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COUPLED DYNAMIC SIMULATIONS OF AIRCRAFT IMPACT: A340 AND A380 BY COMPARISON

Max Gündel[1], Fritz-Otto Henkel[2], Eric Feldbausch[2], Julius Fischer[3], Mario Smarslik[4],

[1] Professor, Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg, Hamburg, Germany (max.guendel@hsu-hh.de)
[2] Senior Expert, Wölfel Engineering GmbH + Co. KG, Höchberg, Germany
[3] Head of Plant Engineering & Realization, Iqony Solutions GmbH, Essen, Germany
[4] Deputy head of Plant Engineering & Realization, Iqony Solutions GmbH, Essen, Germany

ABSTRACT

Since the 9/11 attacks, several studies have been conducted to investigate the impact of commercial aircraft on nuclear facilities. Currently, the Boeing 747 and Airbus A340 are the largest commercial aircraft considered. Studies on the Airbus A380 are limited, although it has a MTOW of 569 tonnes, which is about 50 % higher. Therefore, the aim of the work in this paper is to analyse the effects of an A380 impact compared to an A340 impact. For this purpose, coupled dynamic simulations are carried out, firstly to determine the force-deformation curve for an impact on a rigid wall, and secondly to analyse the load-bearing behaviour of a reinforced concrete wall for impact points relevant to the maximum bending moments or shear forces. The simulations show that the maximum impact force for the A380 and A340 are similar, but the impulse of the A380 is 50 % higher. Furthermore, the maximum displacement of the reinforced concrete wall is up to 2 times higher for the A380 than for the A340. It can therefore be concluded that the A380 is decisive for aircraft impact under the boundary conditions of this study.

BACKGROUND

Over the past five decades, the load case aircraft impact has undergone several stages of development due to technical innovations and social developments. Since the 1970s, the analysis of accidental crashes of military aircraft into nuclear power plants has become common practice. Following the 9/11 attacks, the impact of deliberated crashes of commercial aircraft has also been considered as a design load scenario. In the analysis of the impact of commercial aircraft on nuclear facilities, aircraft are divided into three groups as defined by IAEA (2018): Group A, which includes large aircraft with a maximum take-off weight (MTOW) between 200 and 400 tonnes; Group B, which includes medium aircraft with a MTOW between 100 and 200 tonnes; and Group C, which includes small aircraft with a MTOW below 100 tonnes. Typical examples of aircraft in Group A are the Airbus A340 with a MTOW of 368 tonnes and the Boeing B747 with a MTOW of 377 tonnes.

Currently the largest passenger aircraft, the Airbus A380, has a MTOW of 569 tonnes but is not normally considered in aircraft impact analysis. However, as the impact load of the A380 being distributed over a larger impact area due to its two-story fuselage, it is unclear whether the A340, the Boeing 747 or the A380 is relevant aircraft for design purposes. In this paper, coupled dynamic impact analyses are used to determine the force-time function and to investigate the bending and punching behaviour of reinforced concrete (RC) walls subjected to the impact of the A340 and A380 aircraft.

FE-MODELL OF AIRCRAFT A340 AND A380

The aircraft models are generated using publicly available data to accurately simulate the realistic local and global behaviour of the structure under impact, Table 1. Therefore, the main components of the aircraft with respect to stiffness, strength and mass including the fuselage, wings, horizontal and vertical stabilisers, turbines and tanks, are taken into account, Fig. 1. The aircraft models consist of beam and shell elements, as well as discrete mass points e.g. for the fuel in the tanks. The aircraft are mainly made of aluminium, steel and titanium. Their material behaviour is described using the Johnson-Cook model (Johnson, 1983), which includes nonlinear stress-strain curves, strain rate effects, and failure. Although central components such as wing boxes, rudders, and flaps of the A380 are made of carbon fibre reinforced plastic and glass fibre reinforced aluminium, these materials are also modelled using the Johnson-Cook model for simplicity. The A340 model comprises 57,000 nodes, while the A380 model comprises 84,000 nodes. All finite element models in this paper have been created using Hypermesh (HyperWorks Altair, 2021).

Table 1: Main parameters of aircraft A340 and A380.

aircraft	MTOW [t]	v_{travel} [km/h]	length [m]	width [m]	fuselage Ø [m]
A340-500	368	905	67.90	63.45	5.64
A380-800	569	918	72.70	79.80	7.14 x 8.40

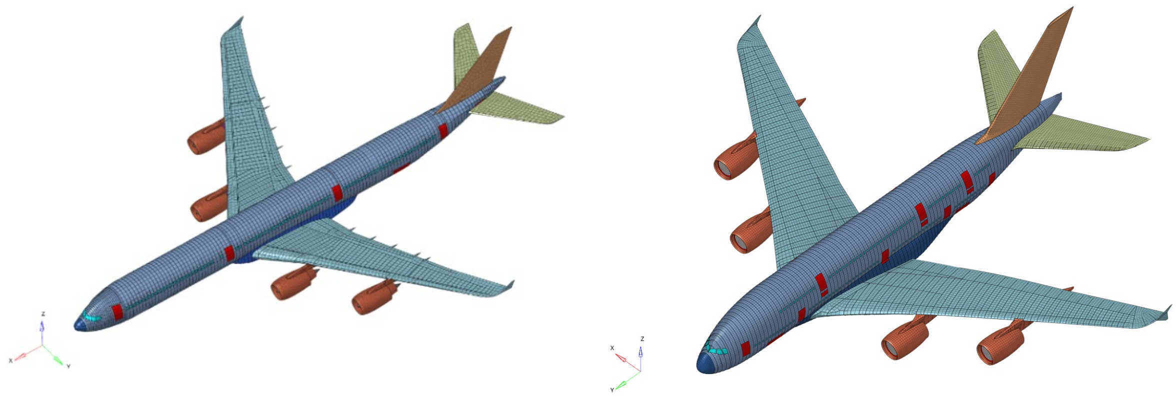

Figure 1. FE-Modell of A340 (left) and A380 (right).

