloping procedure is a practical expediency, but it should also be evident that this approach can be very conservative in certain instances.

It can be observed from a study of the time histories of response for an aircraft impact loading that motions at a given nodal point in three orthogonal global directions tend to be usually in phase and are generally similar in character. Thus, the conventional rationale used in earthquake engineering to combine responses due to motions in different directions by the square root of the sum of the squares method is not necessarily applicable for aircraft impact loadings.

Another area which has not received significant attention is the investigation of the true causes of damage to supported equipment and piping systems subjected to high acceleration, low displacement motions associated with high frequency components. In-structure response spectra provide a convenient representation of elastic response to aircraft impact induced vibratory motions, but they are not adequate indicators of damage. As pointed out by the authors in Ref. 2, the real potential for damage of supported components needs to be thoroughly examined.

7. Conclusions and Recommendations

There is need for major improvements in the procedures currently in use in the industry for the analyses of critical structures and systems for aircraft impact loadings. One of the main shortcomings of the current procedures is the lack of emphasis on the use of rational approaches in the development of loading criteria. Hazard analysis needs to be performed using probabilistic approaches and taking into consideration events associated with aircraft crashes, including the basic parameters for all types and sizes of aircraft. The resulting loading functions should be derived taking into account the nonlinear deformations of the impacting aircraft as well as the impacted structure. Extensive experimental work also needs to be performed to collect needed data on the behavior of the aircraft as well as the structures.

The importance of consideration of the nonlinear behavior of the local impacted area and the energy absorption due to this effect needs to be fully understood. Analyses based on linear behavior of the local impacted area usually provide unrealistic and conservative results. Nonlinear analyses of the local impacted area must be first performed to generate time histories of forces transmitted to the remainder of the overall structure. The analyses must be performed using techniques which can realistically model the complex nonlinear behavior of the reinforced concrete cross-sections, and are not too expensive to use, such as the 'segment' technique described earlier. Use of nonlinear analysis programs which consider the material to be isotropic and employ 'standard' finite element or finite difference schemes, based on 'standard' yield criteria and flow rules mainly applicable to metals, can provide inaccurate and unconservative results for reinforced concrete cross-sections.

The time histories of modified input forces obtained from these local nonlinear analyses should then be used for the dynamic analyses of the remainder of the overall structure and the contained equipment and piping systems. For these analyses standard seismic analysis procedures should not be used directly. The significance of the difference in the behavior of the structures and contained equipment and piping systems under seismic and aircraft loadings must be recognized and the available techniques for seismic analyses should be modified for application to analyses for short duration, high amplitude aircraft impact loadings with high frequency content. In addition, the true potential for actual damage to supported equipment and piping systems subjected to these high acceleration, low displacement input motions should be thoroughly examined.

A considerable amount of research and developmental work is still needed, especially experimental work, in the area of aircraft impact investigations. However, in the meantime, it is very important that the considerations discussed above be properly included in the analyses of structures and contained equipment and piping systems for aircraft impact loadings to obtain safer and economical designs.

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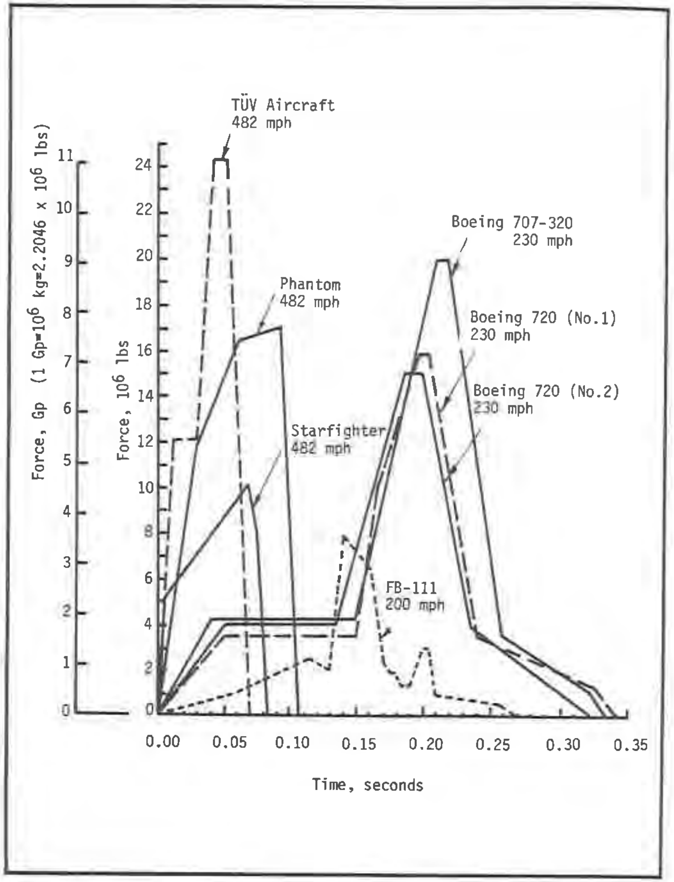

