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AIRCRAFT IMPACT: CRITICAL ASPECTS OF COUPLED DYNAMIC SIMULATIONS

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ABSTRACT

During the last five decades, the load case "aircraft impact" changed constantly with regard to the definition of the threat but also to the applied analysis methods and the required checks. On the one hand, the load case was extended from military aircrafts to commercial aircrafts and on the other hand, the rapid development of computer hardware allowed more and more complex numerical simulations with detailed modelling of aircraft and building structure in a coupled analysis. Keeping this development in mind, as well as additional confidential aspects, increasing authorities' requirements and the lack of detailed normative guidelines, these kind of specialized analyses can only be performed with deep knowledge not only of the general aspects of the aircraft impact load cases but also of the complex numerical modelling and simulation of these situations.

This paper summarizes some of the main issues regarding the actual state-of-the-art Aircraft Impact Analysis (AIA) and points out the most discussed topics with focus on coupled dynamic simulations. On the one hand, the definition of load scenarios and the extended possibilities of aircraft modelling up to the complex use of particle elements are emphasized and on the other hand, the modelling of the structural resistance with the aim of a realistic simulation of the damage state and the induced vibrations is discussed.

One of the main conclusions for a state of the art Aircraft Impact Analysis (AIA) is the recommendation of a detailed numerical aircraft model or at least of the center wing box and the attached wings and a coupled dynamic simulation with the impacted structure. Only this approach includes the consideration of local impact effects and leads to a realistic assessment of the local shear behavior of the structure.

INTRODUCTION

At the beginning of this paper the approach of a probabilistic risk assessment and the definition of possible intentional aircraft impact assessments is briefly addressed. Subsequently, critical issues of the aircraft modelling process, e.g. stiffness of relevant parts or the assumptions of mass distribution are discussed. The following topic is dealing with the analysis of the local structural resistance of the impacted structure. Nonlinear material definitions of the concrete and the reinforcement bars, e.g. strain rate effects, fracture energy and failure criteria are critically discussed with regard to experimental data and normative requirements. The last chapter is focussing on the induced vibration from an aircraft impact and is dealing with different approaches of the corresponding analysis.

DESIGN BASIS FOR AIRCRAFT IMPACT ANALYSES

Probabilistic risk assessment

At the beginning of an aircraft impact assessment a probabilistic risk assessment of accidental impacts with generic aircraft crash rates is required (e.g. Byrne (1997). Based on this risk assessment and the final calculation of the specific crash probability for different aircrafts it is to judge what load scenarios should be treated as a **D**esign **B**asis **A**ircraft **I**mpact (DBAI) or as a **B**eyond **D**esign **B**asis **A**ircraft **I**mpact (BDBAI). Alternatively, certain scenarios can be completely screened out from the assessment. Acceptable limits for probabilities of occurrence have to be specified by the authorities. A typical value for the screening out level is mentioned in Safety Guide No. NS-G-3.1 (2002) with a limit probability of 10^{-7} per year. The categorization in a DBAI or in a BDBAI leads to different safety requirements concerning the assessment of the structural resistance.

Intentional aircraft impact

Besides the probabilistic risk assessment, an intentional aircraft impact assessment can additional be defined by site specific regulations and requirements. Typically, the definition of an intentional impact assessment requires the consideration of a commercial aircraft impact. The definition of the specific aircraft type, the impact velocity and the mass distribution vary for each use case and are defined by the local authorities. However, at the end of the screening process and possible definitions of intentional impact scenarios the load scenarios must be quantified for further assessments.

ADVANTAGES OF A DETAILED MODEL OF THE AIRCRAFT

In principle, there are two approaches for determining the impact of aircraft crashes: the "classical" approach using load-time functions, e.g. as described by Riera (1968), and the explicit modeling of the aircraft and an impact analysis using a coupled model containing the building and the aircraft.

The use of a detailed numerical model of the aircraft (as shown in Figure 1), offers - in extension to the conventional approach by incorporating a load-time function - the opportunity to examine various load scenarios with different impact angels, different mass distributions or different modelling approaches e.g. the fuel idealization with particle elements. The extended possibilities of the modelling and application of the aircraft impact lead to large number of load case scenarios that could be considered. In terms of an economical processing, the responsible engineer has the task to choose which scenarios are relevant and should be taken into consideration.

