Actions on High-rise Buildings due to Aircraft Impact and Assessment of Structural Safety for such Hazards

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Actions due to aircraft impact are normally only taken into account for the design of nuclear power plants [1], [2]. For military structures the impact of missiles is often a relevant hazard scenario. However, there are usually no special design criteria for civilian structures to withstand such actions and also the understanding of how buildings respond to impact is less precise. The goal of the presented study is the development of a hazard assessment tool which helps to predict the performance of high-rise buildings in case of aircraft impact.

For this reason the presented paper deals with aircraft specifications on the one hand and different building structures on the other. With a pragmatic approach, aircraft categories including the various plane sizes, takeoff weights and fuel capacities are compared with typical structures from high-rise buildings. The scope of the investigation is to consider the degree of structural failure due to the initial aircraft impact and the effects of post-crash fires created by jet fuel.

Two Different Aircraft Impacts

On September 11, 2001, terrorists used passenger aircrafts heavily loaded with fuel to destroy the World Trade Center buildings. A few months later a lightweight personal airplane hit the Pirelli high-rise building in Milan without affecting the structural safety of the building at all. The two events showed dramatically how the damage caused by aircraft impact depends on numerous parameters and varies in an extremely wide range.

Different Airplanes

The Boeing 767-200ER aircraft that were used to attack the two towers of the World Trade Center (WTC) is a commercial jet airliner for middle and long distances (Fig. 1). Its maximum takeoff weight, or mass, is almost 200'000 kg. Approximately one third of this mass is jet fuel. The cruise speed of the aircraft is 850 km/h. The airplanes which crashed into the WTC towers were loaded with sufficient fuel for the transcontinental flight to Los Angeles. However, the aircrafts that hit the towers had an estimated gross weight of 125'000 kg. The speed of impact into the north tower (WTC 1) was estimated to be 750 km/h. The second plane that crashed into the south tower (WTC 2) had an estimated speed of about 900 km/h upon impact [3].

The airplane that hit the Pirelli Building in Milan was a small personal aircraft type Aero Commander 112TC (Fig. 2). The weight of this plane is about 1'000 kg, the same mass a small car. The maximum cruise speed of such aircraft is usually less than 300 km/h. The amount of fuel on board of the crashed plane is estimated less than 50 liters.

Figure 1: Boeing 767

Figure 2: Aero Commander 112TC

A preliminary comparison of the two impacts is resulting in a big difference between the two events. For the jetliner, both, the kinetic energy of the impacting plane as well as the amount of fuel is approximately 1'000 times higher than for the personal aircraft.

Different Building Structures

The WTC towers (Fig. 3), also known as WTC 1 (north tower) and WTC 2 (south tower), belonged to the world's tallest buildings. They were almost identical and encompassed 110 storeys and a roof height of 415 meters. Both buildings had a square floor plan, 63 meters long on each side. With its height of 127 meters the Pirelli building is a mark of Milan.

Figure 3: Attack against WTC 2

Figure 4: Pirelli building after impact

The structural configuration of the buildings is also completely different. The WTC towers were steel-framed structures whereas the Pirelli building is built as a concrete framework structure. The WTC towers structural features were the closely spaced box columns around the building perimeters and the service core, housing stairways, elevators and utility shafts at the center of each tower. The floors were supported by trusses, which spanned between the outer columns and the building core. In the structural system the perimeter framework acted as wind bracing to resist all overturning forces. The central core mainly took the gravity loads of the building.

The structural system of the Pirelli building is more conventional. The building perimeter consists of a lightweight curtain wall façade as well as concrete shear walls to resist lateral loads (see Fig. 4).

Different Events

The airplanes that struck the WTC towers causing massive damage to the faces of the buildings within the immediate area (Fig. 5). At the central zone of impact corresponding to the fuselage and engines the exterior columns were completely pushed out. Away from this central zone, in areas impacted by the outer wing structures, the steel columns were fractured (Fig. 6). Interpretation of photographs suggests that approximately half of the columns on the building face were destroyed.

In addition to the damage at the building perimeter, a significant but undefined amount of damage also occurred to framing at the central core. The building's structural system with the exterior loadbearing frame and the gravity loadbearing frame at the central core was highly redundant. Although the structure's global strength was severely degraded, the structure was able to remain standing in this weakened condition. However, the jet fuel of the aircrafts ignited, intense fires spread out and weakened the structure additionally. The north tower collapsed 102 minutes after the aircraft impact. The south tower remained standing only 56 minutes.