FORCE-TIME-FUNCTION OF AIRCRAFT A340 AND A380

The force-time function of a perpendicular impact of A340 and A380 aircraft on a rigid wall is determined through coupled dynamic simulation. To reduce numerical effort, the symmetry of the aircraft is exploited. All simulations in this paper were conducted using Abaqus (Simulia 3DS, 2020).

Both force-time functions demonstrate the typical behaviour of commercial aircraft (see Fig. 2, normalized force-time functions): Firstly, the initial load level is moderate during the impact of the fuselage. Secondly, the impact level increases significantly with the impact of wings, wing boxes and turbines. However, the initial load level of the A380 is remarkably higher than that of the A340 due to the two-storey fuselage. The maximum load experienced by the A380 is only 13 % higher than those experienced by the A340. However, the normalised impulse caused by the A340 is 0.072 s while for the A380 it is 0.106 s, which is 47 % more. Following the impact, the A340 aircraft was completely destroyed, except for the rearmost part of the fuselage, including the vertical and horizontal stabilizers, Fig. 3, left. In contrast, the fuselage of the A380 behind the wing box remained mostly intact.

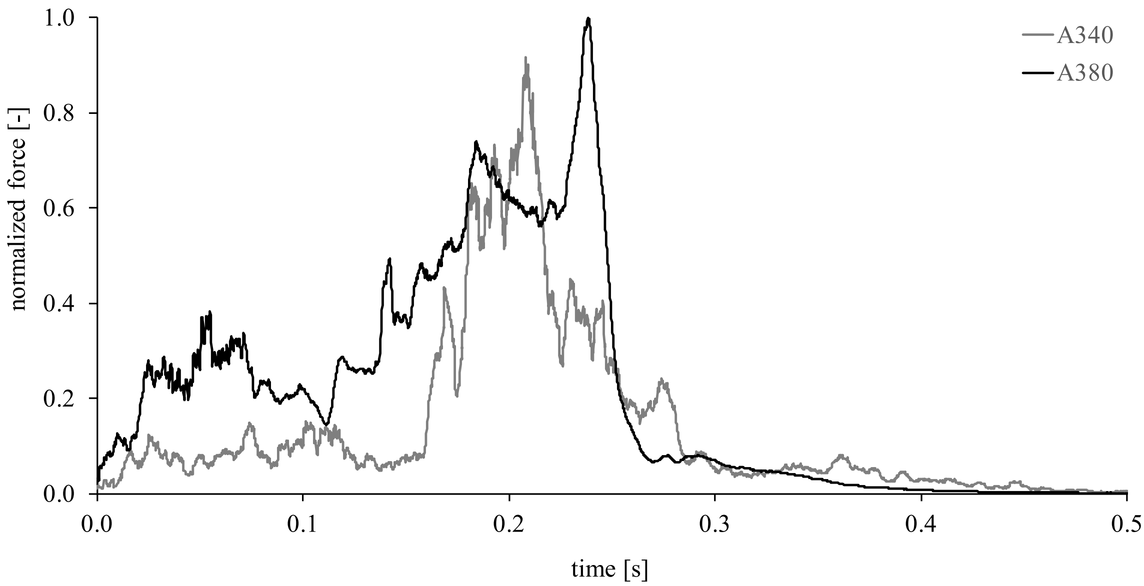

Figure 2. Normalized force-time-function of impact of A340 and A380 on rigid wall.

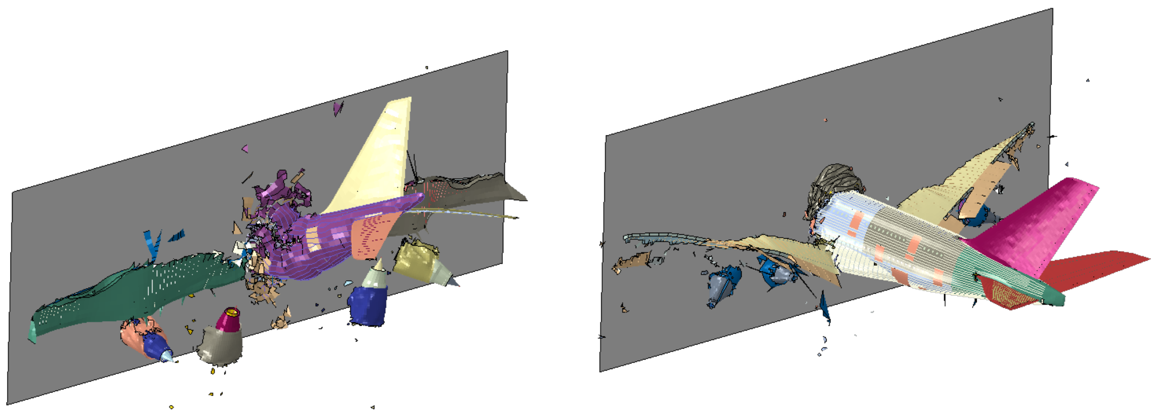

Figure 3. Aircraft after impact: A340 (left) and A380 (right).