FIGURE 1 - Survey of Aircraft Impact Loading Functions

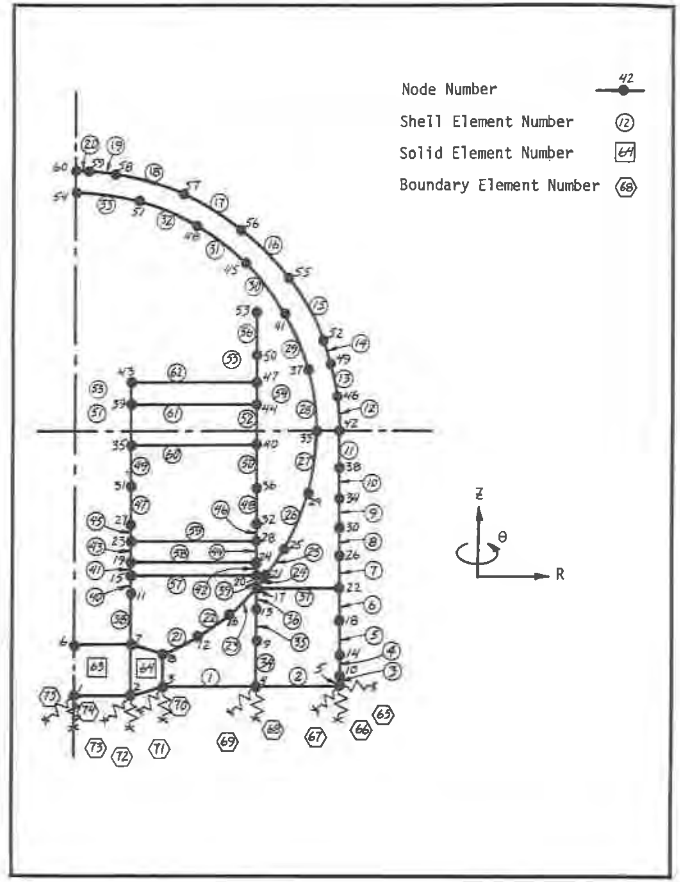

FIGURE 2 - Axisymmetric Mathematical Model

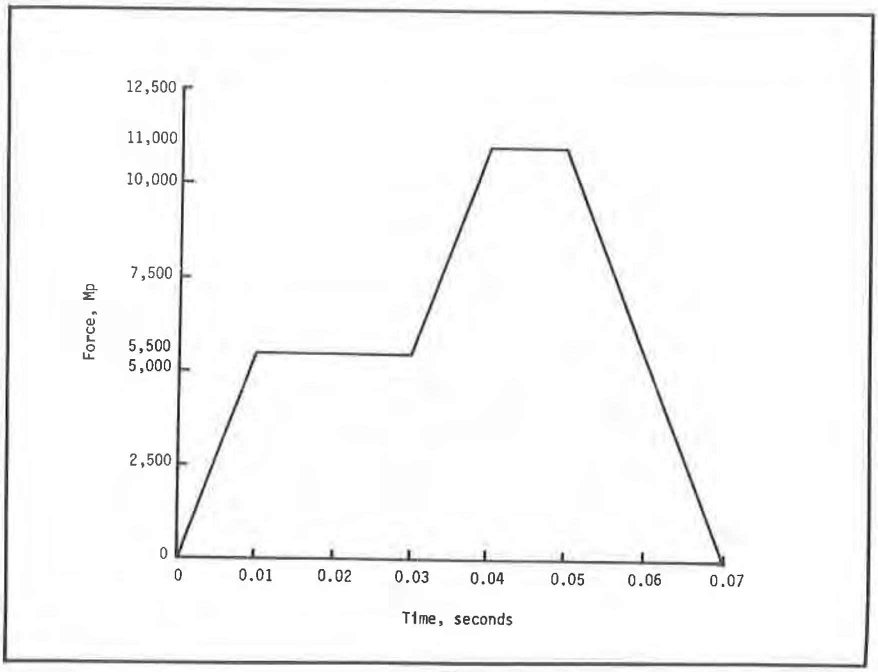

FIGURE 3 - Loading Function Used in the Analyses

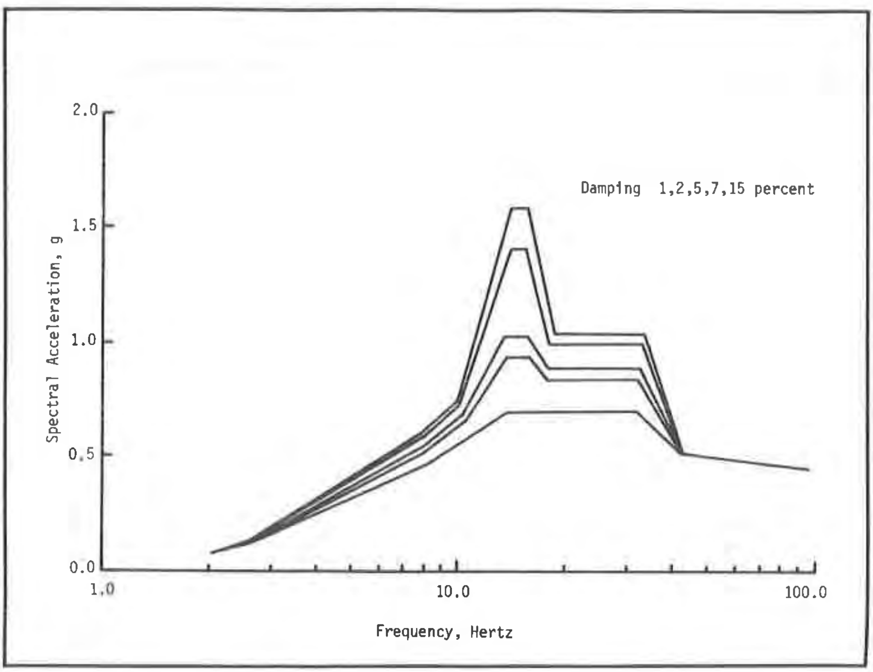

FIGURE 4 - Floor Response Spectrum in the Radial Direction At the Top of the Structure