Large Commercial Aircraft Crash into the Light-weight Nuclear Facility Building

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ABSTRACT

The paper deals with the analysis of large commercial aircraft crash into the light-weight construction of nuclear facility building as a result of terrorist attack. Importance of this loading rises after September 11 and knowledge of response and realistic resistance of the nuclear facilities structures is required. The paper links up to the paper presented at SMiRT18 international conference – [1]. That paper presented possibilities of application of aircraft crash loading on the building structure, determination of loading parameters (aircraft velocities, angles of impact) and introducing into the FEM models. Information was provided on the analyses results of aircraft crash scenarios performed for Interim Spent Fuel Storage Facility building structure. Presented building structure was enough rigid and mass and the aircraft structure was destroyed after impact. As a result, the stored spent fuel containers were hit only by relatively small aircraft and building structure debris with low remain velocity. On the contrary, the building structure presented in this paper is light-weight and has small resistance against large commercial aircraft crash. After impact, the aircraft breaks cladding of building structure and penetrates into the building interior. The aircraft structure is disintegrated into relatively large and mass parts with high velocity. Therefore, there is need to analyze not only the moment of aircraft impact on the building structure but also the motion of aircraft through the building and interaction of aircraft with interior building structure and installed technology. The problems of aircraft crash into the light-weight construction is demonstrated for the case of Interim Spent Fuel Storage Facility building structure located in NPP Dukovany area.

INTRODUCTION

Criteria for nuclear device location consider the suitability of a site from the aircraft crash probability viewpoint. The aircraft crash probability is based on aircraft accident statistical data and on distance of the site from airports and traffic corridors. If the probability of aircraft crash with impact exceeding building resistance is higher than 10^{-7}/year the site can only be used if impact of aircraft crash is taken into account in construction. As far as the analyzed Interim Spent Fuel Storage Facility building located in NPP Dukovany area is concerned, the calculated probability of aircraft crash of any category and weight is lower than 10^{-7}/year, which means that it is not necessary to add extra resistance to the building against the aircraft crash. Nevertheless when designing peripheral building structures (cladding and roof) a crash of an ultra-light plane with maximum weight of 450 kg was considered due to the rapid development of ultra-light plane segment in the Czech Republic.

However this designed load only relates to non-intentional accidents caused by technical failure, pilot mistake or combination of failure of technical and human factors. After tragical experience with terrorist attacks in USA, in which large passenger aircraft have been used, safety of sensitive targets (and therefore also safety of nuclear devices and buildings) has become more important. The Air Traffic Control reacted to these terrorist attacks by restricting the aircraft traffic around nuclear power plants of Temelin and Dukovany. In addition to a previously prohibited area around NPP Dukovany (marked LK P9 on air maps) another restricted area (with so called activation mode) was created around the NPP (marked LK R51). Transiting of this area is only permitted for temporary period and following a special permission. It is only possible to transit this area if both way radio connection with appropriate Air Traffic Control centre (which is the sole authority awarding transit permission) is ensured. For cases of deliberate assaults from air measures excluding or restricting risky sites cannot be defined as all sites are at the same risk to be assaulted. What is more, nowadays it is no longer possible to hide any building and therefore even NPP Dukovany is very easily noticeable on low resolution satellite pictures, which are available to all users of the Internet.

These facts have called for performing analyses of effects of impact of a large passenger plane with Interim Spent Fuel Storage Facility building. The aim of these analyses was not to analyze the safety situation development, probability of terrorist attack or various theoretical ways of building assault and appropriate protection. From the Interim Spent Fuel Storage Facility building structure this is considered as an above project accident regardless the way in which it was induces (e.g. deliberately - terrorist attack or randomly - air crash). The aim of these analyses was to evaluate possible consequences, mainly radiation ones, under extreme external mechanical and thermal conditions, which surpass the testing conditions of container sets imitating external impacts of transport accident. The selected case of airplane crash was therefore selected as a possible initiation event, whose radiation consequences may be used for informative evaluation of gravity of other above project accidents, causing container integrity damage.