FE-MODELL OF RC-WALL

The impacted structure being investigated is a rectangular reinforce concrete (RC) wall with a thickness of 1.8 m and dimensions of 23 m by 70 m. The plate is the exterior wall of a building so that corner moments can be transferred at the edges. The plate has five layers of vertical reinforcement, each with a diameter of 32 mm and a spacing of 150 mm, both inside and outside, as well as two layers of horizontal reinforcement, each with a diameter of 28 mm and a spacing of 150 mm, both inside and outside. Additionally, there is a shear reinforcement of stirrups with a diameter of 16 mm and a spacing of 450 mm and 150 mm, respectively. The reinforcement is made of in B500B steel, in accordance with Eurocode 2 ($E = 200,000$ N/mm², $f_{y,k} = 500$ N/mm², $f_{u,k} = 540$ N/mm²). The concrete strength is C35/45, also in accordance with Eurocode 2 ($E = 34,000$ N/mm², $f_{ck} = 35$ N/mm², $f_{ctm} = 3.2$ N/mm², $\varepsilon_{cu1} = 3.5$ %o).

Hexahedral elements with reduced integration (type C3D8R) are used to model the concrete, with an element length of 225 mm (equivalent to eight elements over the thickness). Linear beam elements (type B31) are used to model the reinforcement, which is embedded in the concrete elements, Fig. 4. The connection between the reinforcement and concrete is assumed to be rigid, requiring sufficient anchoring.

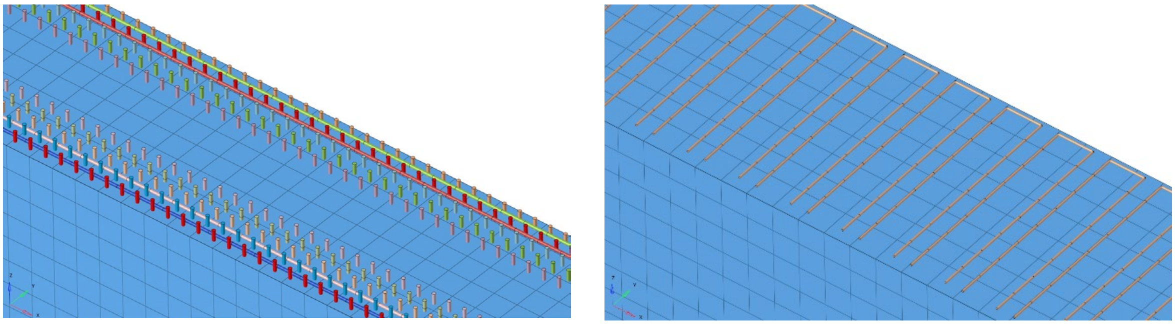

Figure 4. FE-Modell of RC-wall: bending reinforcement (left) and shear reinforcement (right).

The Concrete Damage Plasticity approach in Abaqus is used to represent the material behaviour of concrete, as described by Lubliner (1989). This approach considers hardening and softening in tension and compression, and includes a set of nonlinear stress-strain curves for different strain rates in tension and compression, Fig. 5. The curves are based on the characteristic material parameters in Eurocode 2 (DIN EN 1992-1-1, 2011) and strain rate effects, as described by the CEB-FIP Model Code (1990). In addition, a user subroutine removes elements, when the plastic strain limits are exceeded. The reinforcement's material behaviour is modelled using the Johnson-Cook model (Johnson, 1983), which includes nonlinear stress-strain curves, strain rate effects, and failure. The model parameters are determined using test data (Cadoni, 2015) and an optimisation algorithm. The final stress-strain curve is then scaled to meet the characteristic yield and tensile strength of B500 B as specified in Eurocode 2 (DIN EN 1992-1-1, 2011), Fig. 6.

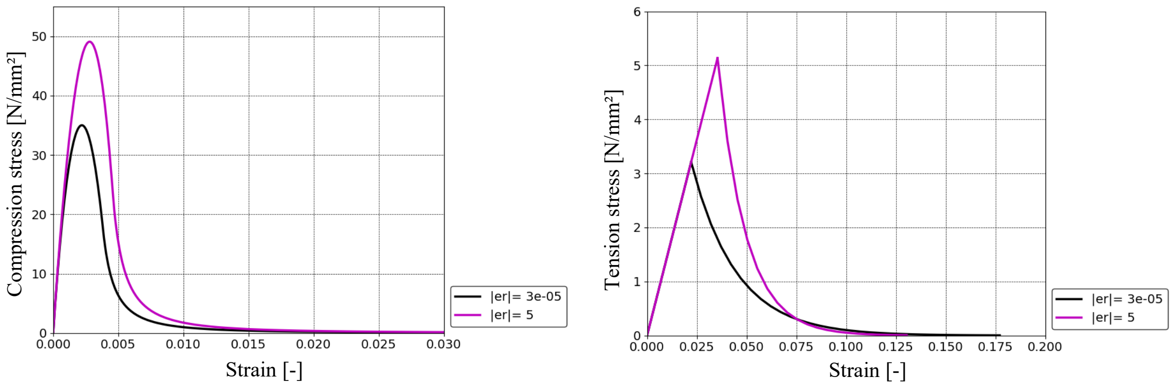

Figure 5. Stress-strain curve of concrete C35/45 under static and dynamic loading: compression (right) and tension (left).