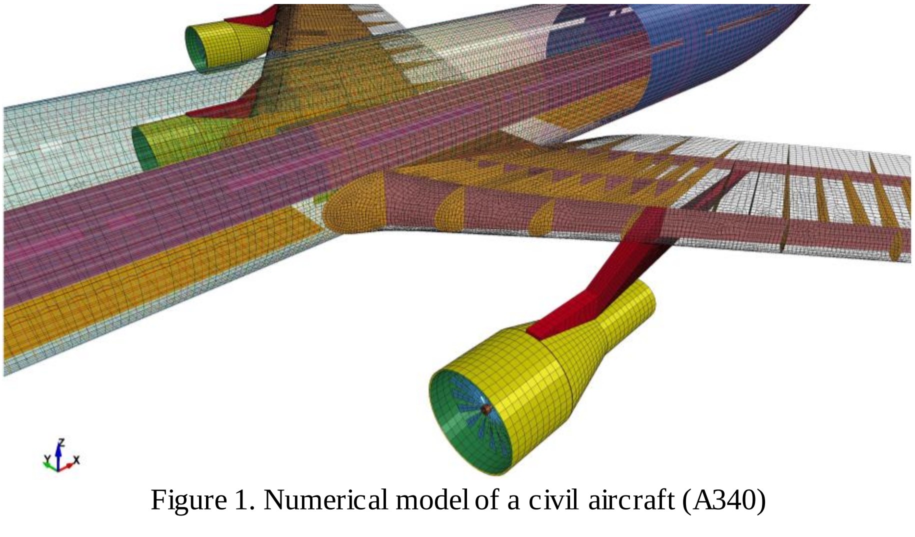

Figure 1. Numerical model of a civil aircraft (A340)

Coping with lacking information

For the idealization of an aircraft, information about stiffness and mass distribution are required. However, detailed information about the aircraft structure are not open source data and even if some data is provided by the aircraft manufactures, engineering assumptions are mandatory because either information is missing or the available information is unsuitable for engineering modeling. It is to mention, that this is mandatory for a detailed numerical model as well as for a simplified analytical Riera model.

The assumptions and mandatory verifications for the aircraft mass distribution in a detailed numerical model or a simplified Riera model are mostly based on semi-empirical methods, e.g. Kundu (2010). Different types of semi-empirical weight-prediction formulas have been proposed by various analysts. Although all of the formulas have similarity in the basic considerations, their results for the different parts of the aircraft could differ by as much as 25% if no detailed information about the mass distribution are available.

The prediction of the crushing behavior is even more complicated, as the exact crushing behaviour is not only determined by the section area itself but also by local buckling effects that are caused by the relatively thin structural parts and the effective buckling length. A numerical modelling of these local effects is in general not within the scope of a civil engineering modeling approach. Keeping this in mind the estimation of the crushing behavior includes certain uncertainties. However, the considered stiffness in the numerical model has only a small effect on the maximum impact force for high impact velocities and relatively small crushing forces. This conclusion is verified with a simplified Riera model and different approaches for the crushing behavior. The results are visualized in Figure 2, with a comparison of two load functions that are based on a best estimated crushing behavior (100% PC) and on a crushing behavior half of the best estimated one (50% PC). Both load functions are derived for an impact velocity of 190 m/s.

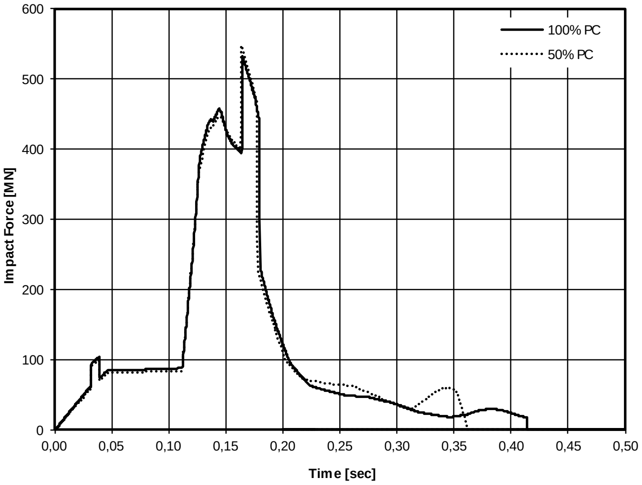

Figure 2. Comparison of load functions with 100% and 50% crushing behavior assumption