Evaluation of load caused by impact with a large passenger plane was based on previously gathered experience from similar analyses, which were prepared for construction of a future Interim Spent Fuel Storage Facility building for NPP Temelin site. Part of these analyses dealt with a possibility of the building being hit by a large passenger plane using the simulator of Boeing B737, which is used for training of crew of this plane. The outcome of this analysis was determination of possible angles of impact and the aircraft speed at the moment of the impact. In analyses of impact of a large passenger plane with Interim Spent Fuel Storage Facility building a Boeing B747-400 plane was used. This type of plane is one of the largest commonly used commercial planes. The results of the analyses are conservative and close to the worst possible consequences of impact of a large passenger plane. Definition of impact angles and speed of the plane, including the computing model of the plane, are described in details in [1].

BUILDING STRUCTURE DESCRIPTION

The Interim Spent Fuel Storage Facility building has a storage capacity to store spent nuclear fuel from NPP Dukovany, which is 1340 t of uranium. This amount of spent fuel can be stored in 133 containers (for 84 fuel assemblies), which, with already full building of Intermediate Interim Spent Fuel Storage Facility building, will store all spent fuel generated during estimated NPP operating life. The operating life of the Interim Spent Fuel Storage Facility building will depend on construction and commissioning of underground storage facility or on review of NPP fuel cycle (system of spent fuel processing), exploitation of new technologies, etc. Between years 2006 – 2013, for which the analyses were performed, 25 containers CASTOR 440/84M is to be stored in the Interim Spent Fuel Storage Facility building (the limitation to this time period was based on a narrow link of performed analyses to a particular and approved containers, which is only known for this initial period). The container CASTOR 440/84M is designed for transport and long-term storage of spent fuel assemblies from pressurized water reactors of VVER 440 type. It consists of a thick wall cylinder body with a closing system comprising two lids (primary and secondary) and of a bearing basket located inside the body, in which the fuel assemblies are stored. The lids are fixed to the body by screws with cylinder head. Primary and secondary lids represent two independent seals of the container. Monitoring of pressure in the area between the lids allows checking of container tightness during storage. As a protection against mechanical impacts and weather conditions a protective slab is installed above the lid closing system.

Layout of the Interim Spent Fuel Storage Facility building is based on technological requirements and connection to already built Intermediate Interim Spent Fuel Storage Facility building. The biggest part of the building is occupied by a single floor storage hall with outer dimensions about 107.9 x 29.3 m. In the hall axis above the storage area there is an air shaft about 10 m wide. The building roof ridge is at about +21.75 m. The bottom edge of the roof girder is at about 15.8 m. The admission section, which is separated from the storage hall by a shielding wall about 6 m high, comprises a railway siding and handling routes for containers, as well as areas for container functional checking and other accessory, storage and workshop areas required for store operation.

The main supporting structure of the hall is divided into two independent dilatation units. The storage building supporting structure consists of reinforced concrete columns (6 m module system). The column cross section is 600 x 1600 mm at the bottom and 600 x 800 mm at the top (over the crane rails). A crane rails, roof steel lattice joining beams and roof structure are fixed to the columns. At the entrance and interconnecting corridor the supporting structure is fully made of steel. The in-building is made of reinforced concrete and of traditional materials.

The supporting structure of the roof cladding in the hall consists of lattice girders made of open profiles (HEA, HEB) and tubes, joining beams are made of HEA 200. The roof slab concrete between lost casing made of profiled metal sheets (concrete layer thickness is 100 mm over the metal sheet rib). Container storage room cladding is made of prefabricated reinforced concrete panels 150 mm thick, which are anchored to the supporting columns. Before the peripheral wall of the storage hall there is another reinforced concrete shielding wall (about 4.8 m high and 500 mm thick). This shielding wall is located at the longitudinal walls at a distance of 1.85 m. At the gable wall the shielding wall 750 mm thick does not overpass the peripheral cladding of the building but is integrated into it.

The container storage room ventilation is of a natural draught type. Inflow holes are located between columns in rows 2 to 14 and are equipped with blinds. The roof of the storage hall is equipped with an intermediate air shaft and blinds.