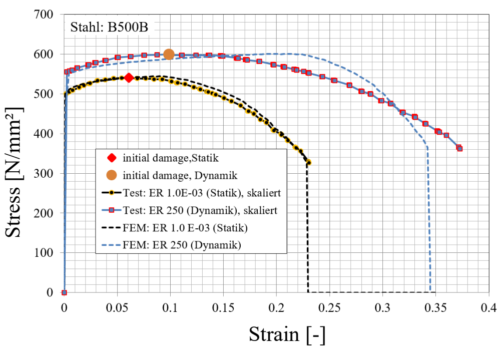

Figure 6. Stress-strain curve of reinforcement B500 B under static and dynamic loading.

RC-WALL BEHAVIOUR UNDER AIRCRAFT IMPACT OF A340 AND A380

General

The study investigates the behaviour of the RC-wall, described in the previous section, when impacted by A340 and A380 aircraft in two scenarios, as shown in Fig. 7: (i) The bending behaviour of the RC-wall is analysed by selecting the impact point at the centre of the plate. (ii) The shear behaviour of the RC-wall is analysed by selecting the impact point at the edge of the plate, while maintaining a distance of 2.5 times the wall thickness from the support to avoid direct load transfer. The impact point is defined as the gravity axis of the aircraft. The interaction between the aircraft and the structure is defined as general contact with a friction coefficient of 0.35. The gravity load on the wall is neglected. The simulation duration is 0.58 s, which is sufficient to simulate the entire aircraft impact and at least one period of free oscillation of the wall.

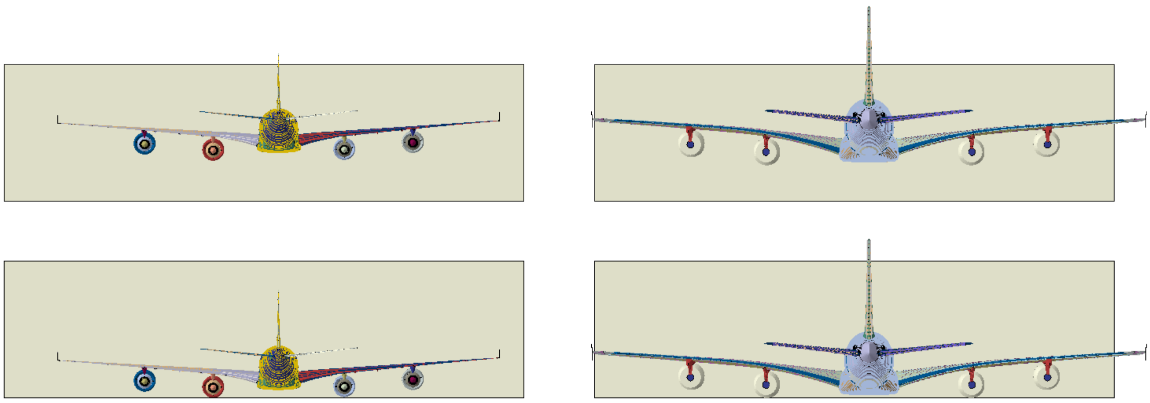

Figure 7. Impact points under investigation: A340 (left) and A380 (right), central impact (top) and edge impact (bottom).

Central impact

Under A340 aircraft impact, the wall displacement remains small for up to 0.18 s and then increases due to the impact of the wings, wing box, and turbines, reaching a maximum of 1.58 m, Fig. 8. The wall carries the impact load through bending and membrane action, mainly in the vertical direction due to the shorter vertical span. Compression stresses occur on the side facing the load over a depth of 0.2 m due to the positive bending moment in the impact area, while tension stresses occur on the side facing away from the load over a depth of 1.6 m, Fig. 9. Outside the impact area, negative bending moment due to the clamping effect of the supports and inertia effects of the wall can be observed, causing a change in the sign of the stresses. The vertical bending reinforcement on the side facing away from the load undergoes moderate plastic deformation, particularly in the impact area between the fuselage and wings, Fig. 10. The horizontal bending reinforcement shows only minor plastic deformation. The shear reinforcement undergoes strong plastic deformations in the area of the turbines and the area between the inner turbines and fuselage, Fig. 11. Due to extensive plastic deformations, single concrete elements on the outside of the wall are removed at the impact area of the turbines.

Under A380 aircraft impact, the displacement increases continuously and almost linearly with time up to 0.30 s when the wing box hits the wall, Fig. 8. The maximum displacement is 3.31 m, which is more than twice the displacement of the A340. The load-bearing behaviour is similar to that under A340 aircraft impact; however, due to the large displacement, the portion of membrane action increases. On the side opposite to the load, the vertical bending reinforcement undergoes strong plastic deformation, while the horizontal bending reinforcement shows only moderate plastic deformation, Fig. 10. The shear reinforcement around the fuselage and the wings, is heavily utilized, with a few stirrups even reaching failure, Fig. 11. At the point of impact of the fuselage only a few concrete elements were deleted.

