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FAILURES OF BUILDING CONSTRUCTIONS CAUSED BY DESIGN ERRORS

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Abstract:

The work presents basic information regarding failures caused by design errors and discusses examples of this type of failures that occurred particularly due to the lack of recognition of the construction stability, as well as shortcomings in the procedure for checking a project. There is also shown the role of independent verification of major projects.

Keywords:

construction failure, building construction, design error, independent project check, construction safety

INTRODUCTION

A construction failure is the condition that prevents or limits the use of a building construction as a result of damage to one or more of its components. A special case of a construction failure is a disaster, which means unintentional hasty damage to a building or part thereof (Art. 73 paragraph 1 of the Act – the Construction Law [32]). The District Building Supervision Inspector (PINB) [23] qualifies for recognition as a building disaster (which does not involve a construction failure). The General Office of Building Supervision (GUNB) has kept the register of all disasters occurred (the Building Disaster Registry) since 1995. Previously, in 1989 the data began to be collected by the Institute of Building Technology (ITB) [24], and since 1992 it has had the form of the computerised database [23]. According to GUNB disasters generally can be divided into two categories [3], [24]:

- category I includes disasters not resulting from random events, that is human errors – faulty design, performance and operation;
- category II includes disasters occurring due to fortuitous events, as a result of, among others, the forces of nature (floods, strong winds, heavy snowfalls, lightning strikes, fires), as well as gas explosions, cars crashing into buildings, boiler explosions.

There are different reasons for the majority of failures of building structures, which usually, but not always, are caused by more than one factor.

This paper focuses on the review and analysis of category I failures, i.e. those arising from design errors. Design errors can and will continue to occur. They can result from the use of improper design methods, the omission of important factors, and not paying due attention to design requirements, e.g. insufficiently understood permanent and operational loads, load combinations that may occur during either the construction or the operation of the facility. Modern advanced calculation methods allow for carrying out complex precise calculations, while at the same time the possibility of errors increases resulting in the lower level of "feeling" of the structure. This problem is more serious for the less experienced designers, some of whom are often enable to verify the correctness of the final solution [29]. New materials with characteristics identified by designers in an inadequate degree in relation to properties of traditional materials, when used, can indirectly contribute to potential serious errors.

The paper discusses the failures of the building constructions caused mainly by two types of errors, namely, the first of them which occurs because of the lack of recognition of the structure stability (the single-layer braced dome in Bucharest and the double-layer grate roof covering in Connecticut), and the second ones – construction faults as well as shortcomings in the procedure for verifying a project (the arc steel-concrete covering of the Air Terminal in Paris and the cycling track roof in Ballerup). Given the importance of these shortcomings in the design of the structure there is presented the role of a controller of major projects.

1. FAILURES CAUSED BY THE LOSS OF STABILITY OF ROOFING CONSTRUCTIONS

Examples of the collapse of structures caused by the lack of recognition regarding their stability include the single-layer braced lattice dome in Bucharest (Figure 1) and the double-layer grate roof covering of Hartford Coliseum in Connecticut, the USA (Figure 3), which collapsed as a result of the loss of stability. Stability, which is the fundamental issue of the solid-state mechanics, should be recognised so as to protect the structure against the collapse [4].

In the light of the considerations, Abedi et al. [2] who investigated the behaviour of such domes found that the domes are susceptible to the progressive collapse due to the buckling dislocation arising when the axial load combines with the torque initiated by the local instability of an element or a node. The instability is produced by inertial forces launching oscillations around the balance state and large local structure deformations that may propagate and as a result lead to the collapse of the structure (Figure 2). The threat of the collapse because of instability in systems of this type increases as the coefficient of the arrow grows in relation to the dome span. Kyriakides identified "the propagation of the local instability" as the new class of structural instability about 50 years ago [28]. When completed in 1961, the dome (Figure 1) constituted a technically approved bold light lattice dome of a diameter of 93.5 m with a top hole of a diameter of 17 m, on the circumference of which there is fastened a rigid steel compression ring having a box section, against which there is leant the 25 tonnes heavy skylight [28]. Its construction is made of steel tubes of a diameter of 102 mm and 6 mm thick walls.