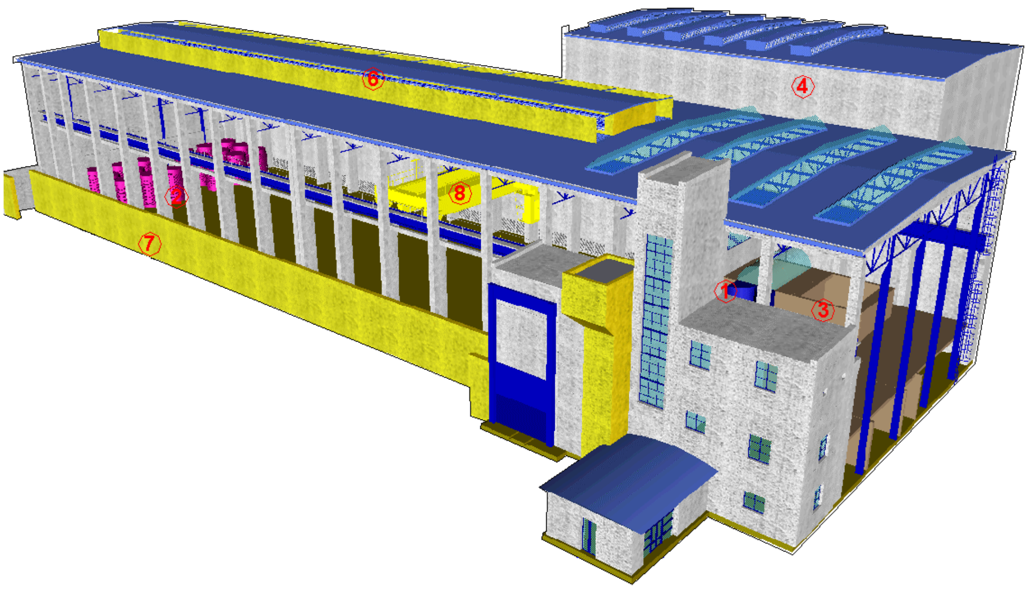

Fig. 1 Global view at Interim Spent Fuel Storage Facility building

PERFORMED ANALYSES AND USED MODELS

Calculation of response of Interim Spent Fuel Storage Facility building structure was made by Abaqus/Explicit software, using the method of finite elements. Input data for calculation were space and material parameters of the aircraft and building and speed and direction of the plane at the moment of impact. Determination of input data for calculation was based on the following assumptions:

- the impact of the plane with the spent fuel storage room is a deliberate assault on the building
- the assault is made with Boeing B747-400 plane
- the assault is aimed to hit the building

Calculations of impact of B747 plane with spent fuel storage room of NPP Dukovany show that the structure of the building cannot bear the impact with such a big plane and the plane will penetrate into the building. In order to add the load caused by the plane to the calculation it was not possible to use already published accessory load curves but a new computing model of the aircraft structure had to be created. The impact of the building with the plane is calculated as the contact analysis of impact of two flexible bodies (building and aircraft). As containers with spent fuel are the target we expected the aircraft hitting the wall of the building with the highest probability of direct hitting of stored containers by the plane. Based on the layout plan of the NPP Dukovany Interim Spent Fuel Storage Facility building two main directions of impact were analyzed - e.g. impact with the gable wall and impact with a longitudinal wall. In addition to these two basic directions of possible assault, in analyses angles of impact between 10° and 35° are considered and two typical layout of stored containers - e.g. either near the gable or in a row along the longitudinal wall of the building. Therefore there are 8 possible combinations of factors based on the direction of impact, angle of impact and container layout. These individual combinations were pre-assessed and for detailed analysis the following combinations were selected:

- impact of the plan with the gable wall of the building (in the longitudinal axis of the building) at an angle of 35°, containers are stored near the gable, the plane penetrates through the gable wall and falls between the containers
- impact of the plan with the longitudinal wall near the gable wall of the building (in the axis of field 2-3) at an angle of 10°, containers are stored near the gable, the plane penetrates through the longitudinal wall and falls between the containers
- the plane penetrates through the longitudinal wall, flies through the hall and hits the row of stored containers. The impact of the plane with the longitudinal wall of the building was (for calculation purposes) selected to be 11.35° (an angle which ensures that the plane fully hits the row of containers at the opposite wall)
- impact of the plane with longitudinal wall at an angle of 35°, containers are stored in a row at an opposite wall, the plane penetrates through the longitudinal wall and falls on the floor in front of the stored containers