Crucial impact and resistance

It is to point out that in numerous coupled numerical simulations of aircraft and building structure with typical impact velocities, it was observed that the impact of the center wing box of the aircraft was the crucial simulation step for the assessment of the structural resistance. Compared to the impact with the fuselage, the impact with the center wing box contains significantly more stiffness and a larger mass ratio. Furthermore, it was noticed that for typical well-reinforced reactor buildings, the shear behavior is decisive for the resistance of the structure. This leads to the conclusion that the idealizations of the stiffness of the center wing box, the contributing masses at that time of impact, the impacted areas and the impact angel are crucial for the reaction of the civil structure. The damage accumulation in the local impact area of the structure before and after the impact of the center wing box has a minor influence on the structural limit resistance.

Considering the fact that the shear forces during the impact of the central wing box determine the structural resistance, it is mandatory to analyze this local impact situation in detail. The use of conventional approaches with the help of Riera load functions and rough estimated impact areas tends to produce optimistic results with respect to the shear resistance, as these approaches are not capable to consider the local effects of the wing box impact. The use of a detailed numerical model of the aircraft or at least of the area of the center wing box and the attached wings is clearly recommended. In addition, several studies with varying stiffness of the center wing box and the wing connection, different approaches of contributing masses in combination with varying fuel filling states and different impact angels should be performed to guarantee the robustness of the numerical results.

As a state of the art approach for the fuel modelling, it is possible to idealize the fuel as separate Smooth Particle Hydrodynamics (SPH) elements, which are not tightly connected with the structure and could spread out independently and obtain large changes in place. This approach leads to a more realistic load situation but requires advanced numerical expertise and hardware requirements. An example of this modelling technique is shown in Figure 3.