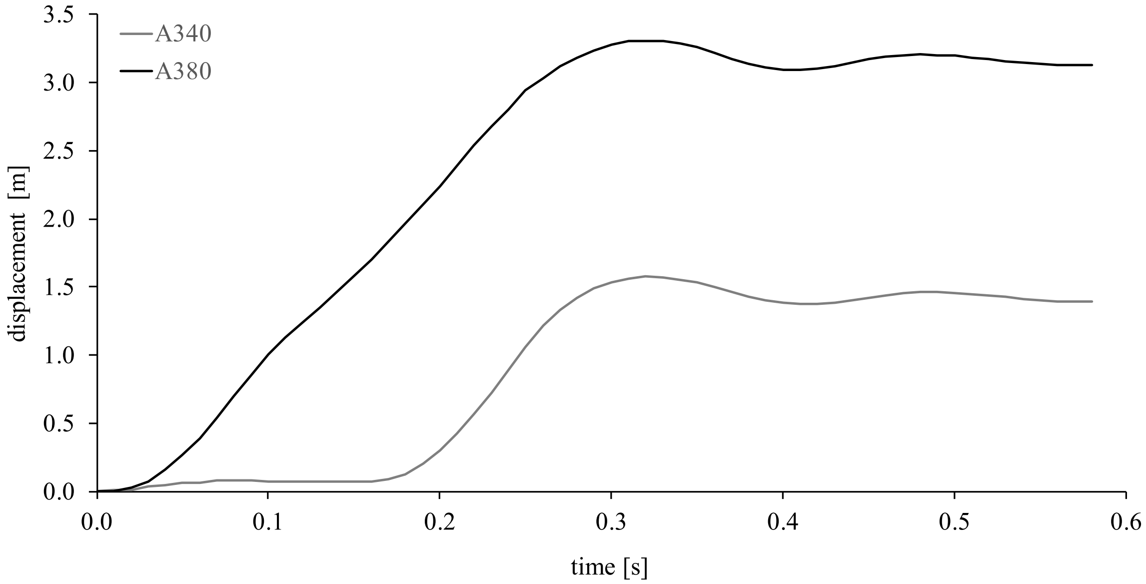

Figure 8. Displacement-time function of RC-wall under central aircraft impact of A340 and A380.

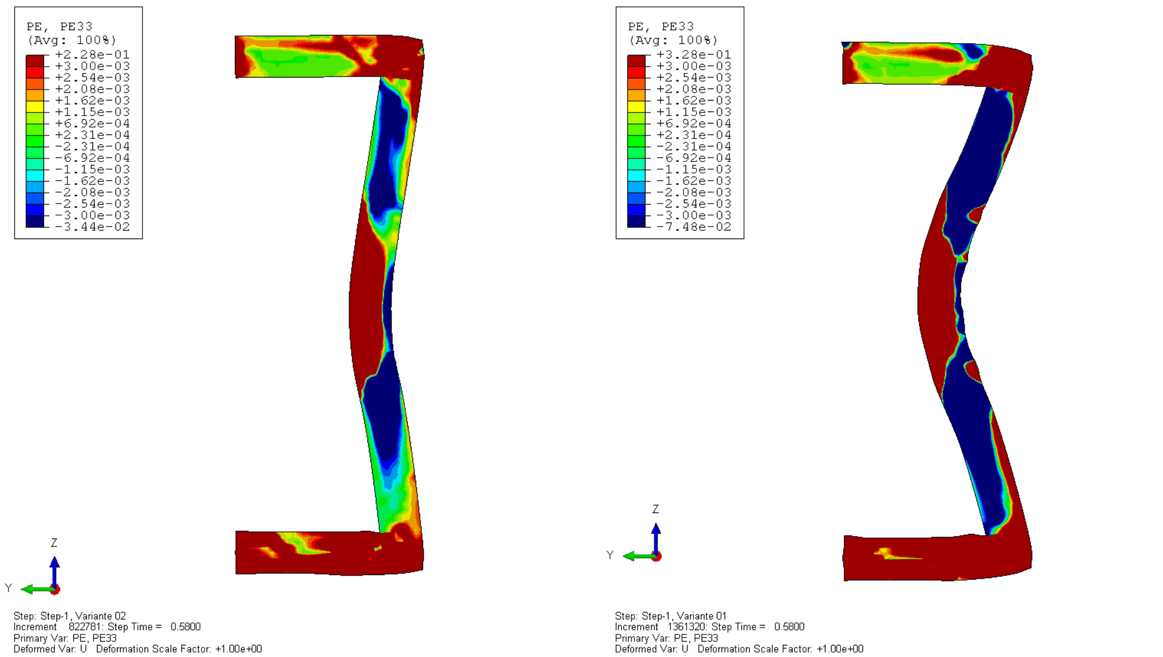

Figure 9. Vertical plastic strain of concrete under central impact of A340 (left) and A380 (right).