The computing model of B747-400 plane was designed with aim to reflect real plane geometry and distribution of mass at least comparable with the rigidity of the plane structure. The model was not designed as a substitute of plane models used by the plane manufacturer. Such precision level cannot be reached as it was necessary to simplify the model and also due to the fact that the detailed documentation of the plane structure is not available. Simplification of the plane structure model is based on the fact (confirmed by analyses of plane behaviour in case of impact) that the major part of the force, which the plane acts on the building is generated by the effects of falling mass and only a minor part of the force is generated by the rigidity of the plane structure. This difference is mainly significant at large passenger planes, where the rigidity of the plane is very low in comparison to forces acting on the building at the moment of impact. Laminated shell elements were used in the model to replace all metal coated parts of the plane (e.g. wings, fuselage, tail surface, cabin, partition walls). For main supports of wings and engines independent elements were created. The engines itself were modelled as a solid element with a ring in the front part. Material parameters correspond to the aluminum alloys (defined using Abaqus classical metal plasticity material model). The model mass enters the analysis in two steps. In the first step the mass of individual parts of the aircraft was considered. In the second step, masses of fuel, transported passengers and cargo was considered at appropriate locations. In both steps the distribution of mass used in analysis was compared to the distribution of masses of a real aircraft. For purposes of the analysis movable parts of wings and tail were also replaced by mass.

When creating a model of a Interim Spent Fuel Storage Facility building structure it was necessary to come to a compromise between the level of model details and model size, which affects the computing time. It was also necessary to consider the fact that this type of a task is a contact type task, which means that not only mass of the structure parts must be considered but also their shape. This was a reason why some parts of the structure, which are normally modelled by a bar type elements, had to be modeled by a different elements, which describe better the structure geometry (e.g. solid elements or shell type elements). Main reinforced concrete columns are modeled by shell type elements. Steel structures of roof, gables and reinforcements are modeled by bar and tube (only axial force) elements. The peripheral cladding, walls and roof slab are modeled by shell type elements. Non-bearing structures (from the hall structure viewpoint) fixed to the main supporting structure are modeled as lumped masses (platforms around the air shaft, corresponding parts of indoor platforms and entrance area). At points where joined parts of the structure do not touch in a single point the joining point of these parts was modeled by rigid joints (connection of peripheral cladding). Rigid joints were also used to model connection between the roof reinforced concrete slab and purlins (longitudinally, the purlin only bears vertical load, horizontal forces are transmitted at the purlin fixation point). The first calculations shown that the plane speed at the moment of impact is so high, that the plane penetrates the building cladding much faster than the structures above the impact area fall down. Based on this experience the computing model was simplified and the roof structure was replaced by lumped masses at fixation points between joining beams and concrete columns. Toughness of the roof structure (concrete slab) was replaced by supports, which capture the horizontal degrees of freedom of the upper edge of columns (axis X and Y) at roof truss fixation points. In the same way the longitudinal span of the model was restricted to rows 1 to 15. Thanks to these simplifications the model size decreased by about a half, which resulted in a considerable decrease of computing time. In addition to the structure of the Interim Spent Fuel Storage Facility building itself also the outer shielding walls and storage hall floor reinforced concrete slab were also included in the analysis. The shielding walls were modeled by shell type elements. The floor slab was modeled as a solid surface and in the model it was used as a support of container structures and prevented the debris of plane or building to fall under the floor level.

Parameters of all materials used in the model were considered also with the non-linear behaviour. The concrete was entered as a type Cracking model for concrete of the Abaqus system, the reinforcement was entered as a Rebar layer parameter. Steel (both reinforcing and structural steel) was entered as a standard material model for steel (Plastic parameter).

As even bigger parts of the plane may penetrate inside the building it was necessary to model the spent fuel containers located inside the building. For purposes of calculation of interactions plane - building a simplified container model was used. The container shape was described by a cylinder, mass distribution corresponds with the mass of the container, lids and content. As far as material parameters are concerned, linear parameters without plastic deformation were used. The result of the calculation from the stored container viewpoint was their path line after the impact with the plane. This path line was used as a basis for subsequent analyses of the containers, which were performed on detailed models.

