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BUILDING STRUCTURE FAILURES CAUSED BY ACCIDENTAL LOADS

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Abstract:

The paper presents the characteristics of abnormal loads and the recommendations adopted for structural design to prevent constructions from disproportionate damage and to limit the consequences of accidental loads in compliance with Eurocode 1 PN-EN 1991-1-7. The article describes progressive collapses and analyses the construction of two buildings: the Murrah Federal Building in Oklahoma and the Pentagon Building in Washington.

Keywords:

progressive collapse, abnormal load, accidental load

INTRODUCTION

Accidental loads comprise all the loads characterised by a very low probability of occurrence and, therefore, usually disregarded in the normal design process. They may cause significant damage to the construction, resulting from a partial or complete progressive collapse, which, in consequence, may lead to casualties. Potential accidental loads that can trigger a progressive collapse include, among others, an airplane strike, a bomb explosion during a terrorist attack and a fire or a gas explosion within a confined space [1]. A construction that is not sensitive to abnormal loads is defined as resistant to collapse. As a result of terrorist attacks the US General Services Administration (GSA) and the Department of Defence (DoD) have developed the relevant regulations, [2] and [3], aimed at ensuring the security of people and protecting building structures from a progressive collapse. The main recommendation arising from the

GSA [3] and DoD [2] regulations (see [4]) is the mitigation of the potential for a progressive collapse. It is related to the design method, which can be direct or indirect (see [5] [6]). The application of a direct design method relies on making all main structural members (columns, load-bearing walls, horizontal beams, joints, etc.) capable of absorbing accidental actions. It is possible owing to the formation of a secondary load-bearing structure in the damaged construction, with the effective redistribution of loads, which arrests its further damage or collapse. When an indirect design method is applied, it is necessary to consider the minimum structural integrity, the continuity of reinforcement, the ductility of members, joints etc., to prevent a progressive collapse.

The purpose of this article is to discuss the aspects of a progressive collapse resulting from abnormal loads and the methods of preventing its occurrence. The paper illustrates the above with the examples of damage to the Murrah Building in Oklahoma City and the Pentagon in Washington caused by terrorist attacks, which took place in 1995 and 2001, respectively.

1. PROGRESSIVE COLLAPSE OF A BUILDING STRUCTURE

A progressive collapse of a building structure means a situation where localised damage to the main structural member leads to the collapse of its adhering members, which, in turn, contributes to further damage [7]. The extent of the total damage is disproportionate to its root cause. In other words, a progressive collapse, described hereinabove, is a chain reaction or the propagation of damage, after it has occurred in a relatively small part of the building structure.

The proper designing of a building structure consists in ensuring its structural integrity by maintaining the correct load-carrying ability, continuity and ductility of its load-bearing members and connections between such members. PN-EN 1991-1-7 standard [8] contains the guidelines regarding accidental actions, identifiable and unidentifiable, and design strategies aimed at mitigating the extent of a localised failure, thus reducing the risk of a disproportionate collapse of the structure. To avoid a disaster posing a particularly serious threat to human life, damage to the natural environment or substantial economic losses, the above-mentioned standard introduces three classes of consequences of failure of a structure or its part:

- CC1 – low consequences of failure, e.g. private houses up to four storeys high, agricultural buildings, buildings where people are rarely present, situated away from other buildings or areas actually occupied by people, at a distance of not less than 1.5 times the height of the building;
- CC2 – medium consequences of failure, e.g. hotels, residential buildings, apartments, educational buildings, offices, retail stores up to 15 storeys high, industrial buildings, hospitals up to three storeys high, public utility buildings with the area of each storey of up to 5,000 m^2, car parks up to six storeys high;
- CC3 – high consequences of failure, e.g. all buildings that exceed the above limitations in terms of their area or the number of storeys, all buildings accessible to considerable numbers of people, stadiums for more than 5,000

people, buildings in which dangerous substances are stored or dangerous processes are carried out.

A localised failure is acceptable, provided that it does not lead to a total collapse of a structure. Figure 1 below shows the sequence of events occurring during a progressive collapse of a building structure.