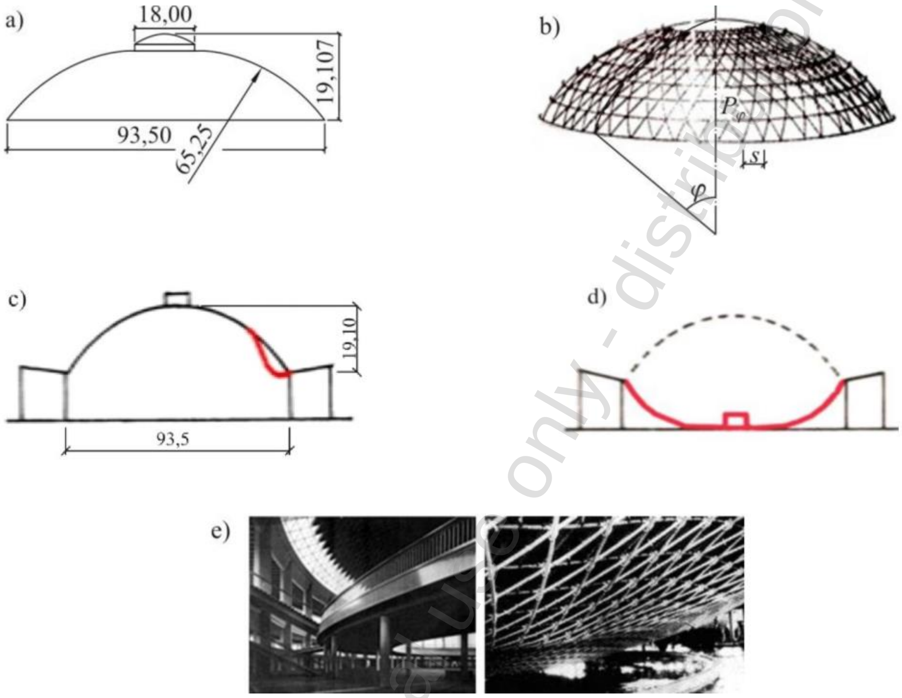


Fig. 1. The collapse of the single-layer lattice dome in Bucharest in 1963 resulting from the development of local deformations [13] during a snowstorm causing asymmetric loading, while moving only 30% of design loads: a) the geometry of the dome b) a view of the lattice dome structure, c) the cross section of the dome during the local deformation occurrence, d) the cross section of the dome after the collapse e) a bottom view of the dome structure before (on the left) and after the collapse (on the right)

Source: Own elaboration

Another well-known case of a disaster caused by the continuing building collapse is the Hartford Civic Center Coliseum [18] (Figure 3), which happened mainly because of errors [12] in calculating the innovative design of a roof covering as a system of trusses arranged in two directions every 2745 mm with spatial pyramidal elements. The collapse of the roof covering in the form of the steel double-layer grate took place because of the faulty design consisting in the underestimation of the weight of the roofing [20] and, above all, in the fact that the main top chord had very understated bearing capacity of the buckling compared to that which was adopted in the project. The buckling length of elements regarding the compression (Figure 3d) was 9.14 m, not 4.47 m as assumed [27], [31], [16], [19].