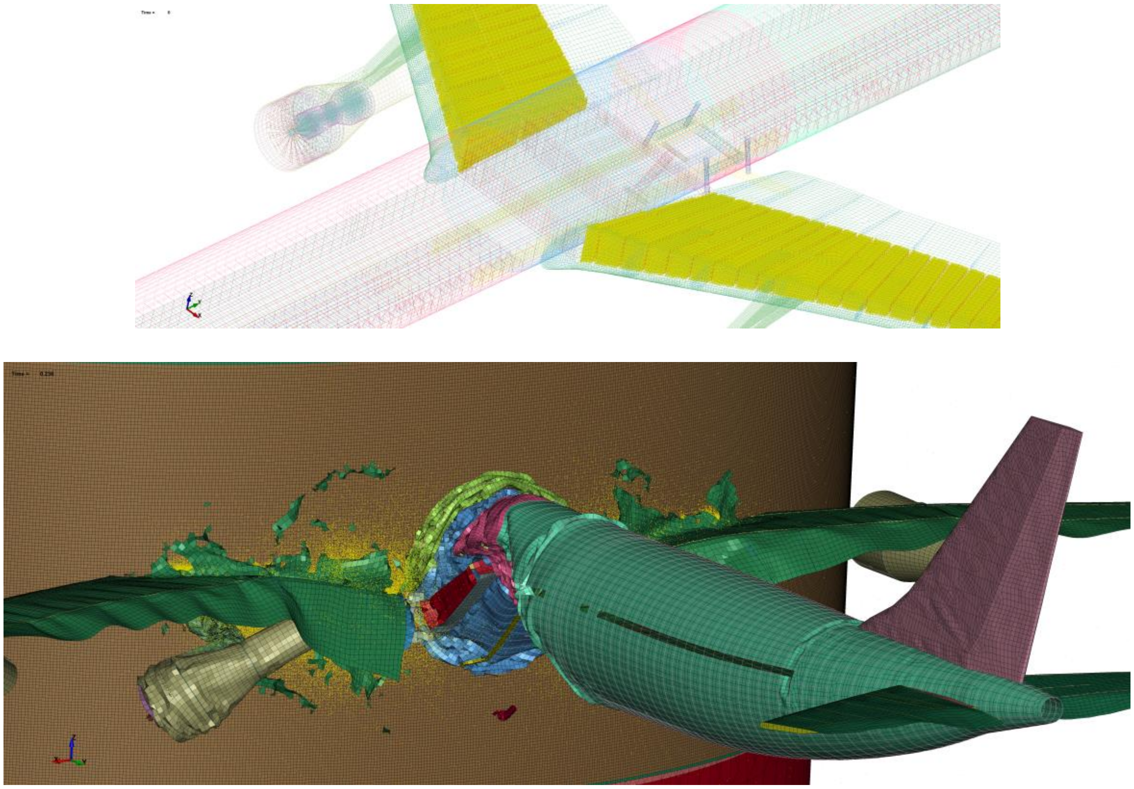

Figure 3. Top: Numerical Modell with SPH Elements for Fuel (yellow)
Bottom: Impact Situation following center wing box impact with spreading of fuel (yellow)

It should also be noted, that a comparison between the resulting load functions of a Riera approach and the numerical aircraft model can only be done in a qualitative way as the Riera approach, in general, does not consider the local impact effects of the center wing box impact and may smooth out local peak forces. If a load function instead of a coupled analysis is used, it is recommended, that these load functions are at least derived for different parts of the aircraft separately (e.g. for fuselage and wings) and applied for different load areas.

LOCAL STRUCTURAL RESISTANCE OF THE IMPACTED STRUCTURE

For the assessment of the structural behavior, it is recommended to use a detailed volume model of the civil structure in the direct impact zone to allow the numerical structural model for possible concrete shear damage patterns besides the general bending behavior. For this purpose, it is proven practice to model the concrete with volume elements and the reinforcement bars with discrete beam elements that are connected to the element nodes of the concrete. For a BDBAI, the occurrence of non-linear material effects in the structure can be accepted as long as the safety requirements are met. To achieve an economic structural design for a BDBAI, it is necessary to include nonlinear effects in the numerical model to get a best estimate approach for the assessment of possible nonlinear damage and the influence on the specified safety requirements. The next paragraph will focus on some critical aspects that are subject to expert discussions. Suggestions are made based on experience of several aircraft impact projects.

Strain rate effects

During an aircraft impact strain rates in the concrete in the range of $5 \cdot 10^{-2}$ up to $2 \cdot 10^{0}$ 1/s may be expected. In order to estimate the ultimate concrete strength and load capacity realistically, hardening effects with regard to strain rates should be taken into account for best estimate results. The consideration of hardening effects has a significant influence on the shear resistance of concrete structures and should therefore be used with care. Common used approaches for considering concrete strain rate effects in compression and tension are documented e.g. in the CEB Model Codes and IAEA Safety Report Series No. 87 (strain rate dependent), extended investigations of the CEB Model Code (Malvar et al. (1989)) or with a simplified approach (constant values) in the NEI 07-13 (2013) guideline. As the various approaches differ from each other (see next figure) the effect of strain rate effects remains a point of discussion between structural design engineers and regulatory authorities and their experts. The discussion may vary, dependent on the safety requirements of the specific load case (DBAI or BDBAI).

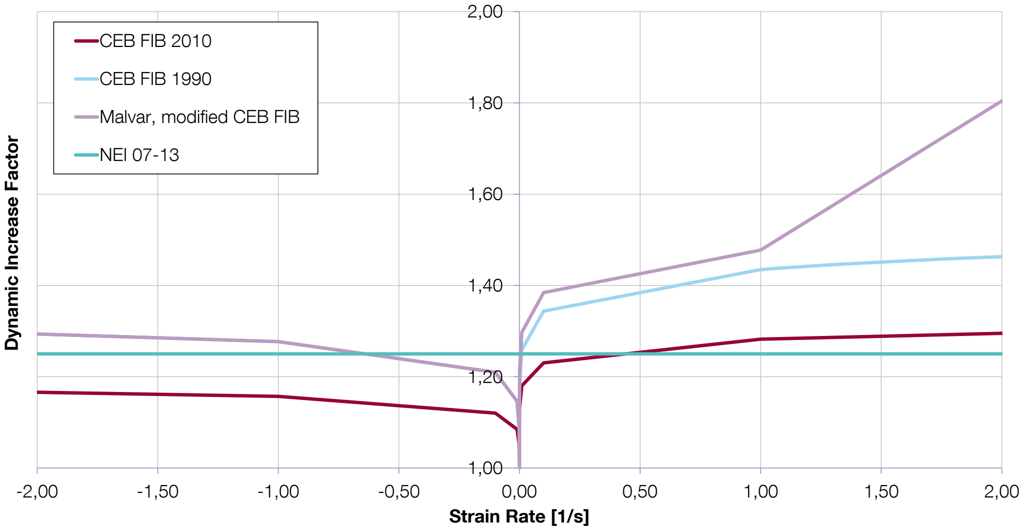

Figure 4. Comparison of different approaches for consideration of strain rate effects for C35/45 (positive strain rates = concrete in tension)