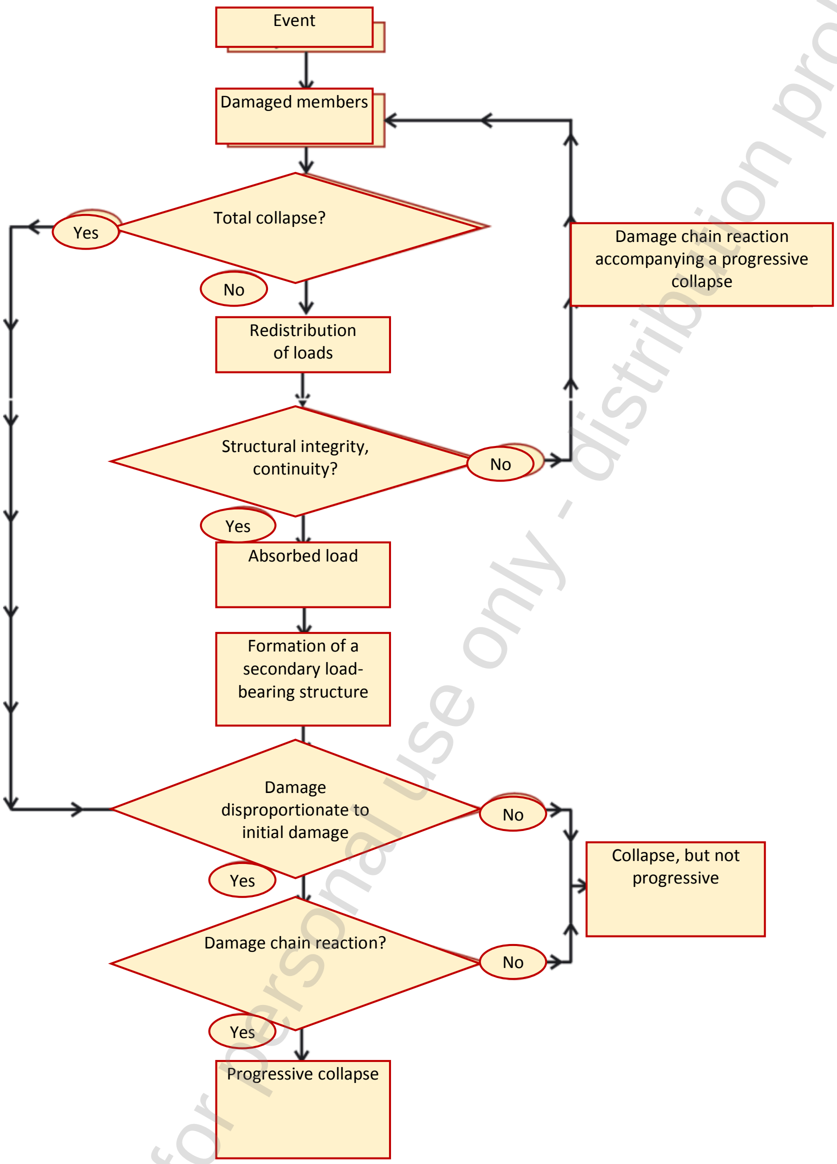

Fig. 1. Sequence of events during a progressive collapse of a building structure

Source: [9]

Figure 2 presents a hypothetical example of a progressive collapse of the building caused by a bomb explosion. The shape of the building may affect the size of damage (Figure 3). The mitigation of explosion effects can be achieved by the appropriate shaping of the site section. In the case of a bomb explosion on the flat ground surface the building is affected by the shock wave spreading without any obstacles.