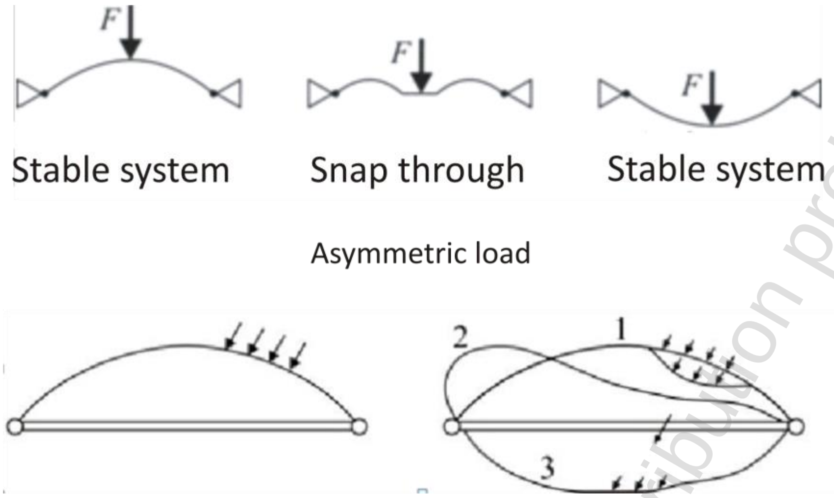
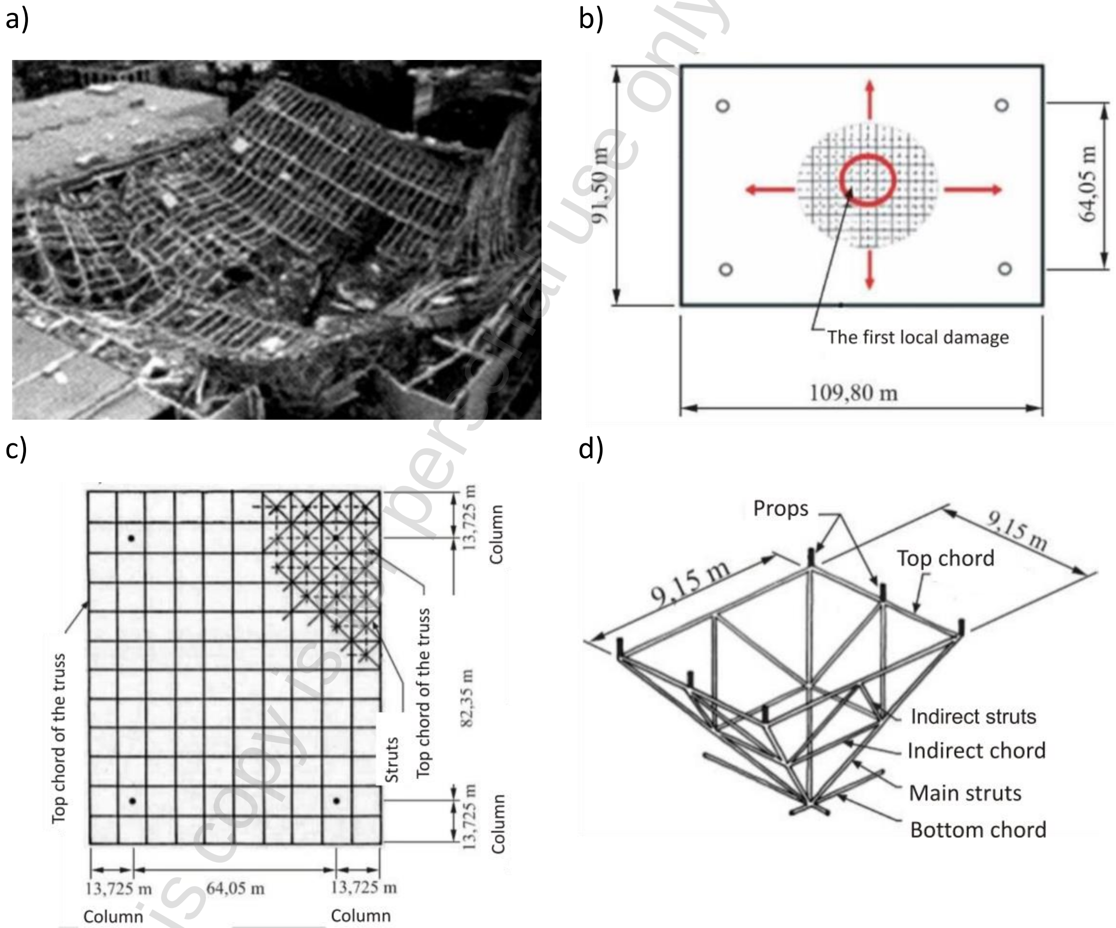


Fig. 2. The local instability of the flat dome occurring with a sudden buckling (snap through) during its transition from one stable system into the second one of the reversed curvature

Source: Own elaboration



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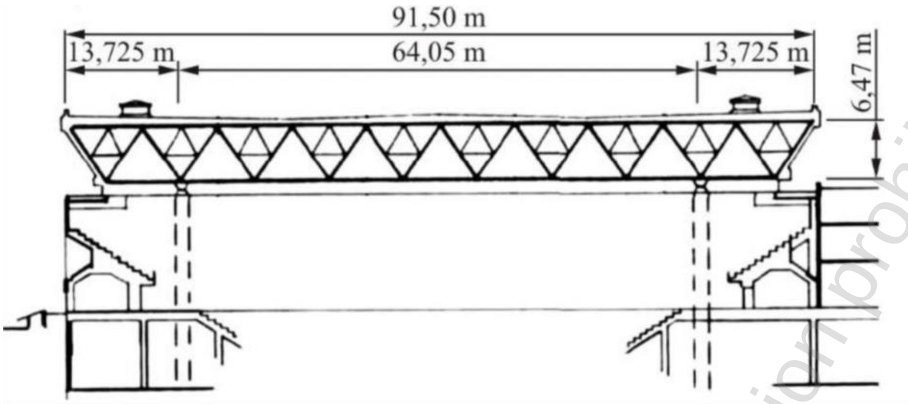