It is not possible to make a final recommendation for all use cases. Compared to experimental results, the choice of the modified CEB FIB approach by Malvar et al. (1989) led to the best fitting numerical results. Based on sensitivity studies, the influence of strain rate effects for concrete in compression was lower than for concrete in tension. Therefore, possible discussions should focus on the strain rates effects in tension.

Strain rate effects for the rebars may be taken into account with the Cowper Symonds approach (IAEA Safety Report Series No. 87). It should be paid attention to an appropriate choice of the input parameter C and P for the Cowper Symonds approach. Various documents refer values of C=40 and P=5 for mild steel, and several aircraft impact assessment documents adopted these values also for the reinforcement bars of nuclear buildings. However, these values do not correspond to typical rebar materials. More reliable values for typical rebars may be taken from Cadoni et al. (2011). For the mentioned approach and for the range of the significant strain rate values for aircraft impact scenarios up to $2 \cdot 10^{-0}$ 1/s the dynamic increase factor is below 1.01 and could also be neglected without great loss of accuracy. It is to mention, that NEI 07-13 suggests significant higher dynamic increase factors for rebars with grade 60 between 1.05 and 1.10. With respect to the experimental results from Cadoni et al. (2011) these values should be challenged for future aircraft impact assessments.

Fracture energy of concrete

Results of nonlinear analyses may strongly be influenced by the concrete softening behavior, depending on the specific load case and the amount of nonlinear effects. A direct relation of the softening behavior in uniaxial tension is represented by the fracture energy. The discussion about fracture energy, especially for higher strain rates, is one of the most controversial topics in the field of mechanics. The CEB Model Code from 2010 recommends Equation (1) to calculate the fracture energy.

$$G_F = 73 \cdot {f_{cm}}^{0.18} \tag{1}$$

Compared to test results with ordinary concrete (e.g. the Meppen Tests documented in Jonas et al. (1982)) the application of the equation (1) led to satisfying numerical results. It is to mention, that Equation (1) is referred to normal concrete with common aggregate sizes. For special concretes with smaller aggregate size the CEB Model Code formulation from 1990 seems to be more appropriate, because this approach considers different aggregate sizes.

Finally, it is recommended to check if the chosen concrete material model and the used element size definition can reproduce appropriately the fracture energy for tension loading. If the material model does not include an automatic regularization for different element sizes, it may be necessary to adjust the material property definition differently for various element sizes. A check of the fracture energy can be performed by a quasi-static numerical testing of one single volume element under tension.

Failure criteria

Besides the general nonlinear material definitions, it is necessary to define failure criteria if no damage models with a loss of strength are included in the material definitions. The rebar strain criterion is dependent of the type of rebar that is used in the civil structure. For B500 B rebars, typically used in Europe, the axial strain limit is set to 5%. Alternative values regarding the specific application and specific material tests may be applicable.

For the concrete material, the definition of failure criteria is not straight forward as they vary for different states of triaxial pressure. However, commonly used material models for concrete already include a damage model that takes account for a loss of strength in compression and tension after reaching certain triaxial pressure and strain limits. A possible methodology to link the numerical results with a statement to the expected damage state is the evaluation of the concrete shear strain values. For the definition of the structural integrity of the concrete structure NEI 07-13 suggests a failure criterion of 0.5% shear strain if these values could be observed in a closed punching cone through the complete thickness of the impacted structural part. It is recommended to check, if this failure criterion corresponds to the used material model. With regard to a four point bending test of a concrete beam without shear reinforcement, a sudden shear failure when concrete shear strains were reaching 0.5% was reproduced in a numerical simulation successfully (see Figure 5).

