RESPONSE OF EQUIPMENT TO AIRCRAFT IMPACT

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SUMMARY

The loading case of an aircraft crashing onto certain safety-relevant buildings of a nuclear-power plant has recently become, in certain countries, as important as that of the safe-shutdown earthquake. Although its probability of occurrence is substantially smaller than that of the SSE, the analysis is justified, as an aircraft impact can also be regarded as representative of other shock loading cases. For the purpose of design it is convenient to distinguish between the response of the actual structure and that of the equipment. The former, which consists of global stress resultants and of local effects such as spalling, scabbing, penetration and perforation of the concrete of the structure, is quite well understood and is not examined in this paper. The latter, caused by propagating shock waves, has, rather surprisingly, received little attention, although, for earthquake excitation, the analysis of equipment is routinely performed. The high accelerations experienced by the equipment are calculated and the corresponding floor-response spectra show that the airplane crash is dominant in the high-frequency range, when compared to the effect of earthquakes.

As the aircraft impacts on a small area of the structure only, and the corresponding function of the load versus time exhibits a substantial content of high frequency, the modelling of the structure has to be rather detailed. Several thousand dynamic degrees of freedom in a finite-element idealization result, when analyzing e.g. a typical reactor auxiliary building, the familiar lumped-beam models used successfully for earthquake analysis can obviously not be chosen. This is demonstrated using the reactor building, the reactor auxiliary and the fuel-handling building of a typical 1 000 MWe plant.

For an adequate finite-element model, the influence of the load vector and of the stiffness matrix, damping matrix and mass matrix on the response is analyzed. The parametric study leads to the following results. From the analysis of a Boeing 707 and of the fighter Phantom with and without freely flying debris, it is concluded that for constant peak load, constant total impulse and constant duration of load, the actual shape of the load-time relationship is of paramount importance. For an elasto-plastic behaviour of the material, the response is also significantly changed. But even for extremely simple systems, the non-linear response cannot be predicted a priori. Compared to the result of an elastic analysis, it can turn out to be increased or diminished. Introducing damping, leads to smaller response, this effect being more pronounced as the distance to the point of impact is increased. Finally, the representation of the mass (lumped, consistent) is of minor importance.

Using the standard load-time curves, an elastic analysis leads to accelerations of the structure in the vicinity of the applied load of several tens of g. Even for rather remote points the response is still considerable.

1. INTRODUCTION

In certain countries some nuclear-power plants are built in areas where a rather heavy air traffic exists, and hence an aircraft impact on safety-relevant structures such as the reactor building and the reactor auxiliary building has become a major loading case for design. Although its probability of occurrence is, in general, substantially smaller than that of the safe-shutdown earthquake (SSE), the analysis is justified, as an aircraft impact can also be regarded as representative of other shock-loading cases as e.g. a blast loading.

As in the analysis of the other major dynamic loading case, i.e. earthquake, it is convenient to distinguish between the response of the actual structure and that of the mechanical and electrical equipment. The former, which consists of global stress resultants and displacements and of local effects such as spalling, scabbing, penetration and perforation of the concrete of the structure, is reasonably well understood and is not examined in this paper. The latter, caused by propagating shock waves, has, rather surprisingly, received little attention, although, for earthquake excitation, the analysis of equipment is common practice. In two recent papers Sharpe et al. [1] and Schalke et al. [2] show that, for an aircraft impact, high accelerations are produced. The response spectra presented therein exhibit larger values than those of a SSE in the high-frequency range.

The pioneering paper on airplane impact on nuclear-shielding structures was written by Riera [3]. For a Boeing 707, he developed the force-time relationship assuming an ideal-plastic impact on a rigid wall. In contrast to earthquake loading, substantial amplitudes of high frequencies are present. In addition, the area on which the forcing function acts is comparatively small. A polygonal approximation of the force-time curve is shown for specific parameters in Fig. 1 and is used for all the investigations in this paper unless stated otherwise. Such diagrams are widely used in the dynamic stress analysis of protective structures. Several authors have recently examined the influence of Riera's basic assumptions. Drittler et al. [4] refine the model of the actual aircraft and perform a dynamic elasto-plastic analysis with the possibility of pieces being torn off. Their force-time curve for a Phantom crashing ideal-plastically on a rigid wall is reproduced in Fig. 2. The total force consists of the deceleration force and that caused by the freely falling debris. The latter contributes a substantial part of the total load and is responsible for the peaks.

As high frequencies are excited, the modelling of the structure has to be rather detailed. This aspect is discussed in Section 2. For an adequate finite-element model, the influence of the load vector, the stiffness matrix, damping matrix and mass matrix on the response is analysed. This parametric study is performed in Section 3. Finally, tentative conclusions of these preliminary investigations are summarized in Section 4. Further research is needed in this area.