Fig. 3. The collapse of the double-layer spatial roof covering of the arena Civic Center Coliseum in Hartford, Connecticut, the USA on 18th January 1978. It was initiated by the damage of one of the spatial pyramidal elements of the grate [8], [25], [18], [20], the accumulated load of snow and rain: a) a view of the structure of the roof covering after the collapse of 01/18/1987 [10], b) the propagation of the first damage, c) the construction of the roof covering of the arena [25/39] d) the pyramidal construction module of the roof covering with stands supporting the roofing plate [8] e) the cross section of the covering [9].

2. FAILURES CAUSED BY CONSTRUCTION ERRORS AND SHORTCOMINGS IN THE PROCEDURE FOR THE PROJECT VERIFICATION

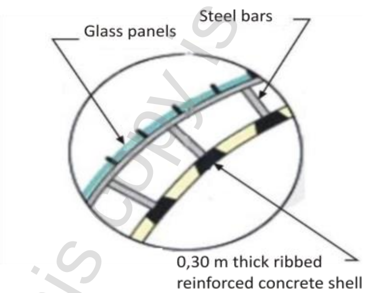
2.1. The partial collapse of Charles de Gaulle Terminal 2E in Paris Building construction failures caused by design errors

In 2004 a number of design errors resulted in the collapse of the AirTerminal in Paris. It was 700 m long and the span of its arc was 33 m. Falling pieces of glass, steel and concrete killed four travelers, 3 others were injured.

a)

b)

c)



d)