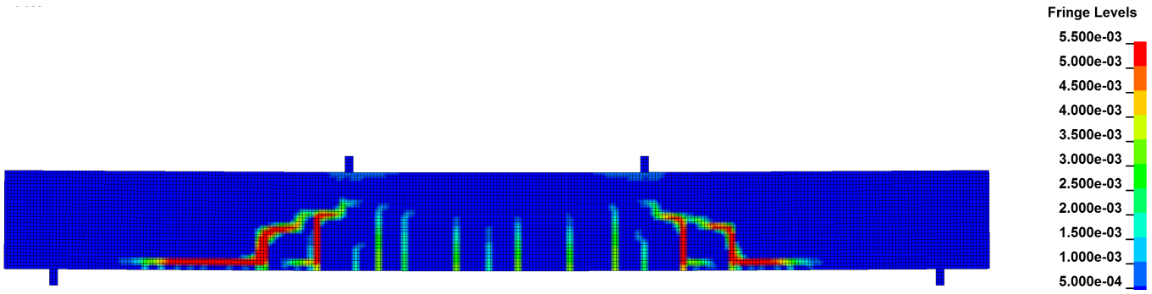

Figure 5. Visualization of concrete shear strains right before sudden shear failure occurs

The above-mentioned failure criterion with respect to a total loss of strength could be verified for reinforced concrete beams without shear reinforcement. Based on the evaluation of well shear reinforced experimental test walls under impact loading and the comparison with numerical results, the allowable concrete shear strains in a closed punching cone could be expected in the range of 5% before a total loss of strength occurs. The structural damage produced by an impact test, with a clearly visible closed punching cone of shear strain in the range of 5%, is shown in Figure 6.

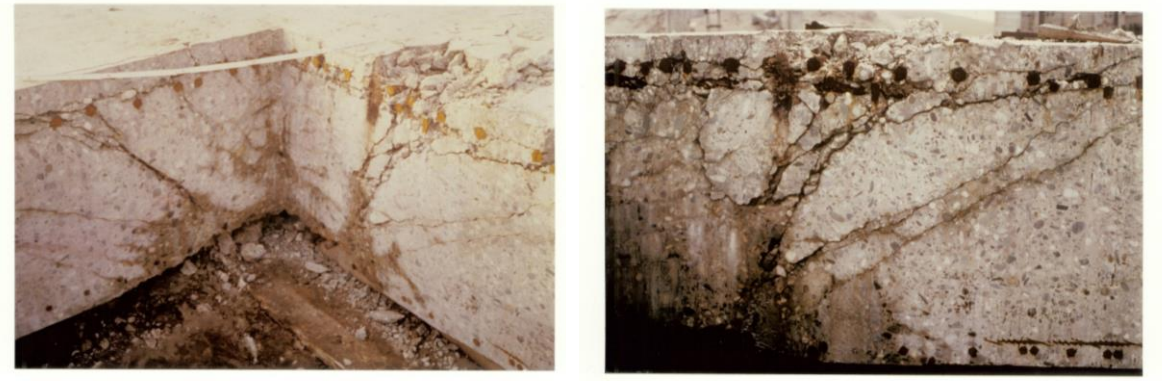

Figure 6. Experimental results of the Meppen II-4 test from Jonas et al. (1982) as reference of an acceptable damage pattern for a BDBAI

Material Verification and Sensitivity Studies

It is the engineer's task to verify the used material definitions. If available, this verification should be done by means of experimental data with large-scale tests, typical concrete types and comparable reinforcement ratios. In order to prove the capabilities and the correct application of the numerical software for the impact simulation of reinforced concrete structures, different loading situations (rigid and flexible) and different damage patterns (bending and shear behavior) as well as quasi-static tests should be considered in the numerical verification process.

If conclusions to the structural resistance and the compliance of radiological requirements are based on significant nonlinear structural effects, the robustness of the numerical model should be proven. For this purpose, sensitivity studies are recommended. The suggested sensitivity studies should include the variation of mesh size, of concrete compressive and tensile strength, of strain rate effects and of fracture energy.