Figure 5: Impact damage to the north face of WTC 1 [3]

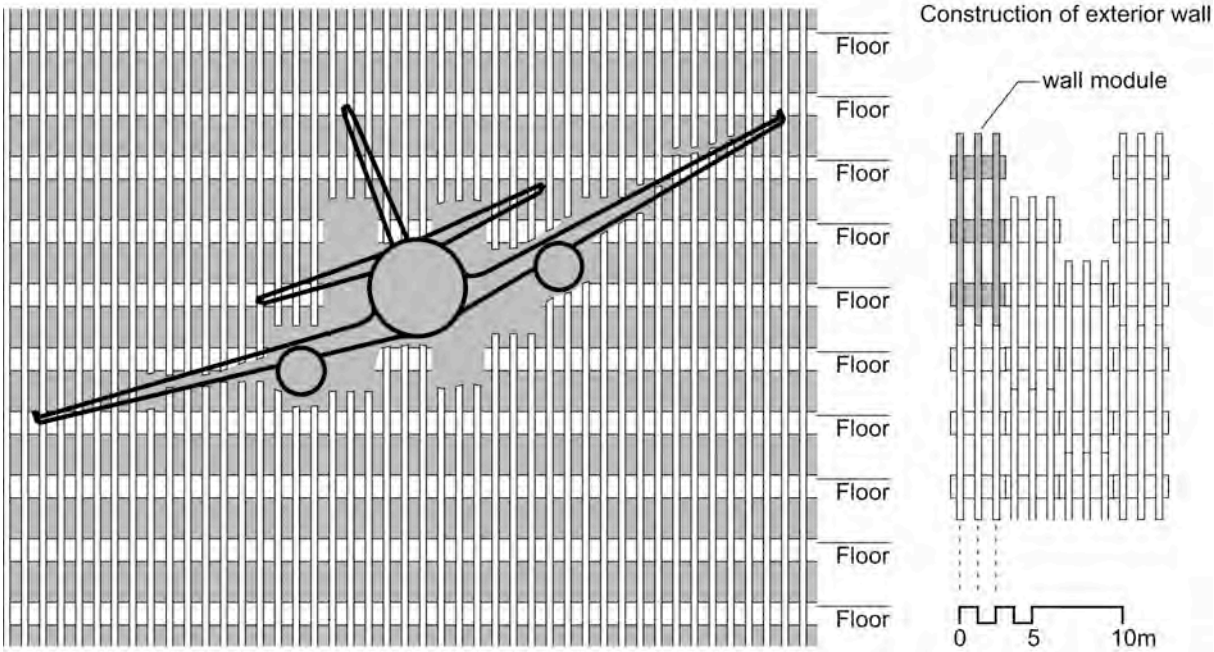


Figure 6: Impact damage to exterior columns of WTC 1 (left) and construction of the exterior wall with modules (right)

Due to the impact of the personal aircraft on the Pirelli building in Milan some local damage on the non-bearing façade was evident (see Fig. 4). However, the building's structural system was not affected at all and the structural integrity of the entire building was not endangered. Because of the small amount of fuel the airplane was loaded with, the effect of the post-crash fire was minor too.

SEQUENCES AND EFFECTS OF AIRCRAFT IMPACT

To assess the effects of an aircraft impact the understanding of the response of the affected building as well as the event sequences is necessary. For this purpose the immediate effects of an aircraft impact and the spread out of fires following a crash were studied. The **initial effects** of impact are mainly depending on the aircraft design and its flight speed and angle of impact. The impact may result in structural damage and immediate local or global collapse of the building. The **effects of fire** are predominately depending on the fuel loading of the aircraft and the dispersion and ignition of the fuel within the building.