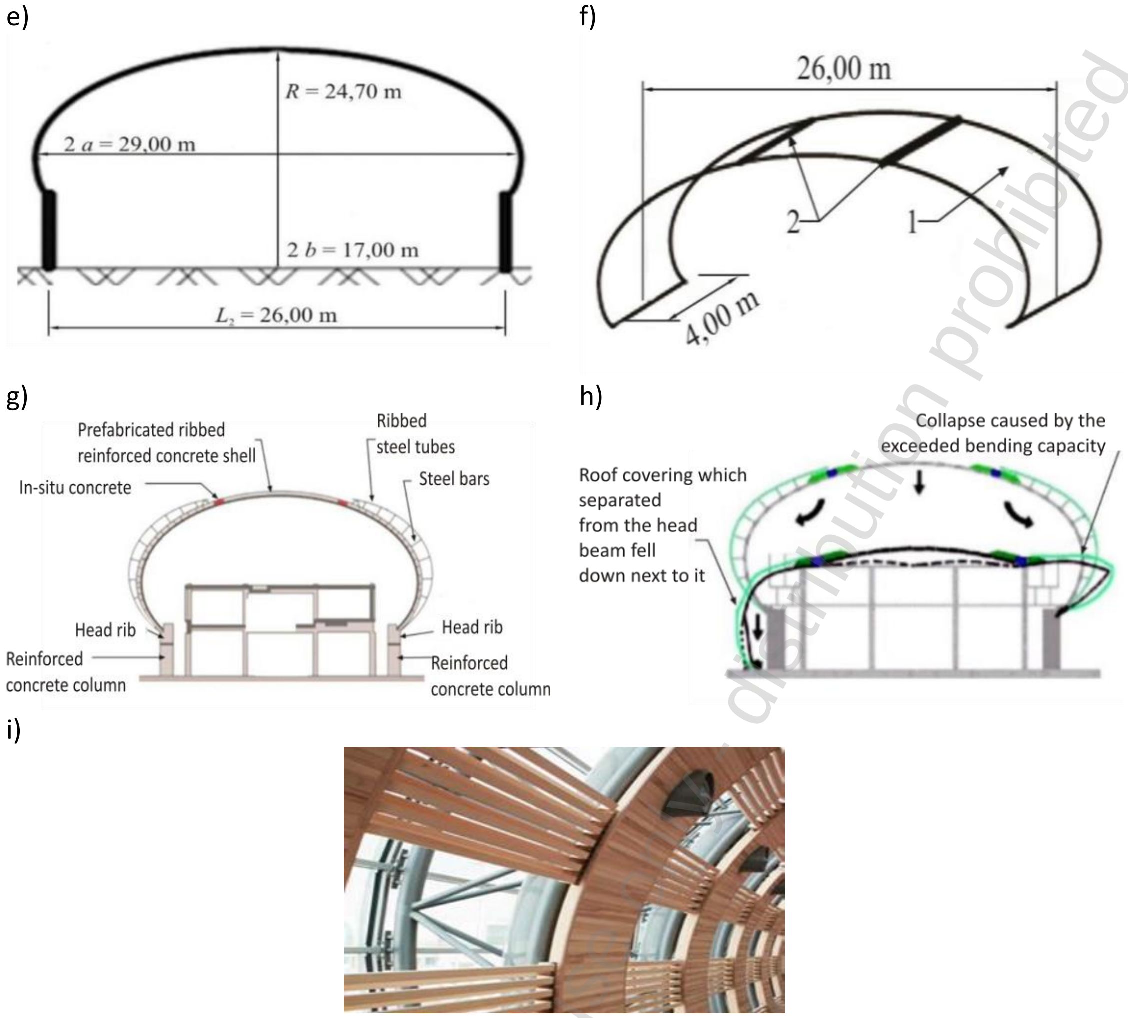


Fig. 4. The partial collapse of the Charles de Gaulle Air Terminal in Paris in 2004: a) a view of the collapsed part of the Terminal, b) a detail of the collapsed roof with a steel rod connecting a steel arch with the ribbed reinforced concrete shell c) a detail of the arc construction, d) the steel and reinforced concrete roof covering during the construction, e) the cross section of the reinforced concrete part of the roof covering [15] f) the cross section of the elliptical shell [15], 1 the ribbed reinforced concrete shell, 2 –the in-situ combination of prefabricated reinforced concrete elements, g) the cross section of the Terminal before the collapse (www.building.co.uk), h) the mechanism of the collapse of the Terminal 2E [5], i) the new solution of the roof covering of the Terminal [22]

The reasons for the collapse of the roof covering:

Construction causes:

- insufficient stiffness of the structure;
- improperly distributed reinforcing steel in concrete elements;
- weak external steel bars (compressed) punching / penetrating in the perforated reinforced concrete shell;
- insufficient concrete support beams.

Procedural causes:

- the inadequate procedure for checking the project;
- poorly organised administrative procedures.

The most important shortcoming were inaccuracies in the procedure for checking the project. The full independent analysis of the project verification would allowed to determine the shortcomings of the project and avoid the collapse of the Terminal.

2.2. The partial collapse of the cycle track roof covering of Siemens Arena in Ballerup, Denmark [1], [21]

The disaster occurred during the heavy snowfall (Figure 5a). The main structure of the roof covering consisted of 12 trusses of the span of 73 metres, each made of two arches of glued laminates connected by vertical connectors. The unaffected truss is shown on the right side of the picture on the right (Figure 5b). Trusses were spaced every 12 m with purlins freely based on them. Two of the trusses collapsed unexpectedly, when there was no wind and only a few millimetres of snow. The incident occurred just a few months after the inauguration of the Arena, when there were no people. Studies have shown that the cause of the failure can be located in one critical cross section in the tension bow in the vicinity of the support (Figure 5c, d), where it was found that the strength was between 25 - 30% of its required value. In addition, the penetration of water was observed as a result of leaks through the membrane of the roof covering and the area of discharging water from the roof surface. However, the concrete structure settlements were not observed, as they could have a significant impact on the roof covering construction. It was agreed that the construction calculations concerning the roof covering were not investigated by a person responsible for checking what is mandatorily required in cases of meeting or sports halls. During the design it was decided not to attach the purlins to the truss too rigidly (?) so that any failure of one of the trusses can initiate the progressive collapse. Owing to this strategy "only" two out of the twelve trusses collapsed.

a)

b)

c) d)