RESULTS OF ANALYSES

The results of calculations concerning the impact of the plane with the containers were used as a basis for subsequent analyses of fire loads and resistance of the containers. For each option analyzed in details the final evaluation was made following these criteria:

- damage of the plane structure – when the aircraft hits the building the plane gets damaged and comes apart. As the building structure is relatively low resistant to bear the impact with a large plane, plane debris (even bigger ones) penetrate in any case the storage hall. The major debris of the plane is the body. Another important debris is plane engines (in comparison with the body, their mass is lower but they form a compact element with relatively high speed). Based on the calculations the speed of plane debris after penetration through building cladding was determined. Also, consequences of impact of bigger debris with containers were analyzed and based on the extent of plane damage the amount of leaked fuel from tanks was determined.
- extent of damage of Interim Spent Fuel Storage Facility building – this is very important to determine the building debris, which can directly fall on stored containers, dynamic effects of the impact of falling building debris on container lids, which can result in loss of container tightness. Building debris have not such a high speed as the plane debris but in comparison to the plane debris their mass is bigger. Based on the scope of damage, amount of debris which may fall on the containers (or cover them) is determined. This information is important for analysis of fire spread and effects.
- movement of containers – impact of bigger plane debris with containers results in container movement. Based on the calculation results the path line of the most hit containers was determined, which was used as a basis for subsequent detailed analyses of the containers. Movement of containers was always described by movement of 3 nodal points on each container (solid body presumption).

Example of results for option of plane impact with gable wall under the angle 35° is shown in the pictures below:

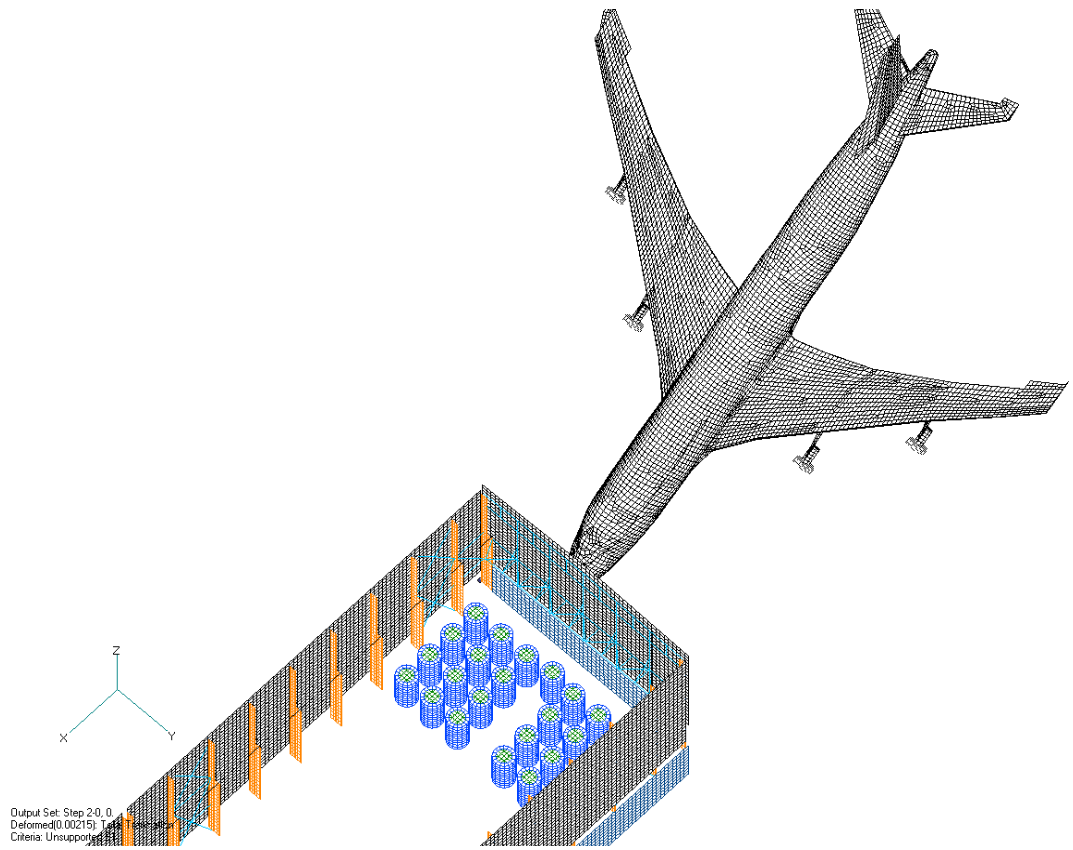

Fig. 2 Time 0 - Overview of initial status for response calculation

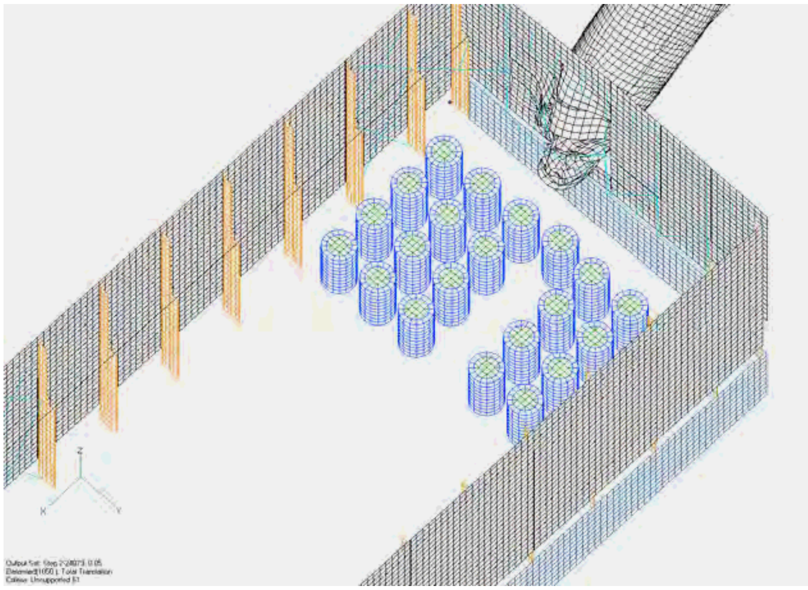

Fig. 3 Time up to 0.05s – After the front of the plane body hits the gable wall of the building the plane shell structure is damaged and the gable wall is broken through. The front part of the plane body penetrates the building and hits the steel columns and horizontal bracing. When the material breaking strength is reached the hit elements are damaged (steel column foot is torn out of the concrete wall in which they were fixed).