INDUCED VIBRATIONS

Apart from the assessment of the local and global structural capacity of civil structures, the impact-induced vibrations and their effects on installed components may also be of concern. The assessment of induced vibrations is usually a downstream step following the analyses of the structural resistance. In principle, decisions must be made whether the analyses of the induced vibrations should be performed using the same model as for the analysis of the structural capacity. If so, nonlinear effects in the impact area could be taken into account. However, nonlinear effects can also be included in the analysis model of the induced vibrations regardless of this, e.g. in the zone of the component connections. Thus, the methods can range from detailed nonlinear finite element analyses to relatively simple analysis methods. The decision regarding suitable and applicable methods for the analysis of induced vibrations depends on numerous constraints. These include, among others:

- new design or assessment of existing structure (building and/or component)
- design basis event (DBAI) or beyond design basis event (BDBAI)
- complexity of the building structure (geometry, structural detailing, etc.)
- local and global structural capacity and load-bearing capacity
- type of failure mechanism (local and/or global, possibly in combination)
- location of the component / distance to the impact location
- loading from deformations of structural elements occurring simultaneously with the vibrations
- requirements on the integrity of the component

Choice of modelling approach / Approaches to a double-shell structure

In consideration of the main conditions to be taken into account for the aircraft impact load case, following approaches are generally used to determine the induced vibrations (as already mentioned above in context with the analysis of the structural capacity):

- Coupled approach: The structure and the aircraft are fully modelled with finite element software in order to analyse the direct interaction and induced vibrations (3d fully coupled analysis). The coupled model is usually generated with non-linear elements and material properties.
- Decoupled approach: The civil engineering structure is represented in a numerical model to a greater or lesser degree of detail. The impact analysis is performed by applying a load-time function.

In order to illustrate the decision-making process which approach is ideally applied, the boundary conditions and expected results are presented and discussed using a typical example of a pressurized water reactor building. Typical for this type of building is the concept of decoupling the internal and external structure.

Obviously, the design of the structure or building where the induced vibrations must be evaluated plays an important role. The shielding against impact (outer shell) is usually of high resistance and made of highly reinforced concrete. Connections to the inner structure are usually in far distance to the impact area. Typically, the shielding is connected to the base plate only. If the inner structure is separated this way, the shock waves generated by the impact can only travel to the foundation and from there on to the point of interest (see Figure 7). During the propagation from shielding to the inner structure, the shock waves will be filtered and reduced in amplitude significantly. In contrast, structural elements or components in direct vicinity of the location of impact, e.g connected to the outer shell, are exposed to very large shock waves with very high acceleration values.

Selecting an effective approach of analyzing the induced vibrations should be based on the behavior of the shielding at the impact zone. The decision which approach should be used depends on allowable and expected deformations as well as structural effects like bending or shear failure. If deformation, bending and shear behavior of the shielding can be expected to be in a certain range, that excludes failure, a decoupled approach is feasible.

A prior analysis, which considers the failure of the aircraft and possibly also the local failure only in the direct impact area, is an efficient option to be considered under these boundary conditions. With this only one non-linear finite elements analysis is needed to determine a nearly realistic load function of the impact. This will reduce the extent of the analysis since modelling and analysis of non-linear finite element models takes much more effort. The second model to determine the induced vibration can be much more simpler. A linear elastic finite element model with good and detailed modelling in the area of interest will be adequate. A simpler second model opens also the possibility to apply the impact load on much more areas of interest due to the quicker analysis run of a linear model. If induced vibrations are determined with a linear elastic analysis model, the results may be more conservative due to the elimination of non-linear effects during load transfer. However, in some cases the results can also be too conservative due to neglecting of global effects.