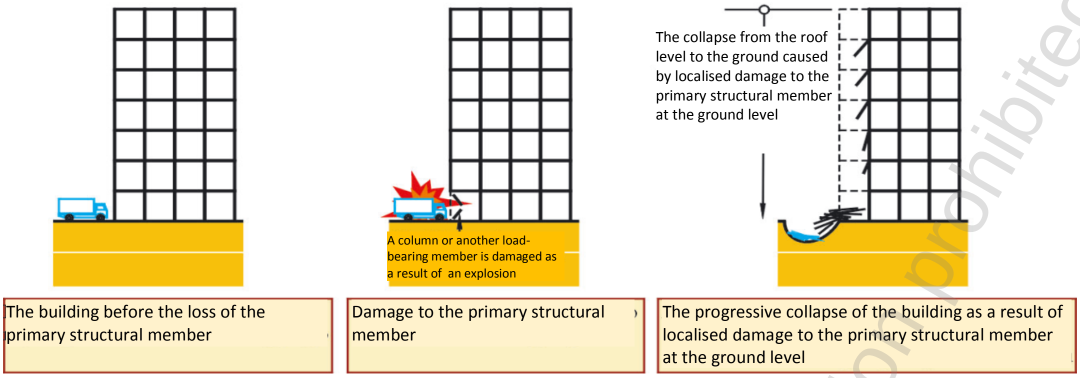

Fig. 2. Progressive collapse of the building with a reinforced concrete structure caused by the explosion of a bomb placed in the car

Source: [4]

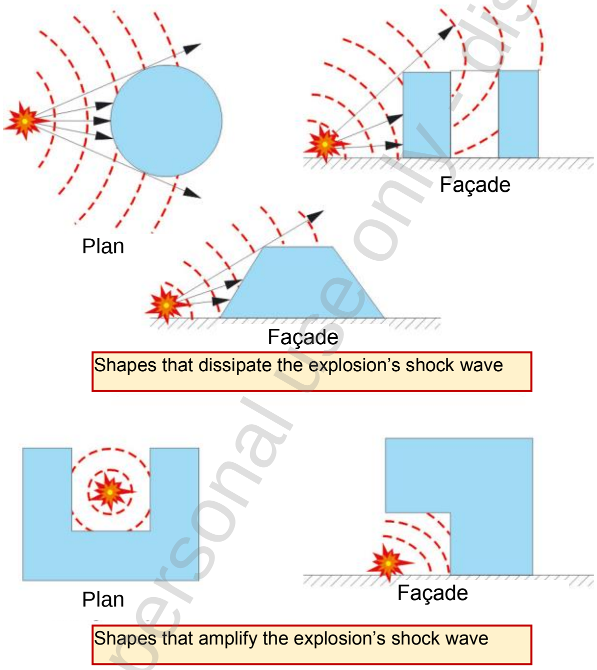

Fig. 3. Influence of the building's shape on the action of the explosion's shock wave

Source: [11]

Figure 4 shows an example of a chain mechanism, after the formation of which the structure is able to resist a progressive collapse. The loss of the reinforcement continuity in the beam above the column may lead to a progressive collapse (Figure 5a). To meet the requirement for the formation of the secondary load-bearing structure (alternative load paths) it is necessary to provide the continuous lower reinforcement on the inner support (Figure 5b). ACI 318-05 regulations [10] contain the requirements for the continuity and structural integrity of upper and lower reinforcement.

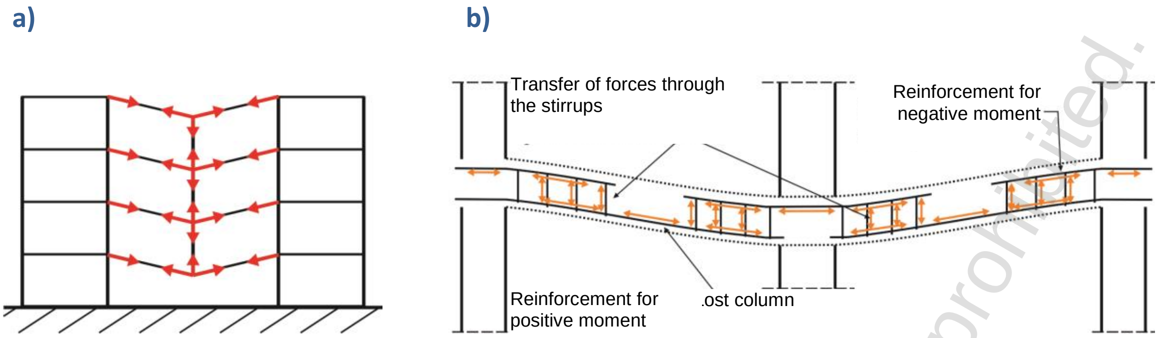

Fig.4. Chain mechanism: a) formed system of forces preventing a progressive collapse, b) transfer of forces through the stirrups in the formed chain mechanism

Source: [12,13]