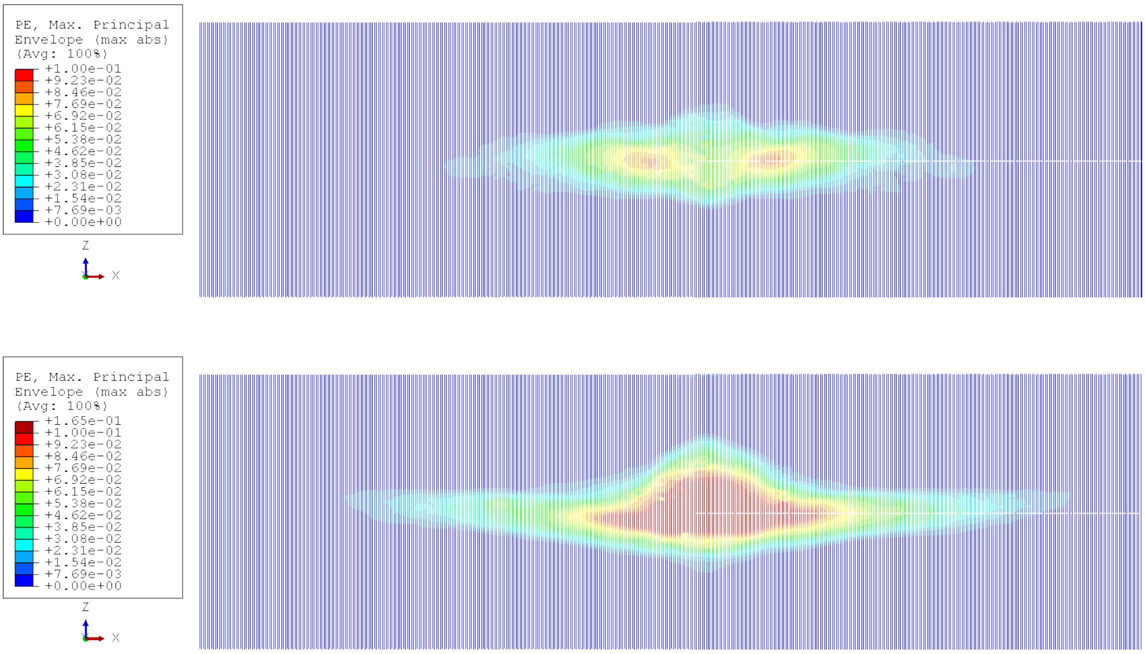

Figure 10. Equivalent plastic strain of vertical inner bending reinforcement under central impact of A340 (top) and A380 (bottom).

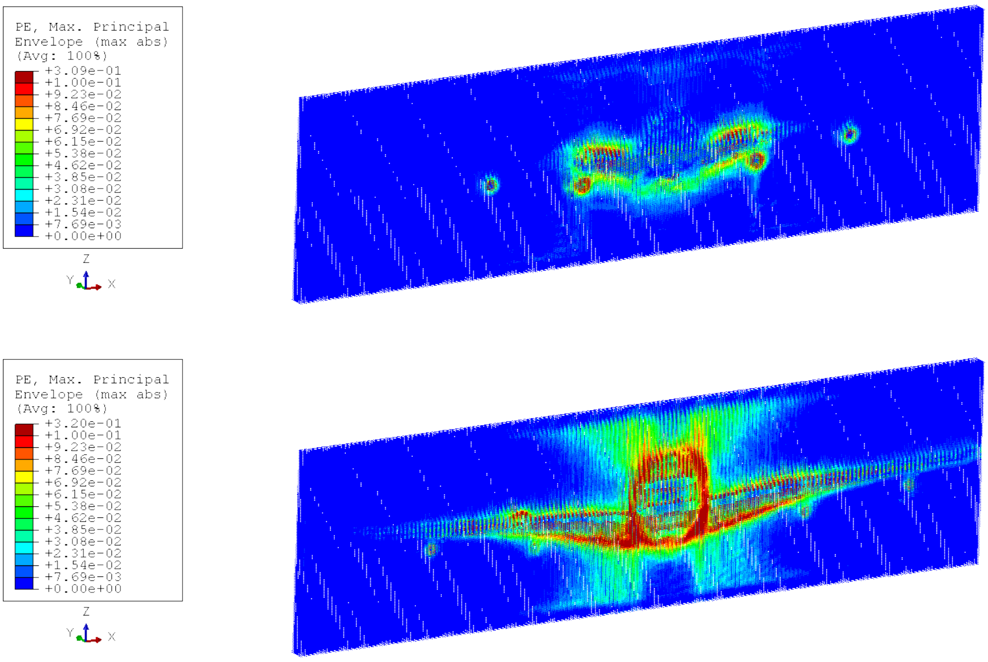

Figure 11. Equivalent plastic strain of shear reinforcement under central impact of A340 (top) and A380 (bottom).

Edge impact

The bearing behaviour of the wall under edge impact is essentially the same as under central impact for both aircraft. However, the maximum displacement is significant lower than for the central impact (0.90 m for A340 and 2.47 m for A380), Fig. 12. Therefore, the bending moment and accordingly the plastic strain in concrete (Fig. 13) and bending reinforcement (Fig. 14) is smaller. The higher stiffness of the wall for edge impact results in some deleted concrete elements. In addition, the shear reinforcement is not only exploited around the fuselage, but also along the lower support, Fig. 15.