2. MODELLING OF STRUCTURES

The response spectra in a point of a typical reactor building, which is described further on (Fig. 4), for a SSE of 0.22 g free-field acceleration and for a horizontal impact of a Boeing 707 (Fig. 1, solid line) are compared in Fig. 3 (7 % structural damping). In the range of higher frequencies, in this case above 5 Hz, the loading case of an airplane crash becomes dominant. While the acceleration caused by the SSE converges to that of the structure (0.35g) at approximately 20 Hz, the response of an airplane crash fluctuates substantially even above this frequency, converging to a much higher value (2.5 g) not until 200 Hz. This dominance in the high-frequency range is caused by the content of high frequencies present in the force-time curve of the airplane crash and by the small area of loading, which leads to the excitation of higher modes. Thus the modelling of the structure has to be rather detailed. The local behaviour has to be adequately represented, and modes up to 100 or 200 Hz must be included. Consequently, the familiar beam models used successfully in earthquake analysis cannot be applied for shell and folded-plate structures. To demonstrate this, the dynamic models of a typical reactor building and of a reactor auxiliary building for an impact of a Boeing 707 are discussed.

The axisymmetric reactor-shield building of Fig. 4b is modelled with 36 curved frusta leading to 333 degrees of freedom for each of the 16 Fourier terms needed to represent the rectangular impact area of the horizontal loading case. The vertical impact acting on an equivalent circular loading area excites only the zero'th harmonic. The beam model of Fig. 4a with 52 nodes is used for comparison.

As can be seen from Fig. 5, the beam solution underestimates the accelerations for horizontal and vertical impact by one order of magnitude. Although the beam model can easily represent modes up to 200 Hz, the assumptions of Bernoulli-Navier turn out to be incompatible with the actual behaviour of a locally loaded shell.

Assuming symmetry of the structure, a quarter of the reactor auxiliary building is modelled (Fig. 6) using 601 plate elements (in bending and in stretching) for walls and floors, 16 beam elements for columns and 273 spring elements for the soil. This results in 2684 dynamic degrees of freedom for each set of boundary conditions. The response spectra (Fig. 7) for two locations on the same floor as the point of impact again underlines the importance of adequate modelling. Obviously the effect of the diminishing response parallel to the direction of impact and the increase perpendicular to it at Points A and B cannot be achieved using a vertical-beam model.

For the two models mentioned above a linear elastic analysis with 7 % modal structural damping is performed. The equations of motion are integrated in the time domain using the constant-acceleration method of Newmark, which does not numerically introduce any amplitude decay. The time step is selected as 1/10 of the smallest period represented, i.e. 0.0005 s. To represent the high frequencies properly, the frequency-response method could be used. However, to remain consistent when introducing material nonlinearity (Section 3.2), a method working in the time domain is selected.

3. PARAMETRIC STUDY

The differential equations of motion are given as

$$[M] \cdot \{\ddot{u}\} + [C] \cdot \{\dot{u}\} + [K] \cdot \{u\} = \{F(t)\},$$

where $\{u\}$ represents the displacement vector, $\{F(t)\}$ the load vector, $[K]$ the stiffness matrix, $[C]$ the damping matrix and $[M]$ the mass matrix. A dot denotes differentiation with respect to time. In the following the influence of each of the three matrices and of the one vector on the response is examined separately and compared to the solution obtained with a lumped-mass, undamped linear-elastic system subjected to the polygonal approximation of the force-time curve. The constant-acceleration algorithm of Newmark with a time step of 0.0005 s is used for all examples.

3.1 Force-Time Relationship

The five-span beam shown in Fig. 8, which has typical dimensions as encountered in a reactor auxiliary building is used for further investigations. As the impact area of the Boeing 707 is approximately 12.0 m by 3.0 m (Fig. 1), the force acting (symmetrically) on the beam is about 1/12 of the total force.

Any approximation of the force-time curve which exhibits the same peak-force, total impulse and duration of impact, as developed by Riera [3], results in adequate dynamic stresses of the supporting structure. However, for the response spectra used for the analysis of equipment, the actual shape of the force-time curve is of paramount importance. For illustration, the polygonal approximation in Fig. 1 is represented by its first eleven and five Fourier terms, which correspond to cut-off frequencies of the series of 30.30 Hz and 12.12 Hz respectively. As can be seen from Fig. 9 the accelerations are reduced by one and two orders of magnitude respectively, based on this smoothing process. However, the polygonal approximation does not lead to conservative results. Using the actual total force (Fig. 2) which exhibits peaks results in a response approximately more than twice as large as that of the polygonal idealized force of the Phantom fighter, as can be seen in Fig. 10.