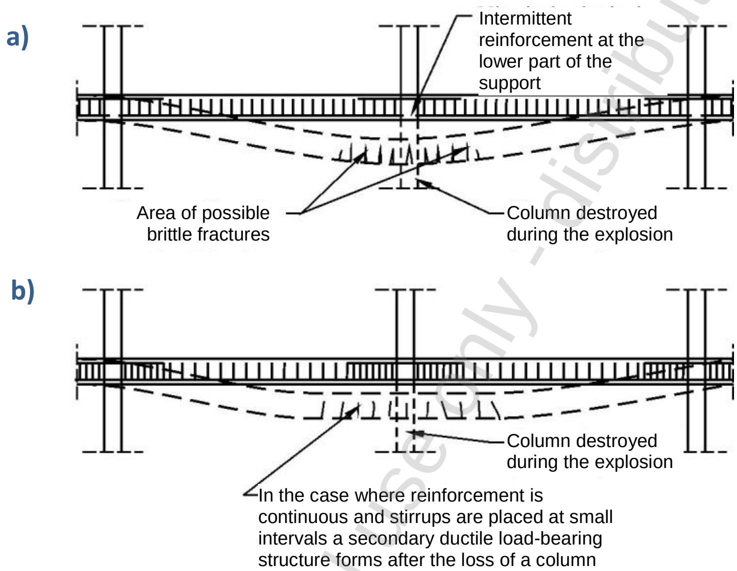

Fig. 5. Loss of the reinforcement continuity in the beam over the column may lead to a progressive collapse [14]: a) situation before the loss of the support, b) situation after the loss of the support

Source: [14]

2. COLLAPSE OF BUILDINGS CAUSED BY TERRORIST ATTACKS

2.1. Introductory remarks

Starting from the 80s of the previous century a considerable number of buildings in different parts of the world were the target of attacks using car bombs. As a result of explosions a partial or total progressive collapse would occur. Among the former, the progressive collapse of the Murrah Building in Oklahoma City in 1995 is an example of the most spectacular and best documented ones.

Among the buildings that suffered a total collapse the New York World Trade Center Towers have to be mentioned, which were struck by passenger airplanes hijacked by terrorists in 2001.

a) b)

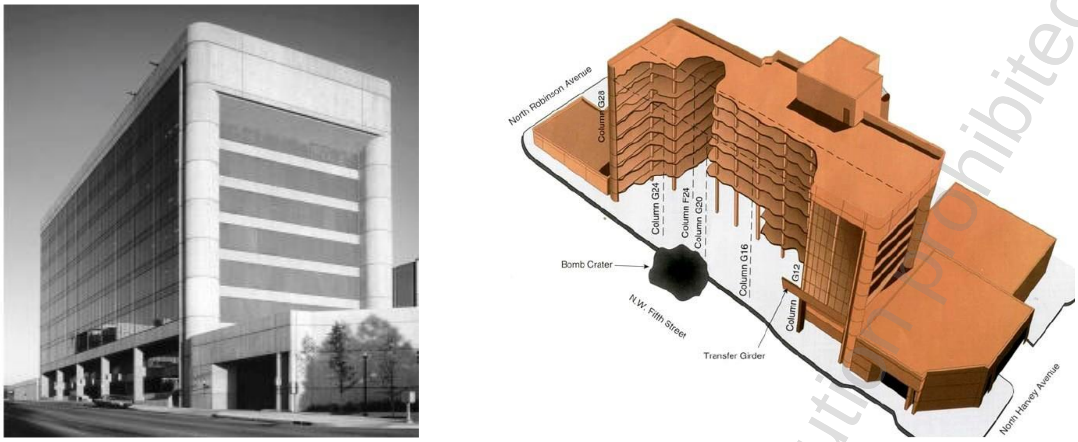

Fig. 6. Murrah Federal Building in Oklahoma City before and after its collapse (photo: NIST)

Source: [14]