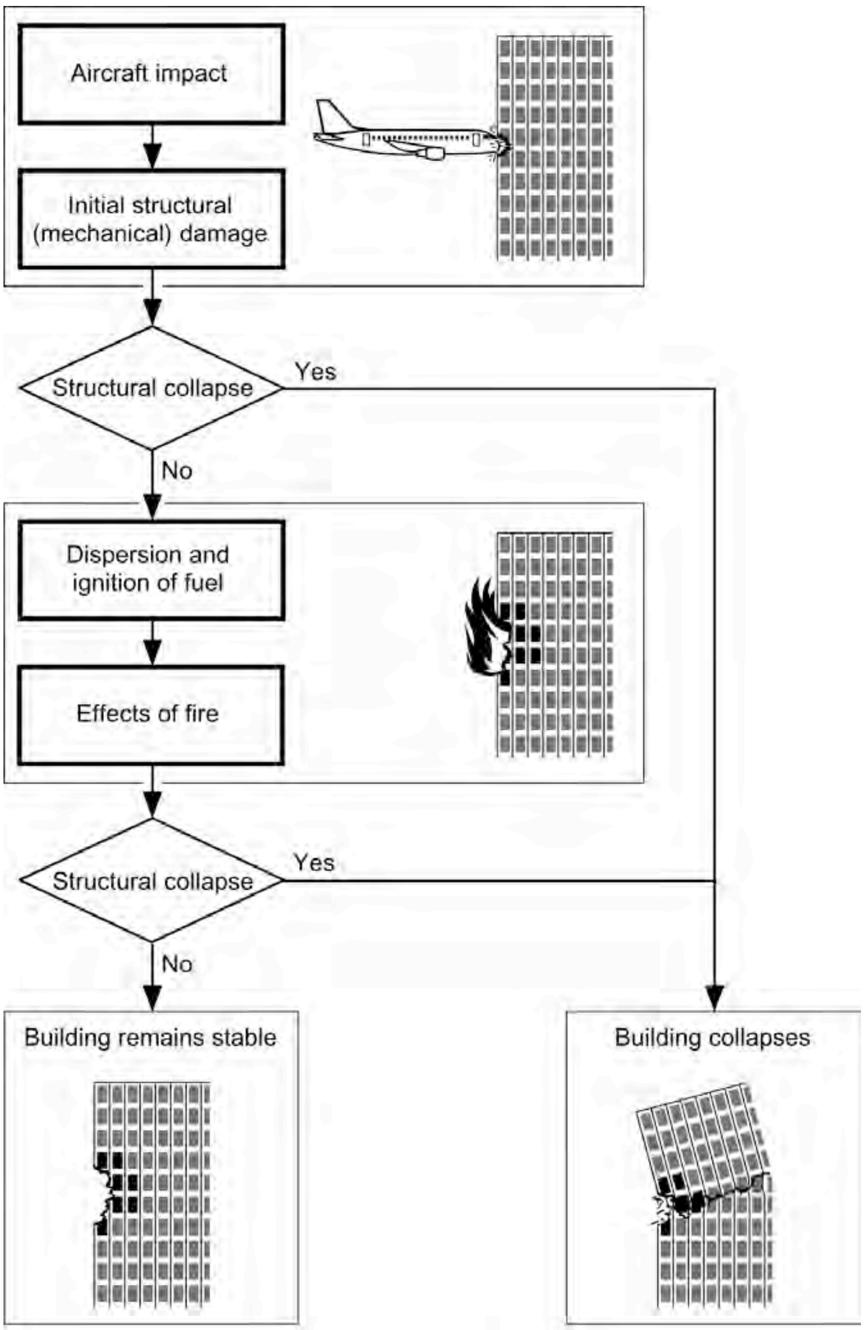


Figure 7:
Event sequences of aircraft impact

Initial Effects

Building design usually considers environmental or external loads that a building must have the strength to resist. These loads are gravity, wind and earthquake loads. Outside the military and the nuclear industry the considering of aircraft impact loads is not usual. However, aircraft impact is an accidental action that may lead to structural failure. Because aircrafts generally are less stiff constructions such events are physically described as so called soft impacts [4]. Penetration and perforation effects or only relevant when very stiff elements like engine shafts are impacting. The force of a soft impact is typically depending on the aircraft mass as well as its speed and the angle of impact (Fig. 8).

Effects of Fire

Modern structures are designed to resist fire for a specific time. Safety features like fire retarding materials or sprinkler systems help to extinguish flames or prevent steel from being exposed to excessively high temperatures. In case of an aircraft impact, fuel spreads across a large area in the building. Depending on the violence of impact, a fuel vapor cloud is arising. The ignition and deflagration of this cloud generates more severe fire conditions than those in a typical building fire. Fuel, which is not consumed in the fireball, will flow down interior shaftways, igniting simultaneous fires across several building floors. This may overcome the building's fire resistance considerably faster than expected.

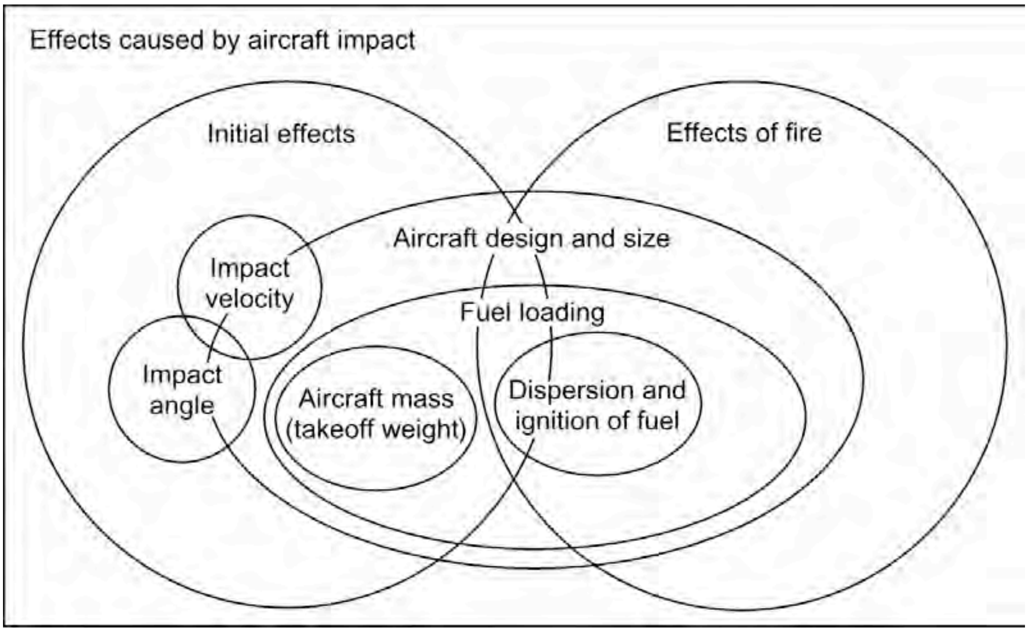


Figure 8: Aspects of the effects caused by aircraft impact on buildings

AIRCRAFT SIZE

To develop a tool to assess the effects of aircraft impact aircrafts have to be classified into different categories. Therefore, aircrafts for civilian purposes are distinguished in four categories. Trainers and hunters for military purposes are similar to business aircrafts in this distinguishing. According to their size, the following four representing categories of aircrafts were defined:

- **Personal aircrafts** (Fig. 9) are in most cases small single engine propeller machines, usually for four person. The maximum takeoff weight is equal to a small or medium sized passenger car. The cruising speed of such airplanes is about 300 km/h. Depending on the range or flight distance the fuel capacity is maximum some hundred liters.
- **Business aircrafts** (Fig. 10) are typically aircrafts with two jet engines for more or less than ten person. The takeoff weight, or mass, is about 10'000 kg. By reason of the good flight performance (cruising speed, range) the fuel capacity is relatively big.
- **Regional commuters** (Fig. 11) are small commercial aircraft for about 70 passengers. Typically they have two, sometimes four jet or turboprop engines. Because these aircraft are used for short distance flights, the fuel capacity is small compared with the takeoff weight of the airplane.
- **Passenger jetliners** (Fig. 12) are aircrafts for a hundred or more passengers. The new Airbus A380, which is expected to be flying in 2006, has a capacity of 555 passengers and a range of up to 15'000 km. The maximum takeoff weight of such huge long distance jetliners may be 500'000 kg. The mass of the jet fuel can be more than one third of the takeoff weight.

The main characteristics like aircraft mass or flight speed, influencing the consequences of an aircraft impact are summarized in Figure 13.

Figure 9: Personal aircraft

Figure 10: Business aircraft

Figure 11: Regional commuter aircraft

Figure 12: Passenger jetliner

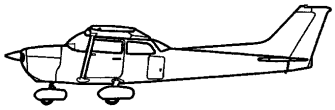
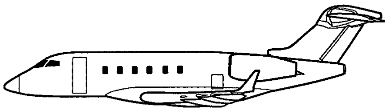
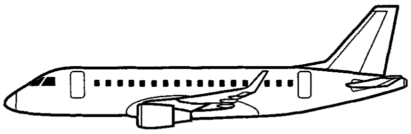
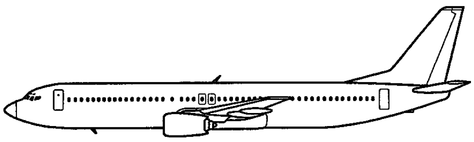
Aircraft Category (Size) (Number of crew and passengers)	Span s [m]	Maximum Cruise Speed v_{max} [km/h]	Maximum Takeoff Weight m_A [kg]	Fuel Capacity m_F [kg]
Personal Aircraft (4 – 6 person) 	10 - 13	400	2'000	100 - 500
Business Aircraft (7 – 20 person) 	14 - 20	500 - 900	3'000 - 20'000	1'000 - 5'000
Regional Commuter (30 – 100 person) 	20 - 30	600 - 900	20'000 - 50'000	5'000 - 10'000
Passenger Jetliner (100 – 500 person) 	30 - 70	800 - 900	50'000 - 500'000	10'000 - 200'000

Figure 13: Aircraft categories

BUILDING SIZE

To analyze the effects of aircraft impact for high-rise buildings, four representing building sizes are defined. A building with medium size and a tall building are shown in Figures 14 and 15. The representing building sizes are described below. Together with typical floor sections these building sizes are shown in Figure 16.

– **Small buildings** are less than 50 meters in height. So, they have no more than 15 floors with a typical area of about 400 m^2.

– **Medium buildings** (Figure 14) have a height of 50 to 100 meters and about 20 storeys. The representative floor area is 500 m^2.

– **Tall buildings** (Figure 15) are typically 50 storey buildings with a height up to 200 meters. Representative upper floor plans of such high-rise buildings have an area of about 1'000 m^2.

– **Super Tall buildings** are towers like the destroyed World Trade Center. Such high-risers have a height of several hundred meters and typical cross sections with areas of 2'000 m^2 or more.