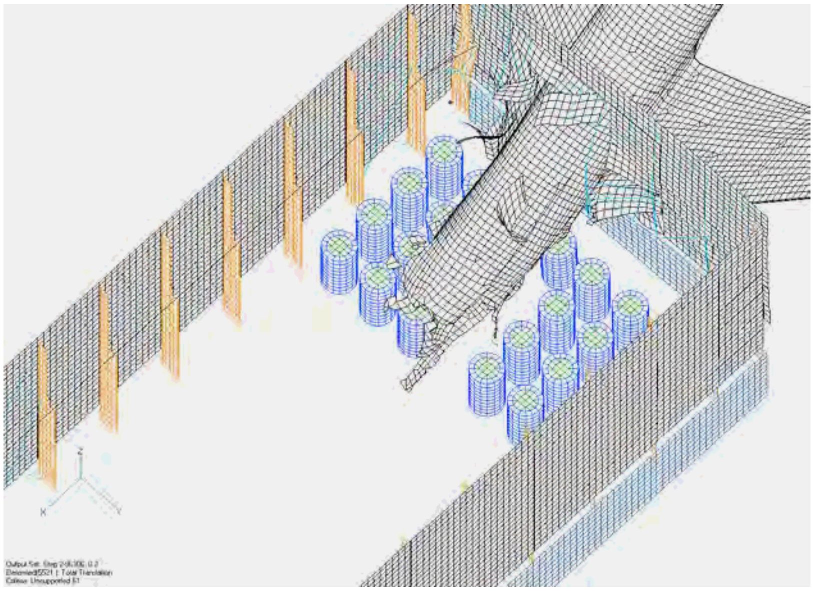

Fig. 4 Time up to 0.2s – The penetrating plane body enlarges the opening in the gable wall up to the full cross section of the plane body. In the second half of this time period the gable wall gets hit by a front edge of the root part of the plane wing. The wing further enlarges the opening in the gable wall and more gable wall columns are torn out of the wall. Plane body penetrates between containers hits the outer containers which start to roll over and move as the plane body hits them in their upper part. As the plane wings are damaged the plane fuel starts to leak inside the storage area of the spent fuel containers.

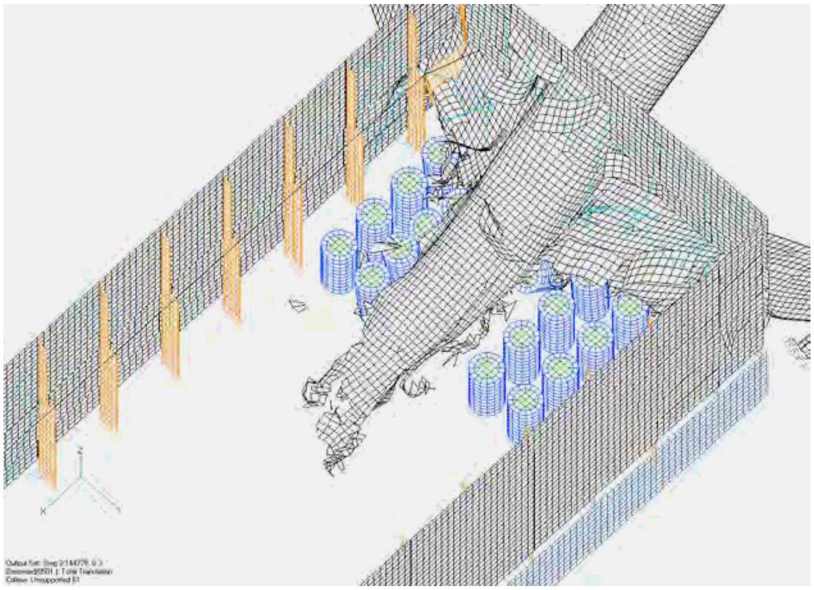

Fig. 5 Time up to 0.3s – At the beginning of this time period the internal engines and wings hit the reinforced concrete columns in row 1. After the impact the columns are rapidly damaged (the force comes from their low bearing direction and an important surface of them is hit). At the same time the containers are hit by a solid intermediate part of the plane body (where the wings and central fuel tank are fixed). The hit containers start to move at higher speed, individual containers hit each other and fall down. As the wings and the intermediate part of the plane body hits the containers, plane fuel tank is damaged and important amount of fuel leaks among the stored containers.