2.2. Collapse of the Murrah Building in Oklahoma City in 1995

Figure 6 shows the views of the Murrah Federal Building before and after the explosion of a car bomb, the location of which at the time of detonation is presented in Figure 7a, while Figure 7b illustrates the crater formed after the explosion. As a result of damage to a part of the floor and the columns on the ground floor, the remaining part of the floor was subject to a progressive collapse. A secondary load-bearing structure, capable of accommodating the applied increased load, did not form (Figure 8). The building was erected before the guidelines were developed to mitigate the risk of progressive collapse. It should be pointed out, however, that in accordance with the typical designing procedures, taking account of accidental actions, structures are designed to be resistant to the failure of a single load-bearing member (e.g. a column). In the discussed attack three neighbouring columns were simultaneously destroyed, so it can be assumed that the completion of the building in compliance with the current guidelines would not protect it from collapsing, either.

a) b)

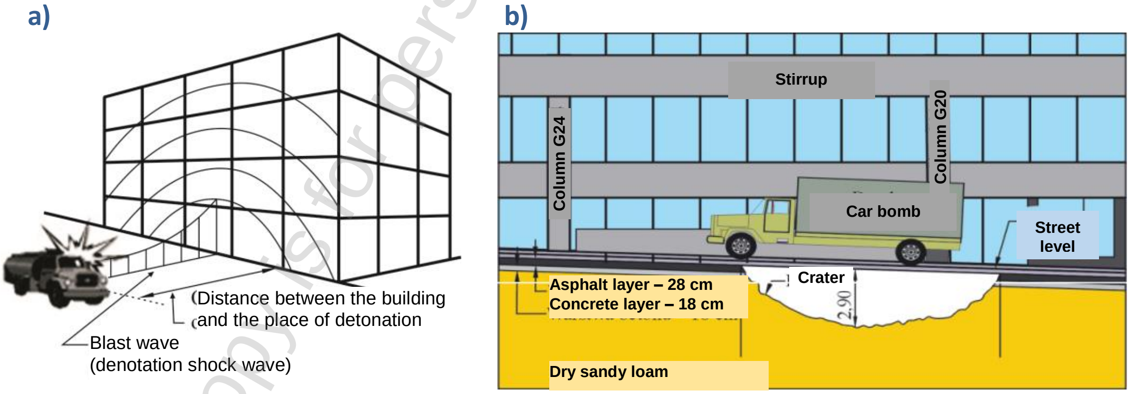

Fig. 7. a) Location of a car bomb and the pressure plot; b) crater formed as a result of the explosion against the northern wall of the MFB building

Source: [15, 16]

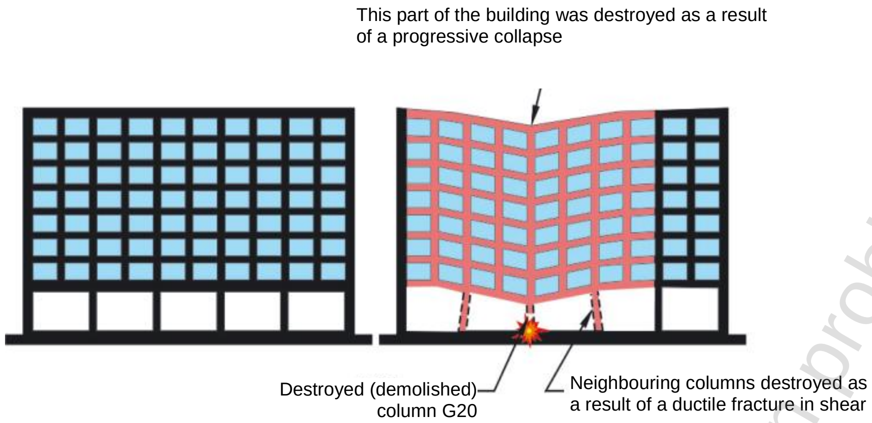

Fig. 8. Structure of the Murrah Federal Building before and after the car bomb explosion

Source: [17]

2.3. Partial collapse of the Pentagon building caused by the terrorist attack

On 11 September 2001, a Boeing 757 airplane of American Airlines (flight 77 from Dulles Airport), carrying 13.5 ton of fuel, struck the Pentagon building, killing 64 passengers on board and 125 Pentagon employees. It caused little damage to the building and the plane itself disintegrated completely. Figures 9 and 10 show the damage caused by the impact and resultant fire and the temporary shores safeguarding the building structure.