3.2 Material Nonlinearity

When a structure is subjected to loads which cause partly plastic behaviour, energy is dissipated. This influence on response spectra is investigated using the five-span beam (Fig. 8) subjected to the polygonal force-time curve of the Boeing 707 of Fig. 1. The material nonlinearity is accounted for, selecting an elastic - ideally plastic moment - curvature relationship. For an elastic analysis, the moments at Points A and B are 5.58 MNm and 3.27 MNm respectively. Three elasto-plastic cases are studied. First, the plastic moment at A is chosen as 5.00 MNm while at B the behaviour stays elastic. In the second analysis, Point A remains elastic and a plastic hinge develops at B, as a plastic moment of 3.00 MNm is assumed. In the third case, the moments at A and B are restricted to the values mentioned above, and hence a mechanism forms. The resistance ratio, defined as the ratio of the plastic moment and the maximum elastic moment, is, for all cases, approximately 0.9. For all three cases the plastic behaviour of the structure extends over only a short period. The

response spectra for Points A and C are shown in Figs. 11 and 12 respectively. For the two cases where only one plastic hinge forms, the response is similar to that of the elastic system. For a mechanism, however, the accelerations are increased by an order of magnitude in both points. It is rather surprising that this also happens in Point C, which lies outside the plastic zone.

In order to investigate this phenomenon more thoroughly, it is preferable to study simpler systems as the 1-DOF and 2-DOF systems shown in Figs. 13a and b. As the vertical force-displacement relationship in Point A is bi-linear for all three cases (the second line being horizontal when a mechanism forms) and in Point C for the first case, a parametric study is performed on a 1-DOF system with the bi-linear resistance - displacement relationship of Fig. 13c. With k_e and k_y defining the two spring stiffnesses, $R_e^{\max}$ and R_y being the maximum resistance of an elastic analysis and the yielding resistance respectively, and $|\ddot{u}_e^{\max}|$ and $|\ddot{u}_p^{\max}|$ denoting the maximum absolute elastic and maximum absolute elasto-plastic acceleration respectively, the three ratios defined in Fig. 13c are introduced. Again for the polygonal force-time relationship of the Boeing 707, the acceleration ratio is plotted in a logarithmic scale (Fig. 14) as a function of the natural frequency ($= \sqrt{k/m}/2\pi$) for various resistance ratios, while maintaining the stiffness ratio equal to zero. For this case, the acceleration ratio which corresponds to that of a point located on the mechanisms is, with few exceptions, considerably larger than 1. In Fig. 15, the acceleration ratio is represented as a function of the natural frequency for various stiffness ratios and for a constant resistance ratio of 0.8. Again, in general, the elasto-plastic response is larger than the elastic one.

To investigate the behaviour of a point located in the region of the structure which remains elastic, as e.g. Point C of the five-span beam (Fig. 8), the 2-DOF system of Fig. 13b is used. Point 1 is associated with that part which suffers direct impact, Point 2 the region which always remains elastic. If springs 1 and 3 exhibit elastic, ideal-plastic behaviour, a mechanism forms. If only spring 3 becomes plastic, then local hinges develop between the two regions without any mechanism appearing. To reduce the number of variables for the parametric study, the 2-DOF system is associated with the three-span beam of Fig. 8 (Points A to D only). To determine the spring constants k_1 , k_2 and k_3 , the displacements u_1 and u_2 (Fig. 13b) coincide with the vertical displacements at Point A and C respectively. For these spring constants, the masses m_1 and m_2 are varied, resulting in the first natural frequency up to 100 Hz and the second one up to 200 Hz. The acceleration ratio at Point 2 is plotted in Figs. 16 and 17 for the frequency range mentioned above. For the case in which springs 1 and 3 become plastic (Fig. 16), the acceleration ratio varies between 1 and 19. When only spring 3 yields (Fig. 17), this ratio oscillates wildly in the range of 0.5 and 1.7. The corresponding curves for Point 1 are similar.

Elasto-plastic analysis as discussed above is meaningful only for types of structures such as flat and folded plates. For doubly curved shells, as e.g. the dome of the reactor building, an analysis up to rupture shows that significant nonlinear behaviour occurs only in the zone of impact and that failure is caused by compressive stresses (Fig. 22 of Ref. [5]).

3.3 Damping

The influence of structural damping on the response is examined using the model of the reactor shield building (Fig. 4b). The response spectrum for the crash of the Boeing 707 at the location of impact is only slightly reduced when 7 % modal damping is introduced in the analysis (Fig. 18). For a location at some distance, the reduction in accelerations is more pronounced.

As the structural system in each mode behaves essentially as a narrow-band filter, the introduction of the more realistic hysteresis type of damping instead of the viscous type will lead to the same results from a practical point of view.