Figure 14: Building with medium size

Figure 15: Tall building

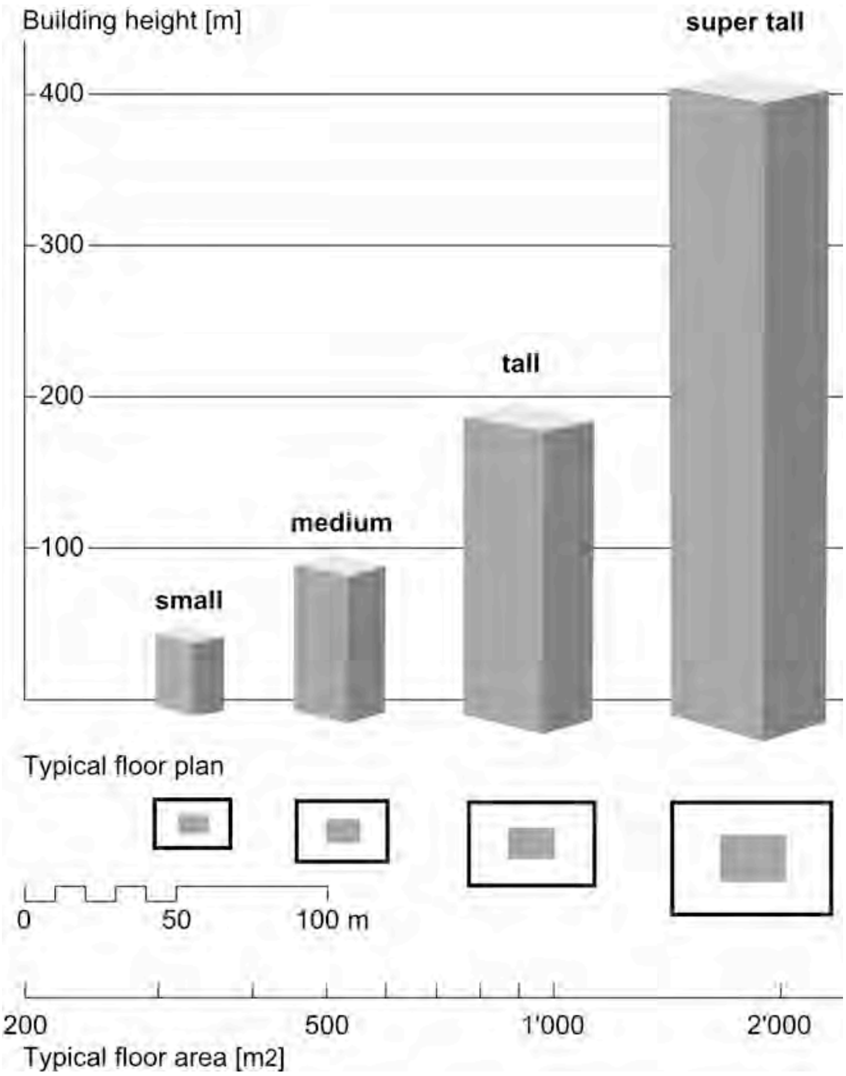


Figure 16: Classification of high-rise buildings

STRUCTURAL DAMAGE

In the presented study the defined building structures were analyzed (see also [5]). The plan view and the configuration of these structures are shown in Figure 17 below. For all building sizes the typical storey height was assumed to be 3.80 meters. The structural framing plan is representative of an upper floor in the building. The columns are spaced at typical 5.0 m for small buildings and 8.0 m for tall and super tall buildings. The representative aircraft are also drawn in Figure 17 in the same scale. That makes it possible to compare it directly with the building structure.

