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CONSTRUCŢII. ARHITECTURĂ

UNDERSTANDING FAILURES, AN USEFUL TOOL IN STRUCTURAL ROBUSTNESS EVALUATION

BY

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Abstract. Learning from failures is a powerful educational tool for all civil and structural engineers. Although structural designers do not wish to discuss their shortcomings and mistakes from their activity a detailed analysis of failure cases is an instructive way of preventing similar events.

A first step for the design of robust structure resistant to different loads is the knowledge of the failure mechanism of existing constructions. The aim of the paper is to collect and to synthesize information on damages/ failures/ collapses of structures from different countries.

Key words: robustness of structures, structural failures, failure causes.

1. Introduction

Experience and judgment, which play an important role in structural design, receive less attention in technical literature than the description of new and efficient structural designs. Technical literature concerning the failures of the past is rare; engineers do not wish to discuss their mistakes. Full discussion of failures can be useful, as presentations of great achievements.

Structural failures, although not desirable, do not always mean collapse [6].

Excessive distortion, due to lack of adequate stiffness, can prevent the structures from proper functioning [5].

Generally, the collapse or the rupture of the structure may occur when

a) some of the principal structural members or connections fail;
b) as a result of fatigue after a large number of alternating stresses;
c) buckling of the main members;
d) severe blast or impact.

Structural failures can be caused by unsatisfactory material, fabrication or erection errors as well as faulty design.

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Frequent causes of structural failures are

e) foundation movements;
f) connection failures;
g) incorrect assessment of the buckling strength;
h) lack of adequate bracing;
i) overloading;
j) fatigue.

The analysis and design of an isolated compression member with known conditions of loading and support is a relatively simple problem; when the element is considered as a whole, it is difficult to assess the effectiveness of the stiffeners and bracings, the rigidity of the end supports and the load eccentricity [5].

Overloading may occur as a result of changes in the use of the structures. For example, during the latest decades, the traffic on bridges has become heavier and more severe [3]. In addition, buildings converted from one destination to another are often overloaded. In all these cases, investigations of the existing structural safety of the framing system are required [9]. The experience from failure of different constructions provides a valuable knowledge base and gives an overview of the reliability of civil engineering structures [1].

2. Review of Some Typical Failures and their Causes

To establish a classification of failures it is difficult, but nevertheless, some principal causes and typical examples can be pointed out. Among those the following can be mentioned:

2.1. Overloading

Is a consequence of incorrect appraisal of the initial loadings. In a general classification, 28% of the failure cases can be ranged in this category. Two classical examples can be presented. Firstly the Tay Bridge in England (Fig. 1 and 2) was designed for a wind pressure of 1.5 kN/m² (corresponding to a wind velocity of 34 m/s) and started its functioning in 1878. During a strong storm, one of the piers and consequently the whole bridge collapsed. It was a typical under-evaluation of the wind loads [2].

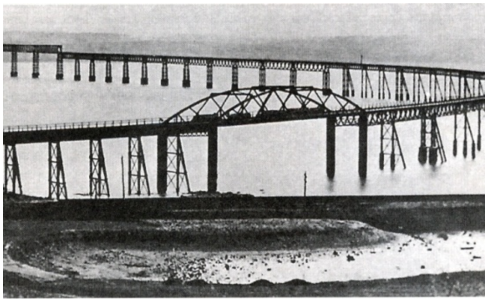

Fig. 1. – The first Tay Bridge before failure.

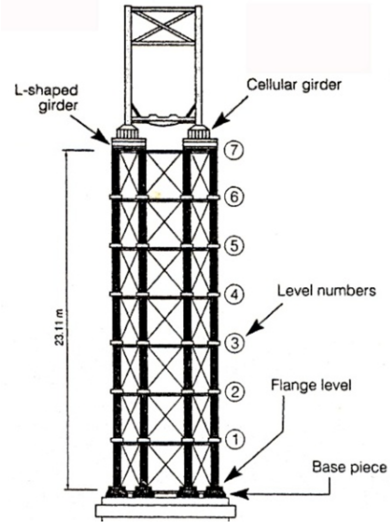

Fig. 2. – Typical bridge pier of the navigation channel.

It is worth mentioning that some years later, when the Romanian Danube bridges in Feteşti – Cernavodă were built, Anghel Saligny, the chief designer of the structure selected a value of 2.0 kN/m² for the wind loading. Before completing his design, he made a short documentary trip to Scotland, where the famous "Firth of Forth" bridge was under construction. The information acquired during his discussions with the bridge designers John Fowler and Benjamin Baker, influenced undoubtedly the final solution of the Cernavodă Bridge. This value proved to be correct since the bridge is still in operation.