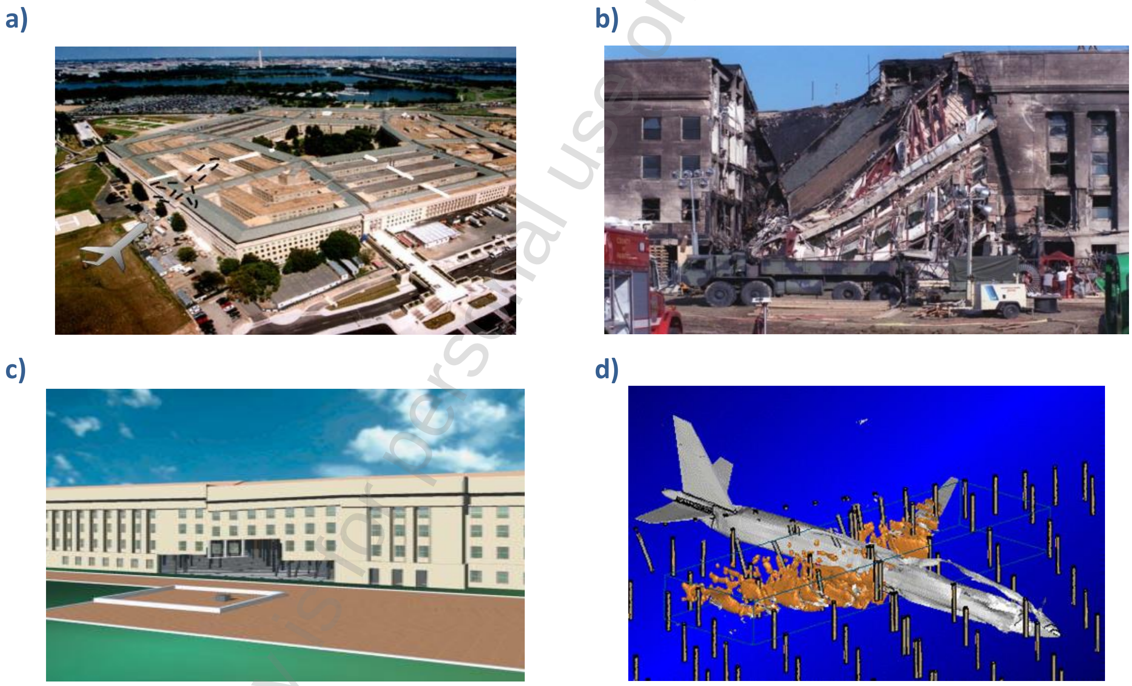

Fig. 9. Terrorist attack on the Pentagon building, Washington: a) location and angle of impact; b) collapse after the strike, c) place of impact before collapsing d) idealisation of the strike into the columns

Source: [17]

CONCLUSION

The terrorist attacks resulting in the collapse of the building in Oklahoma City, the Pentagon building in Washington and the WTC Towers in New York as well as the collapse of numerous other buildings caused by accidental actions inclined research and standardisation units to focus to a greater extent on the influence of loads on the behaviour of buildings and the development of necessary design guidelines. The designing of building structures exposed to the risk of progressive collapse requires a broader knowledge than that applied in the case of building structures designed to resist normal loads. In conclusion, it should be added that taking account of the current socioeconomic climate around the world it is impossible to eliminate completely the risk of building structure collapse, however, when buildings that may be subject to abnormal loads are designed, attempts should be made at eliminating such risk or reducing it to an acceptable level.