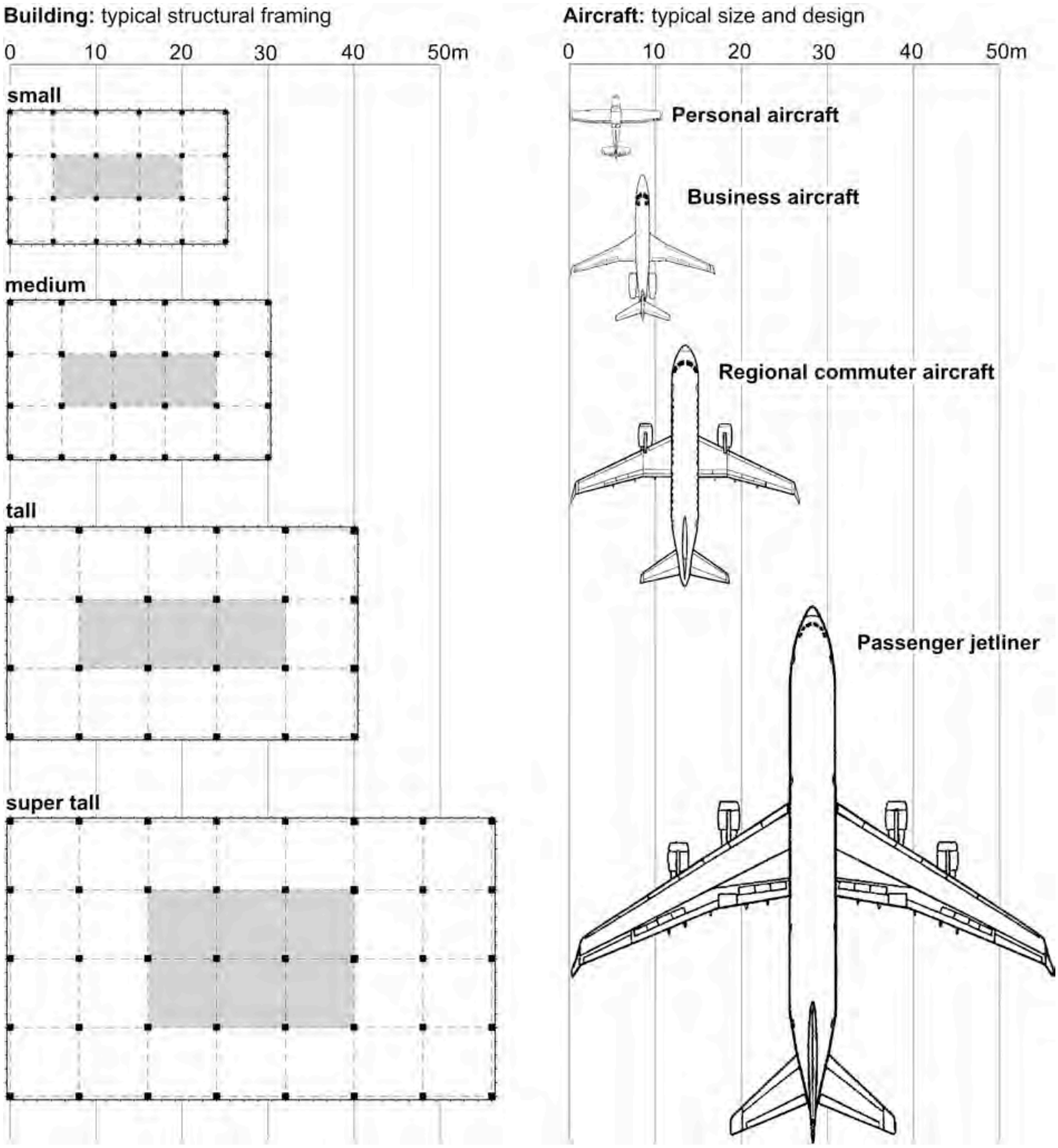


Figure 17: Representative structural framing and typical aircraft size

Global assessment was carried out to estimate the impact damage. The goal of the analysis was to point out failure mechanisms, which lead to immediate or progressive collapse of the structure. Figure 18 shows the result of these studies for medium size buildings. It is for example evident that the impact of a personal airplane in the worst case leads to the failure of one column. Depending on the structural design and redundancy a building collapse in case of such an impact is quite improbable. The impact of regional commuter or even a big jetliner on the other hand results in extensive damage across multiple floors. An immediate collapse of the struck building is very probable respectively certain.

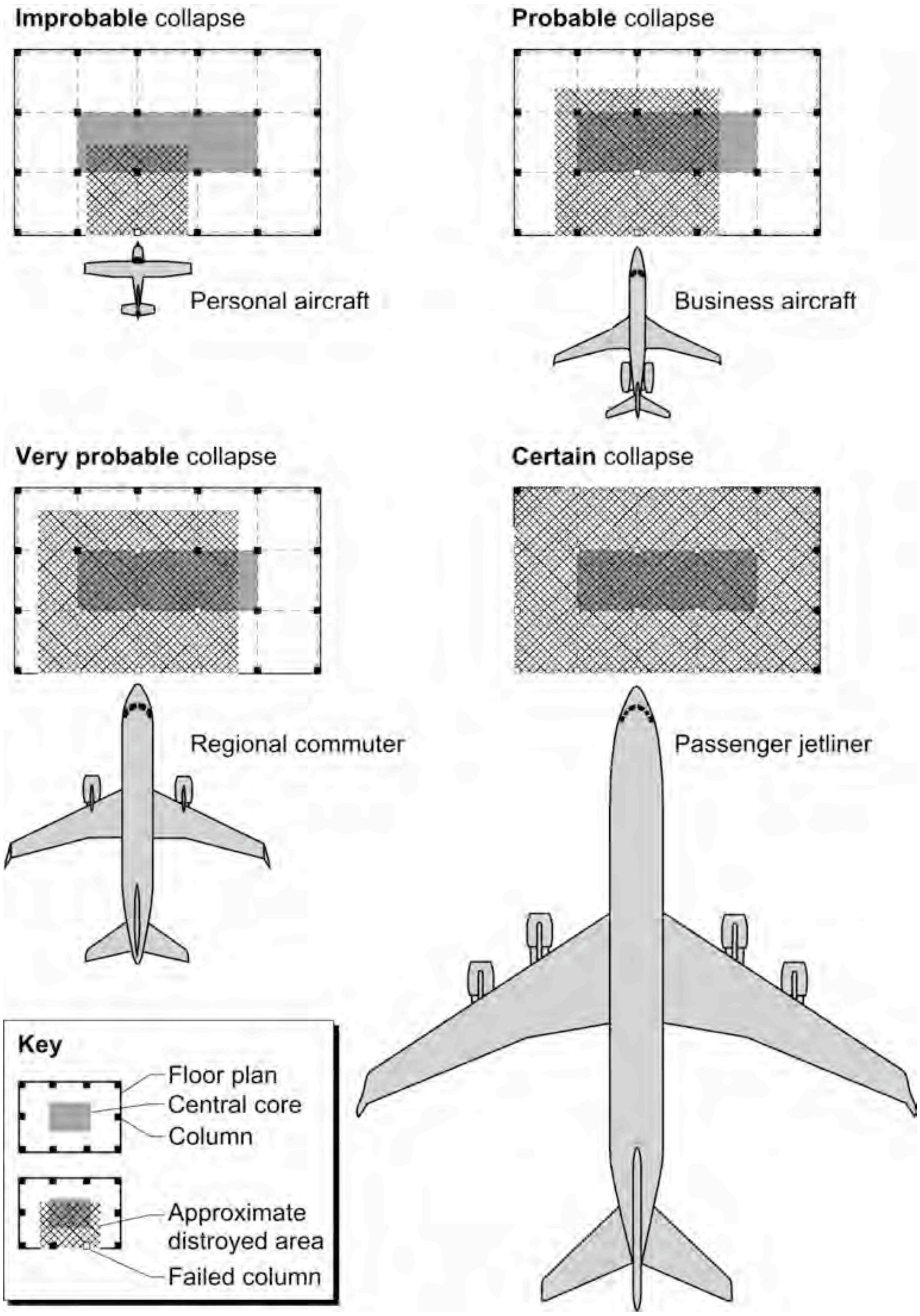


Figure 18: Structural damage and probability of building collapse for medium size high-rise buildings

PROBABILITY OF BUILDING COLLAPSE

The risk of a global structural collapse of high-rise buildings caused to the initial aircraft impact and the effects of post-crash fires created by jet fuel is assessed in the following section.