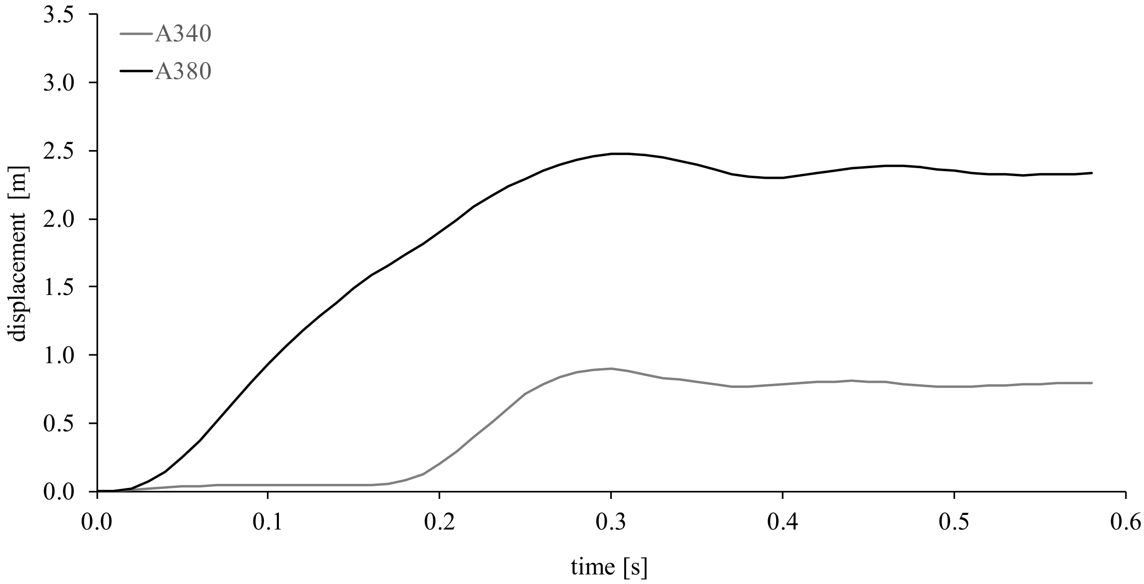

Figure 12. Displacement-time function of RC-wall under edge aircraft impact of A340 and A380.

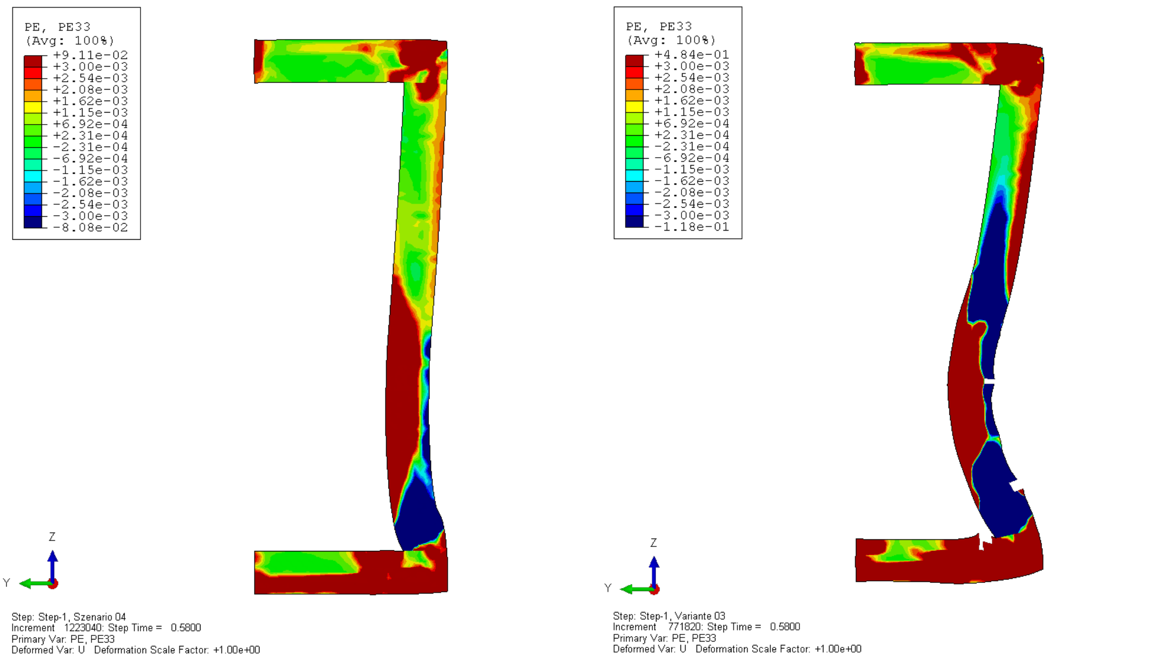

Figure 13. Equivalent plastic strain of concrete under edge impact of A340 (left) and A380 (right).