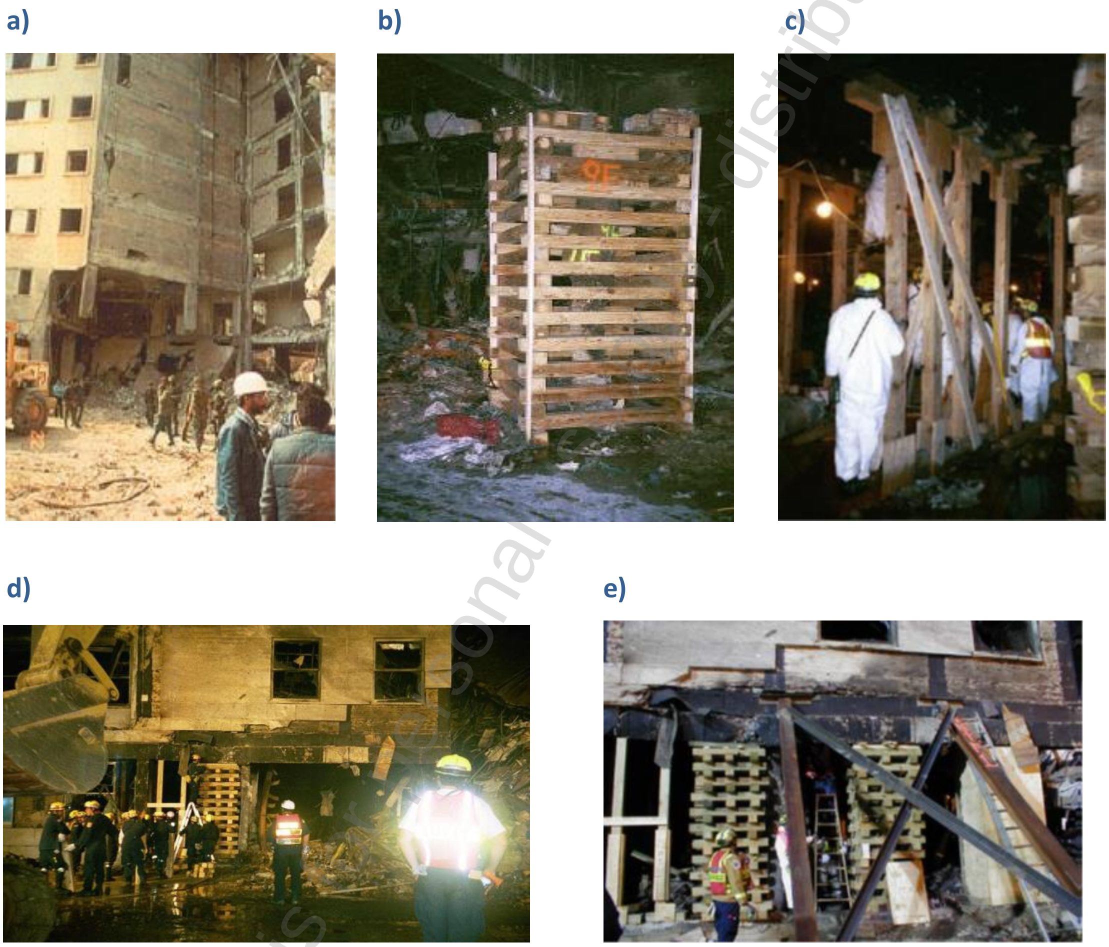

Fig. 10. Terrorist attack on the Pentagon building, Washington: a) reinforced concrete infilled frame acts like a shield, compensating for the lost columns; b) single point support of the severely damaged columns; c) vertical support; d) shoring operation; e) supporting with raking shores

Source: [18, 21]

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BIOGRAPHICAL NOTES

Sylwester KOBIELAK, Prof., PhD, DSc., Eng. – Sylwester Kobielak received his B.Sc., M.Sc., Ph.D. and D.Sc. degrees in civil engineering from the Faculty of Civil Engineering at the Wrocław University of Technology (WUT), Poland, in 1961, 1963, 1973 and 1992, respectively. Currently, he is a full professor at the Faculty of Environmental Engineering and Geodesy of the Wrocław University of Environmental and Life Sciences (WUELS). Prior to joining the WUELS he was employed at the Faculty of Civil Engineering at the Wrocław University of Technology (1967-2007) and at the Department of Military Engineering Officers' College in Wrocław (1994- 2002). In 1988, he stayed at the Faculty of Architecture of the University of Mosul (Iraq). From February to October 1985, he was a visiting scientist at Northwestern University, Evanston (Illinois, the U.S.). He has a building license for designing, supervising and managing constructions (1964) and is a certified structure expert (1971). He is the author of many important projects, engineering and construction expert studies, a specialist in the field of concrete structures, including concrete protective structures. He is the author or coauthor of seven monographs and more than 240 scientific papers. He is a member of the American Society of Civil Engineers (ASCE) and the American Concrete Institute (ACI). He works in ACI Committee 313 Concrete Bins and Silos and is a member of the Editorial Board of *Quarterly Archives of Civil and Mechanical Engineering*, ELSEVIER.

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