- The impact of a **personal aircraft** is generally not critical. Because of the small mass, the lightweight construction and the slow flight speed of such planes, the initial effect of an impact is mostly not severe. However, the ignition of fires after the impact may be a serious hazard if the aircraft has a relatively large amount of fuel on board and the fuel spread across a wide area in the impacted floor.
- The effect of an impacting **business aircraft** is mainly depending on the impact speed and the loading with fuel. Due to the limited takeoff weight the immediate mechanical action of the impact is often not severe. Nevertheless, there is relevant hazardous potential when the aircraft has a large fuel capacity and a high impact speed. In such cases the initial spread of fires may be very extensive and can affect the structural integrity of the building.
- Due to the initial effect of impact of a **regional commuter aircraft** the immediate collapse of high-rise buildings with small and medium size is very probable. Because of the limited fuel capacity, the effect of fires is comparable with the post-crash fires of a business aircraft. For this reason, for tall and super tall buildings the probability of collapse is not much higher than in case of business aircraft impact.
- The impact of a **passenger jetliner** results usually in very severe initial effects and also in extensive effects of fires. Caused to the high takeoff weight and the large jet fuel capacity, a structural collapse due to the immediate impact effects and the widespread intensive fires are very probable even for super tall buildings.

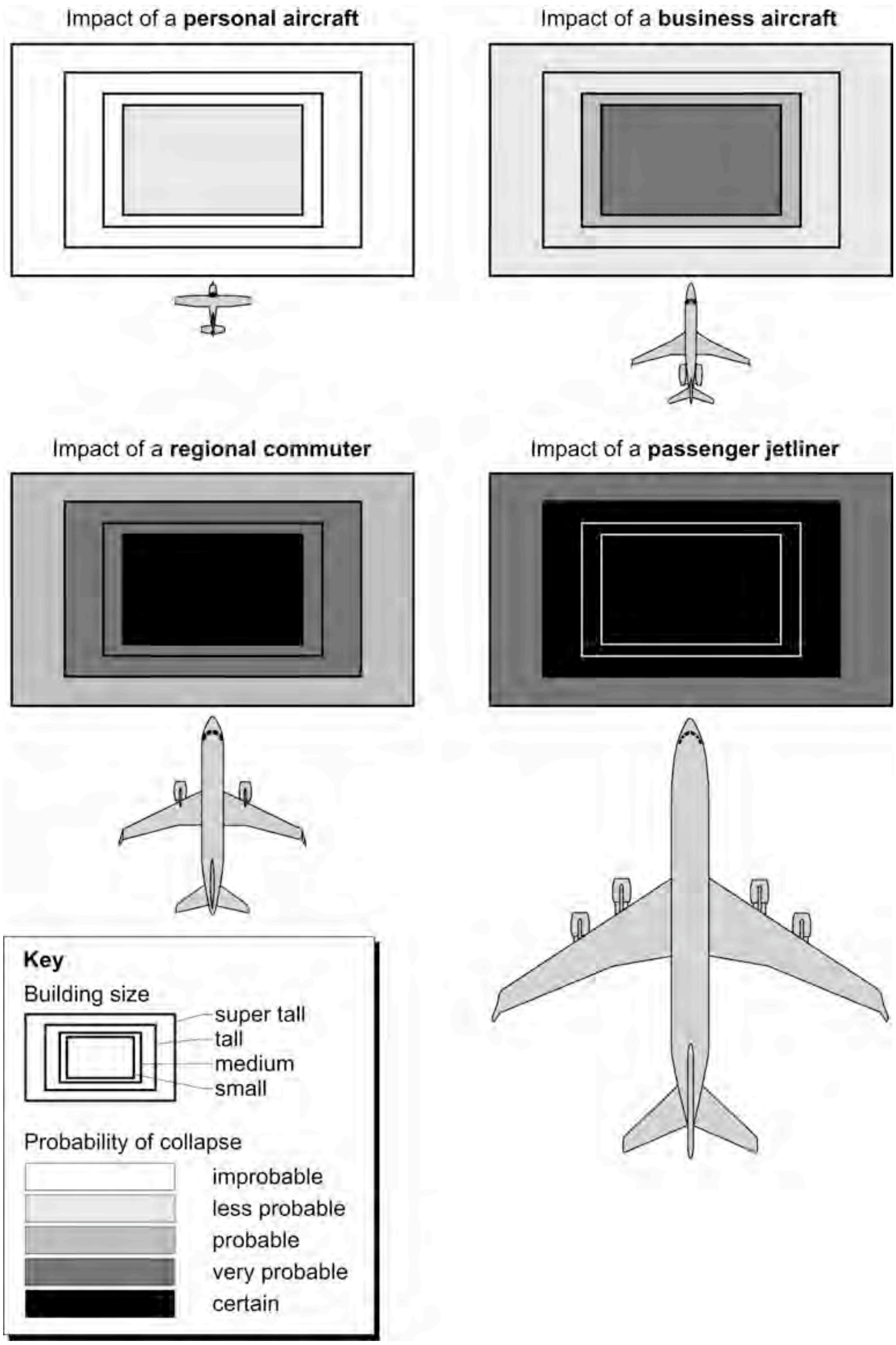


Figure 19: Probability of building collapse caused to aircraft impact

SUMMARY