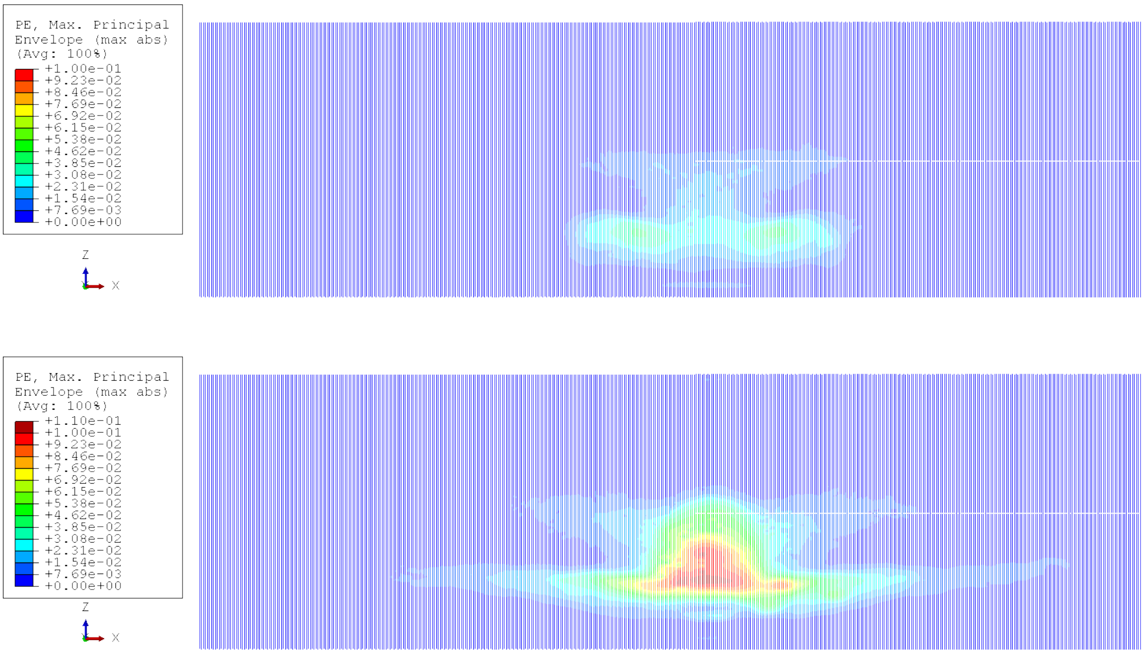

Figure 14. Equivalent plastic strain of bending reinforcement under edge impact of A340 (top) and A380 (bottom).

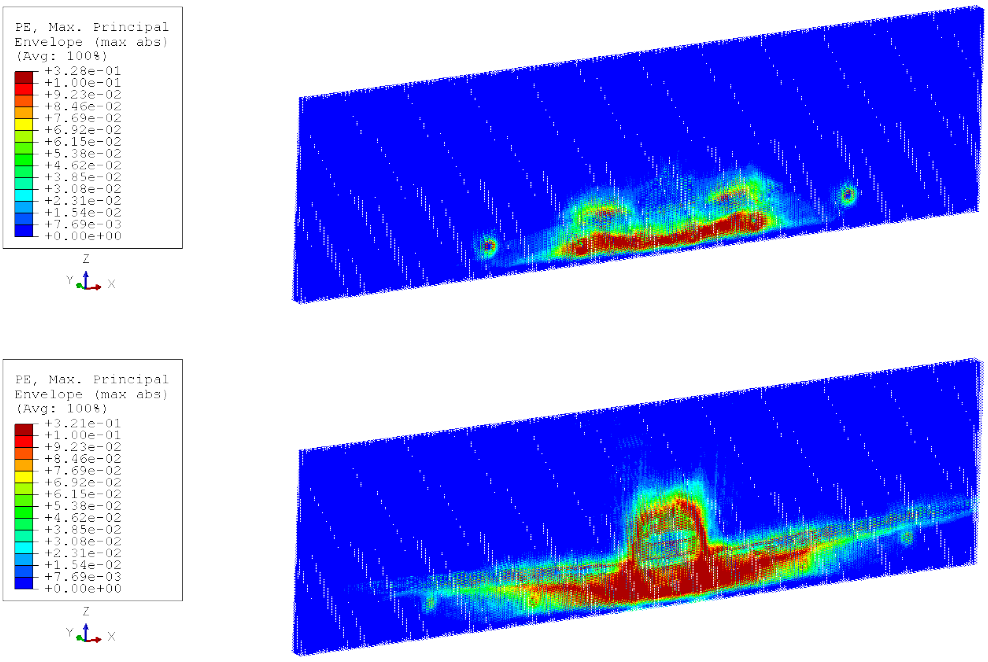

Figure 15. Equivalent plastic strain of shear reinforcement under edge impact of A340 (top) and A380 (bottom).

CONCLUSION

Until now, investigations of commercial aircraft impact on nuclear facilities focuses on aircraft models up to A340 and B747, which are known as type C in the IAEA Safety Reports. However, the airbus A380 aircraft, which is the largest commercial aircraft, with a MTOW of 569 t (about 50 % more than A340 and B747 is usually not considered in the design and assessment of nuclear facilities. To assess the relevance of the A380 in the design process, an A380 aircraft impact is compared with an A340 by means of coupled numerical simulations. For this purpose, the force-time function of the impact on a rigid wall is determined and the load bearing behaviour of a rectangular RC wall under central and edge impact is analysed for both the A340 and the A380 aircraft.

The maximum load of the force-time function is very similar for both aircrafts; however, the force level up to the impact of the wings is significantly higher for the A380 due to the higher mass and strength of the two-storey fuselage. This results in a 49 % higher impulse of the A380 in respect to the A340. For central impact the maximum displacement of the impacted RC wall is 2 times higher for the A380 than for the A340, which results in higher plastic strains in concrete, bending and shear reinforcement. Also for edge impact the A380 leads to higher exploitation of concrete and reinforcement. Hence, it can be concluded that the A380 is decisive for aircraft impact under the boundary conditions of this investigation.

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