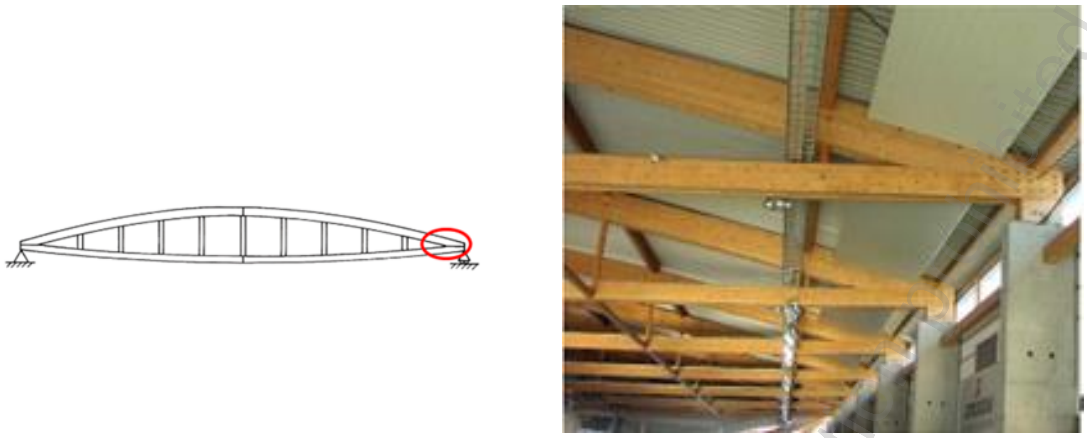


Fig. 5. The partial collapse of the Sports Arena, Ballerup, Denmark (Photo: Munch-Andersen, J.) a) a view of the collapse of two trusses, b) a view of the intact truss, c) the truss of the 72 m span and the maximum height of 5.0 m with the section limited by only 30% of the required load capacity d) the detail of the supporting node of the undervalued strength [30]

3. THE ROLE OF A CONTROLLER IN MORE IMPORTANT PROJECTS

The independent project validation must be introduced with the aim to reduce the risk of failures caused by design errors, in particular as regards innovative projects of long span constructions and high-rise buildings or structures working in extreme conditions. The necessity to introduce the independent verification was recommended after the collapse of the bridge in Milford Haven, South Wales, and the bridge in Melbourne in 1970. [14].

Responsible investors and designers should appoint committees to have their projects independently checked, in particular when it is required by the scale or complexity of the project. Based on the experiences gained in England [11] with respect to larger projects, especially bridges, it shows that the cost of such verification is very small compared to that major benefits achieved in terms of increased confidence and reduced risk of the undertaking. Figure 6 presents the diagram of dependency of costs of the project independent verification on construction costs based on data from a number of completed projects.

Fig. 6. The diagram of the percentage share of costs of the bridge independent verification and the cost of its construction [11]

The need for checking is undisputed, since the engineers are only humans and mistakes happen to all of us. Sad history shows how easily mistakes can occur and it would be very unwise to assume that studies are always correct and never need to be checked. Designers of building structures bear enormous uncompromising responsibility resulting from professional obligations for public safety. Therefore, they are supposed to verify projects responsibly and appropriately. Construction safety is the main but not the only task of designers. They are obliged to ensure investors as far as it is practicable and reasonable that there will not occur errors, which could expose him / her to problems and as a consequence the time loss and additional costs. In order to avoid this kind of situation, the most effective way is to identify and remove errors in a project.

There are various methods to check a project, appropriately to different circumstances, starting from the statement that *two heads are always better than one*. One of the methods used for checking the project is the numerical checking made by an expert who should investigate, regardless of a designer, the behaviour of a construction with the assumed design criteria in order to to work out an opinion on meeting the necessary requirements in a project.

This work [14] provides recommendations regarding the need to test projects and requirements imposed on a controller. An independent engineer should have relevant experience and qualifications commensurate with the size and complexity of a project. Another way of the project verification consists in the discussion of a designer with a friend not involved in the design process, when comprehensive questions are raised about the used or missing solutions / details of the project. The latter verifies the project through its review and it ought to be part of normal activities of any office design. This method of checking is good for the relation a designer – a controller, because a designer does not need to be forced on the defensive after any error found by a controller who, in turn, does not seek "points" through finding faults, but both parties strive to gain mutual benefits [11].