2.2. Design Errors

In a similar classification, 18% of the cases can be ranged in this category. Various design codes have been in use for more than 100 years, but design errors are still frequent. One of the most famous examples is the bridge over the St. Lawrence River in Québec (Fig. 3). In 1902 the erection of the bridge started. The structure collapsed two times. One of the reasons was the lack of lattices in the lower compressed chord.

2.3. Insufficient Knowledge of the Material Properties

Approximately 18 % of the failure cases belong to this category, but probably these are the most frequent known cases.

Fatigue failure is an old enemy; cracking due to fatigue is responsible for some major catastrophes. A typical example is presented in Fig. 4.

Calculation was performed with the Palmgreen Miner rule, taking into account the total damage. An inspection of the structure was established on the basis of the real stress-history. In this way a major crack was detected (Fig. 5) and a catastrophe was avoided.

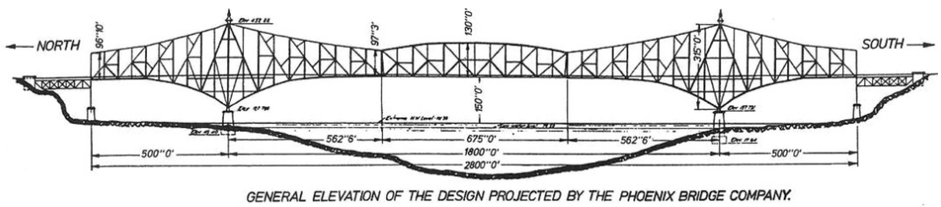

Fig. 3. – The bridge across the St. Lawrence River near Québec.

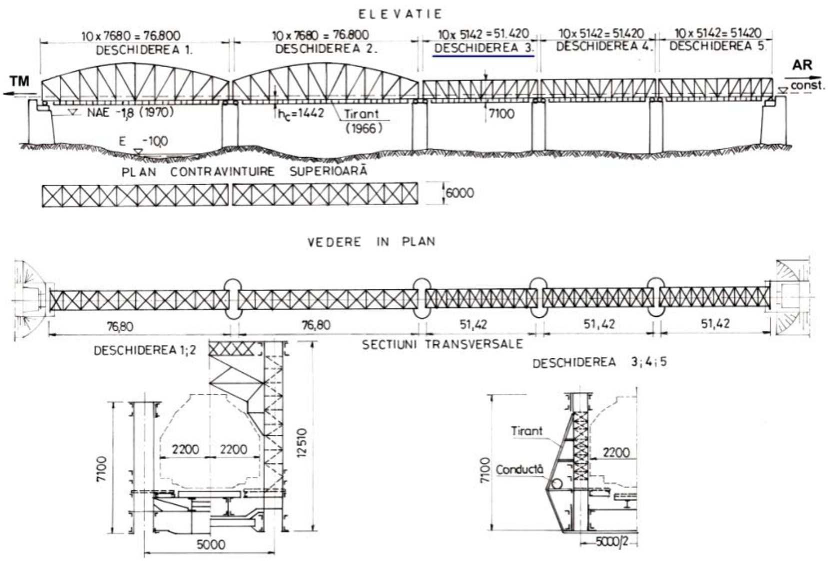

Fig. 4. – Railway bridge in Arad.

The use of fusion welded structures introduced new uncertainties concerning fatigue behavior. One factor that affects the fatigue performance of welded joints is the presence of residual tensile stresses.

One of the most known examples is the failure of the Hasselt Bridge in Belgium (1938) due to the embrittlement of the Thomas type steel (Fig. 6) [2].

Fracture toughness is a major factor in determining the reliability of engineering structures [9].

Another source for failure is lamellar tearing. In many cases the contraction due to welding has opened up lamination in the steel in a region close to the fusion boundary. The primary cause of this type of failure is the presence of laminar sulphide inclusions.

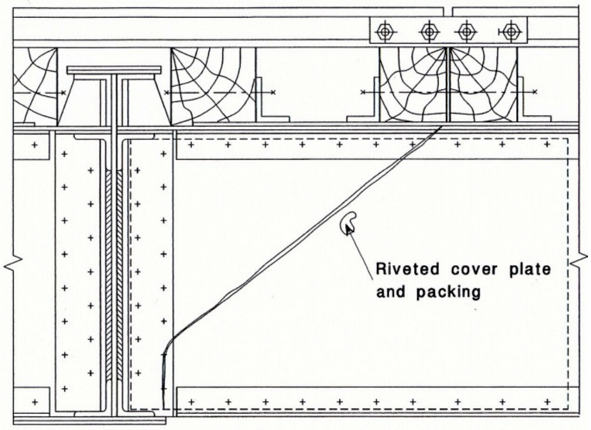

Fig. 5. – Crack detected in the stringer.