3.4 Mass Representation

All response spectra are calculated using lumped-mass matrices. Other representations of the mass, such as the consistent-mass matrix and the average of the two, lead to nearly identical results. For the five-span beam the accelerations differ by less than 4 %.

Another aspect of the mass representation concerns the mass of the crushed part of the aircraft. The force-time curves are established assuming an ideal-plastic impact on a rigid wall. For an impact on a flexible structure, no such relationship can be established a priori. In a rigorous analysis, the aircraft and the structure have to be included in the same dynamic model. As an approximation, the mass of the crushed part of the aircraft, which increases during impact, is added to that of the structure in the dynamic analysis. This is at least consistent with the assumption of an ideal-plastic impact. The original force-time curve is kept. An upper bound of the influence of these additional inertia forces can be established by adding the total mass of the aircraft to that of the structure in the impact area for the complete dynamic analysis. For illustration the impact of the Boeing 707 on the five-span beam (Fig. 8) is used. Response spectra are shown for the elastic analysis and for the case in which plastic hinges develop at Points A and B (mechanism) in Fig. 19. When the mass of the aircraft is included, the response in the high-frequency range is reduced and the maximum response arises at a somewhat lower frequency.

4. CONCLUSIONS

The following tentative conclusions regarding the response of equipment to an aircraft impact are reached:

1. As for the loading case of earthquake, the response of the protecting structure and of the equipment has to be determined. A typical response spectrum shows that the airplane crash is dominant in the high-frequency range when compared to the effect of a SSE.
2. Detailed structural models capable of representing local behaviour of high frequency have to be used.
3. The actual shape of the force-time relationship is of paramount importance.

4. In an elasto-plastic analysis without mechanism, the response can be increased or diminished compared to that of an elastic analysis. If a mechanism forms, the accelerations throughout the structure will, in general, increase by one order of magnitude.
5. Structural damping leads to smaller response. This effect is more pronounced as the distance to the point of impact is increased.
6. Further insight into the phenomenon of the airplane crash can be gained by including the aircraft and the structure in the same dynamic analysis.
7. The response of equipment can be drastically reduced by considering the following possibilities:
 - a) Shock-absorbing devices for support of equipment.
 - b) Shock-absorbing shielding and supporting structures, e.g. separation of outside walls and roofs from internal structure, preferably on its own foundation, dummy floors on rubber bearings.
 - c) Spatial separation of redundant systems.

References

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Fig. 1 Force as a Function of Time (Boeing 707)

Fig. 2 Force as a Function of Time (Phantom, Fig. 3 of Ref. [4])

Fig. 3 Horizontal-Response Spectra (0.5% Damping), Point A, Reactor Shield Building

Fig. 4 Dynamic Models of Reactor Shield Building

Fig. 6 Dynamic Model of Reactor Auxiliary Building

Fig. 5 Response Spectra (1% Damping), Reactor Shield Building (Beam/Shell Mode)

Fig. 7 Response Spectra (1% Damping), Reactor Auxiliary Building for Impact in y-Direction

Fig. 8 Five-Span Beam Model

Fig. 9 Shape of Force-Time Relationship, Boeing 707, Response Spectra (1% Damping), Point C, Five-Span Beam

Fig. 10 Shape of Force-Time Relationship, Phantom, Response Spectra (scaled to 1.0 g, 1% Damping), Point C, Five-Span Beam

Fig. 11 Nonlinear Material Behaviour, Response Spectra (1% Damping), Point A, Five-Span Beam

Fig. 12 Nonlinear Material Behaviour, Response Spectra (1% Damping), Point C, Five-Span Beam

a) 1-DOF SYSTEM

b) 2-DOF SYSTEM

c) FORCE-DISPLACEMENT RELATIONSHIP FOR SPRINGS

Fig. 13 Systems and Nomenclature of Dynamic Elasto-Plastic Investigations

Fig. 14 Acceleration Ratio for 1-DOF-System with Variable Resistance Ratio and Zero Stiffness Ratio

Fig. 15 Acceleration Ratio for 1-DOF-System with Variable Stiffness Ratio and Resistance Ratio of 0.8

Fig. 16 Acceleration Ratio of Mass 2 of 2-DOF-System with Elasto-Plastic Behaviour of Springs 1 and 3

Fig. 17 Acceleration Ratio of Mass 2 of 2-DOF-System with Elasto-Plastic Behaviour of Spring 3

Fig. 18 Structural Damping, Horizontal Response Spectra (1% Damping), Reactor Shield Building (Shell Model), Horizontal Impact

Fig. 19 Mass of Aircraft Attached to Structure, Response Spectra (1% Damping), Point C, Five-Span Beam