The following highlights the importance of the independent verification on the basis of the work by Firth [11]. The independence may be technical and financial. Technical independence requires two suitably experienced engineers who have independent approaches to professional opinion through the process of technical analysis or research. A controller must also be free from excessive financial constraints or conflicts of interest. Generally, a checking person should be independent from a designer. This means that he / she should be designated not by a designer but by an investor / a client (Figure 7a) If a designer appoints a controller (Figure 7b) he / she can try to influence the result of the check. A controller may be under pressure, hence in certain circumstances the conclusions reached may be in conflict with his / her professional opinion.

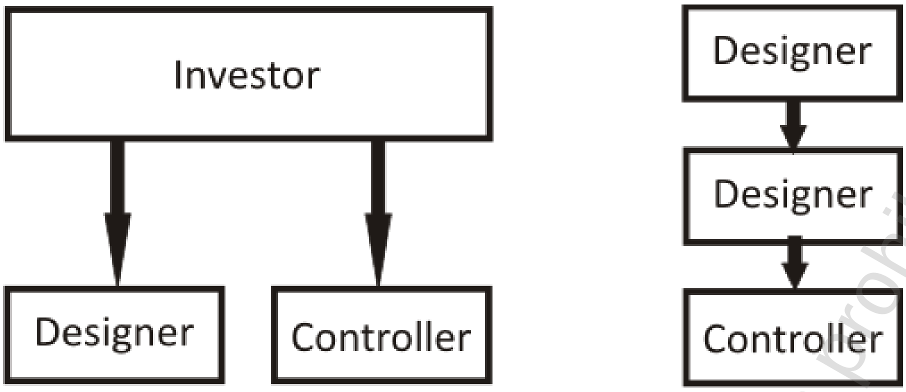


Fig. 7. Possible *a designer – a controller* arrangements [11].

Today, more and more public sector projects is purchased through contracts for a design and implementation [6], [7]. Generally accepted is the approach when the investment design and build contractor (D & B contractor) defines both a designer and a controller, which allows him / her to have the control of design and checking areas, according to the project implementation program (Figure 8a).

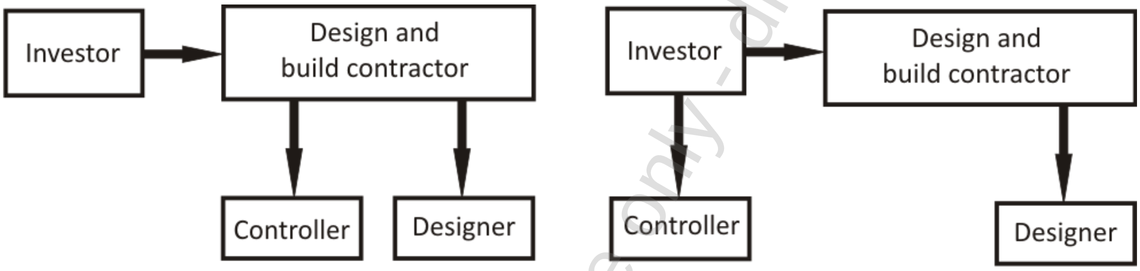


Fig. 8 Alternative arrangements of a design and implementation contract [11]

From the point of view of the verification, the arrangement is sometimes better when an investor / employer appoints a person to verify a construction contractor's project proposals (Figure 8b). In this case, a controller is able to advise an investor, regardless of a contractor and a designer, as well as participate in supervising the construction [11].

CONCLUSION

The paper presents basic information regarding disasters caused by the project-related shortcomings and the role of a controller in major projects. On the basis of the study of the attached literature the following conclusions can be drawn:

- the investigation / analysis / studying the causes of disasters / failures leads to a significant reduction in their occurrence;
- while attempting to reduce the frequency of their occurrence it should be remembered that this activity is a continuous process;
- a special effort should be undertaken by government organisations (e.g. GUNB) in order to help designers, contractors and users of buildings to ensure appropriate training, opportunities for carry out studies, apprenticeships, seminars or workshops for the personnel [26];

- publishing a wide range of educational materials by the above mentioned organizations;
- a disaster / failure can never be totally eliminated, but the construction environment should be permanently improved;
- to reduce the risk of failures caused by design errors it seems purposeful to introduce the independent project verification and the relevant decree on the design process in particular with regard to long span constructions and high-rise buildings or structures working in extreme conditions.

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