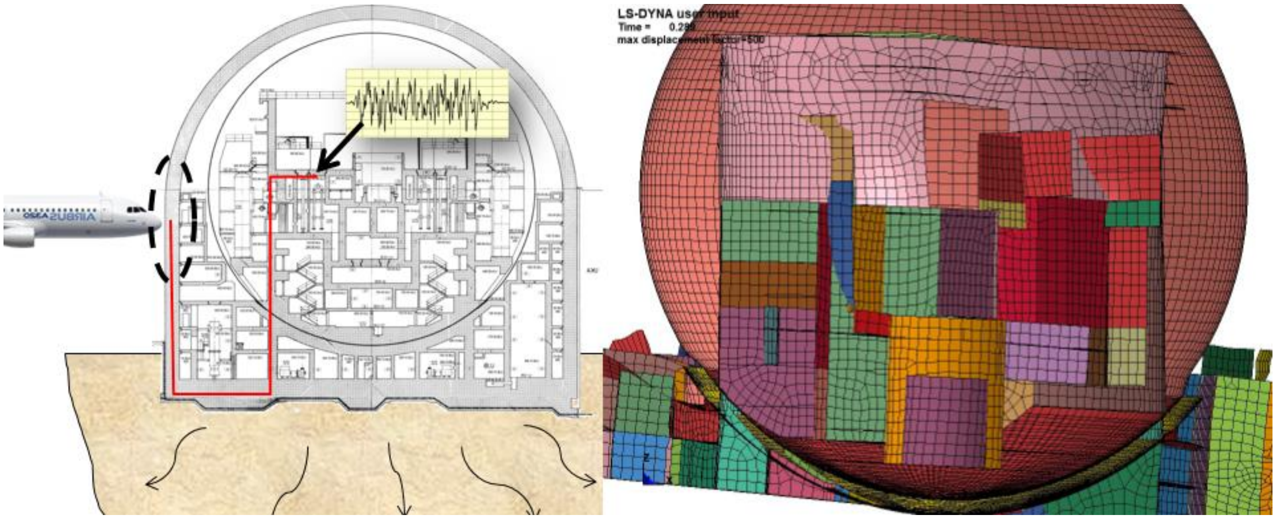

Figure 7. Induced vibrations on a PWR; left: Propagation path of the vibration waves; right: oscillating internal structure.

A fully coupled analysis for instance, will better picture the interaction of global and local behavior. The coupled approach can include in one analysis run the global stability, the local structural resistance and soil structure interaction, if modelled, as well as high energy dissipation and reduction of the forces transferred. The set backs are the large effort in modelling, analysis time and the intense evaluation needed to assess the results of the non-linear analysis.

Coupled approaches should be used in any case if the behavior of the shielding is nonlinear and the shielding is directly connected to the internal structure.

Acceleration and displacement response

The vibration response extracted from the analysis of a finite element model includes usually a huge range of frequencies. In order to correctly identify and assess the dynamic behavior of structural parts or components the time histories of the determined response should be truncated to a range of significant frequency content.

The truncated or filtered time history response could be used to design or assess internal structural parts or components directly. However, typically a determination of response spectra is performed, because thereby enveloping and/or quasi-static analysis become possible. The determination of response spectra is the more preferred way, especially in assessment of existing structures and components where design spectra already exist.

A response spectrum for a certain location inside the structure under consideration can generally be determined for all motion quantities (e.g. acceleration, velocity, displacement). Usually, components or internal structural parts are designed or assessed by using acceleration response spectra. For design purpose the uncertainties of modelling, structural behaviour and material definition are usually taken into account by enveloping, broadening and clipping the peaks of a response spectrum. However, in assessments of existing structures and components considering beyond design events, the smoothing of the determined response spectra may not be applicable (best estimate approach).

Due to the shock excitation, response spectra determined from impact analysis result in very high spectral acceleration values, especially for high frequencies. However, the associated spectral displacement values are often very small, so that it can be expected that there will be no significant excitation of the component. Therefore, it is reasonable to determine both acceleration response spectra and displacement response spectra. On this basis, the engineer can make decisions and recommendation in the design process and assess the resistance of the component efficiently. For example, if the engineer assesses a component for induced vibration and the eigenfrequencies of the component are known, then it is possible to show functionality and integrity of the component by simple design criteria, such as the 1-mm rule of the displacement response spectra. The 1-mm rule for components is a common used approach and based on the fact that the allowable displacement of 1 mm can usually be absorbed by plastic deformation or possible movements at the supports of a component.

CONCLUSION

This paper summarizes a typical process of an Aircraft Impact Analysis (AIA), beginning from the definition of load scenarios, the development of finite element models of aircraft and structure and finally leading to a realistic assessment of the resulting structural damage and induced vibrations.

It is to emphasize, that in numerous coupled numerical simulations of aircraft and building structure with typical impact velocities, the impact of the center wing box of the aircraft was the crucial simulation step for the assessment of the structural resistance. Therefore, one of the main recommendation for a state of the art Aircraft Impact Analysis (AIA) is the consideration of a detailed numerical aircraft model, especially of the center wing box, and the approach of a coupled analysis. Only this approach allows the necessary detailed analysis of local impact effects and finally leads to a complete assessment of the structural resistance.

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