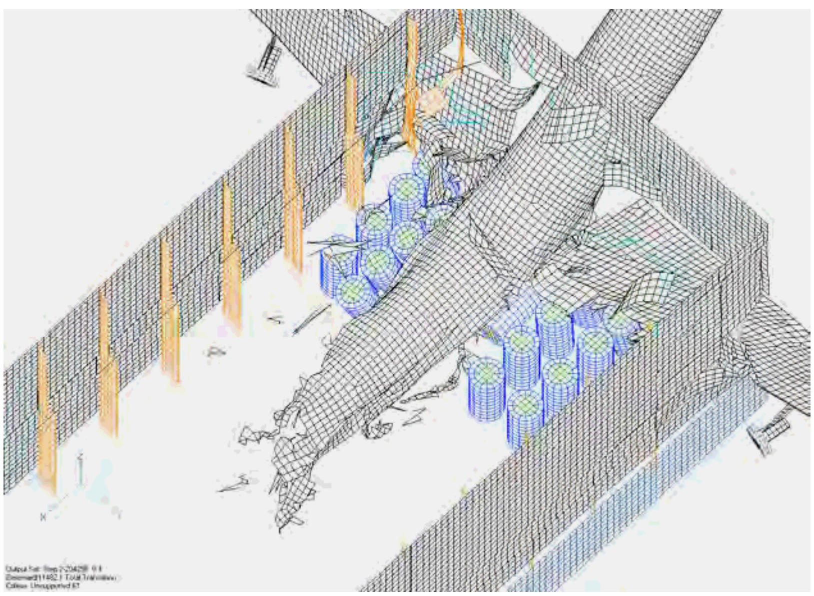

Fig. 6 Time up to 0.4s – Plane kinetic energy is being transmitted to hit containers. Wings hit the reinforced concrete columns in row 2. As the plane wings and body are damaged at the fixation point, the wings come apart. The right wing, which hits the columns near its fixation point to the plane body gets torn out of the body at its fixation point. Due to persistence of motion of the edge part of the wing the wing tends to go out of the building after being torn out of its fixation. The plane left wing hits the columns at a distance further from the fixation point and breaks. The part of the wing which remains fixed to the plane body penetrates between the stored containers with the plane body, the torn part of the wing remains out of the building.

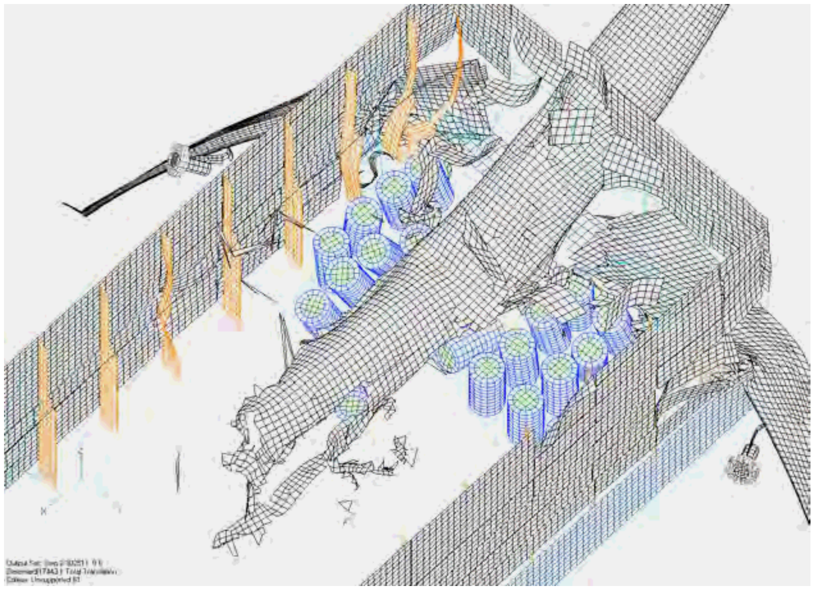

Fig. 7 Time up to 0.6s – Wings come apart from the plant body, the right wing is gradually drawn out of the building while the left wing breaks down to 2 pieces, the inner stays in the building the outer is out of the building. The containers hit by the plane body are moving, the whole intermediate part of the plane is inside the building. Fuel is leaking from damaged fuel tanks.
Time after 0.6s – The plane body stops inside the building, the tail part of the plane is out of the building. The right wing and a part of the left wing are also out of the building.

CONCLUSION

The presented analyses of impact of the large commercial airplane with the Interim Spent Fuel Storage Facility building located in NPP Dukovany were a basis for determination of mechanical and thermal load on stored spent fuel containers. The calculations allow us to determine the extent of building damage and speed of plane debris after the plane penetration through the peripheral cladding of the building. Based on the results of analyses, which were performed for all evaluated options, generalization of possible mechanical impacts on stored containers was made and fire spread and load were analyzed (temperatures, temperature distribution, time of combustion). Fire and mechanical loads of the containers (impact with plane and building debris, impact between containers as a result of their impact with the plane and building debris) were a basis for detailed analyses of container resistance. These analyses focused on mechanical and thermal resistance of the outer jacket of the containers and lids and on temperature distribution in the stored spent fuel.

REFERENCES

1. Stepan, J., Maly, J. and Holub, I., “Consequences of the Large Commercial Aircraft Crash into the Interim Spent Fuel Storage Facility” Transactions of the 18th International Conference on Structural Mechanics in Reactor Technology, paper J04-2, August 2005, pp. 258.