The extensive analysis of the WTC collapse has shown that, depending on the size of the aircraft, it is technically hardly feasible to design high-rise structures that resist the effects of heavy aircraft impacts and the ensuing fires without collapse. The likelihood of a building surviving an aircraft impact decreases as aircraft size and speed increase. For example, the weight and the fuel capacity oft the new Airbus A380 are approximately three times those of a Boeing 767. So, it was not the goal of the presented study to give recommendations how to design buildings more resistant to such attacks. The purpose of the study was to develop an understanding of the mechanism that lead to a building collapse.

Figure 20 summarizes the findings of the described investigations. Depending on the size of the aircraft the probability of a structural collapse due to aircraft impact is shown in the diagram below. Because of the large quantity of jet fuel even for super tall buildings a global structural collapse is very probable in case of a jetliner impact. On the other hand, the hazardous potential of personal planes is little. Even for small size buildings an entire structural collapse caused to the impact is less probable.

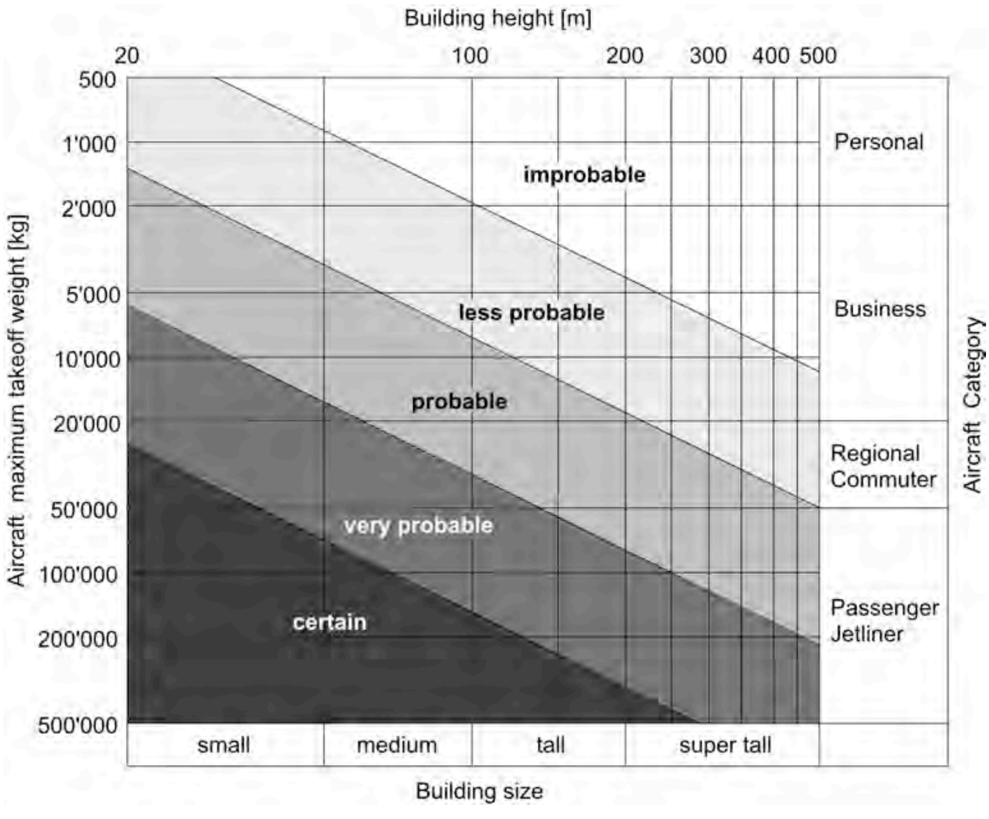


Figure 20: Probability of building collapse due to aircraft impact depending on aircraft and building size

The decision to include aircraft impact as a design parameter would result in a major change in the design and cost of buildings. Further more, building design to survive the impact of large aircrafts is not possible. Including aircraft impact as a design load also requires selecting a design aircraft, as well as its speed, weight, fuel and angle of impact. Nevertheless, it is appropriate to have an assessment tool to estimate the probability of a fatal collapse in case of an aircraft impact. Such tools are also needed when the likelihood of terrorist attacks is not relevant. Especially for built-up areas near airports, hazards due to an aircraft crash have to be taken into consideration in risk analysis.

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