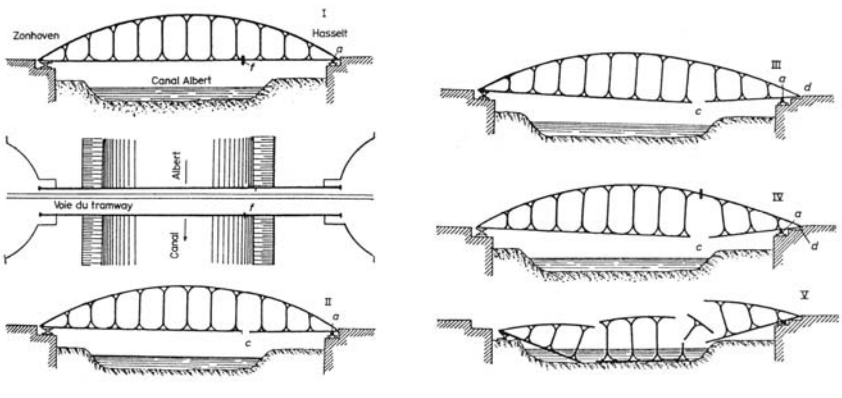

Fig. 6. – The failure of the Hasselt Bridge.

Some cracks were detected in the railway stringers of the Danube bridges (Fig. 7). It was concluded that the principal cause of cracking come from the direct placement of the track on the steel deck; out of plane and torsion stresses (eccentricity of the rail) have also occurred. At the time of design the fatigue requirements were not developed at the present level of knowledge and those cracks could not have been prevented using the design details. The repair was difficult and very costly. However it must be emphasized that not all fatigue failures start from the welds.

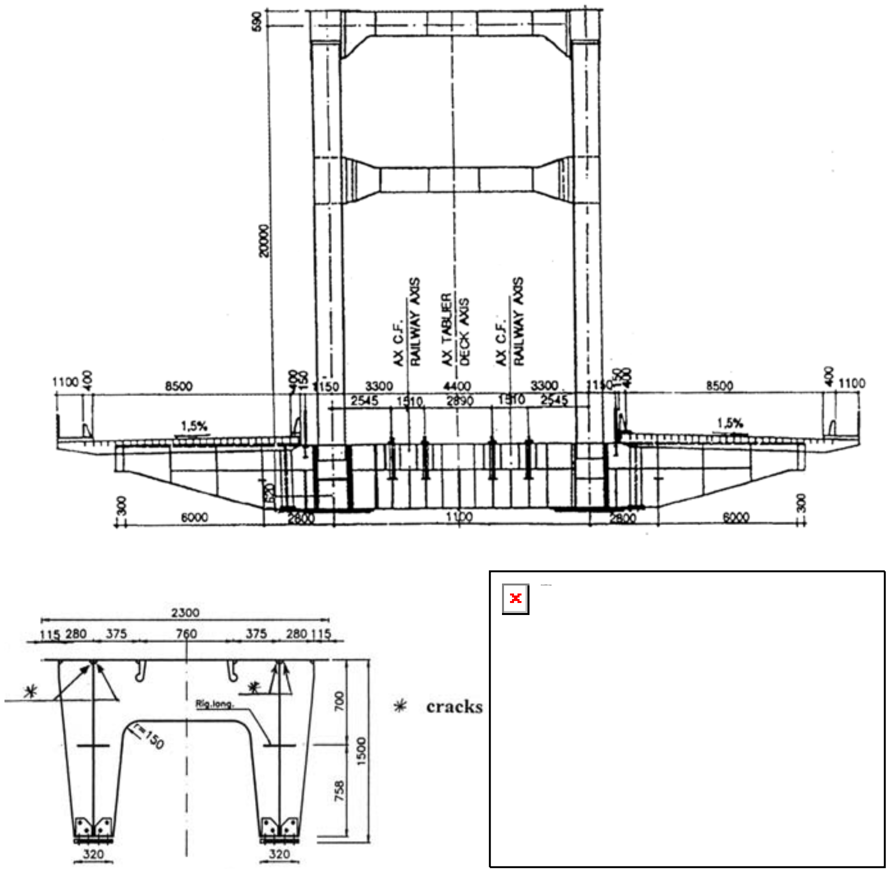

Fig. 7. – Defects in the stringers of the Danube bridges and repair.

2.4. Errors in Conceiving and Detailing

Approximately 21% of the failure cases belong to this category.

A typical example is the collapse of the Civic Center Coliseum, Hartford, Connecticut (Fig. 8). The double layer spatial truss failed during a snowstorm. The real snow loads were quite close to the computed values, but the slenderness coefficients of the compressed diagonals exceeded the acceptable values. It must also be mentioned that these structures are considered to be robust because of their redundancy [2].

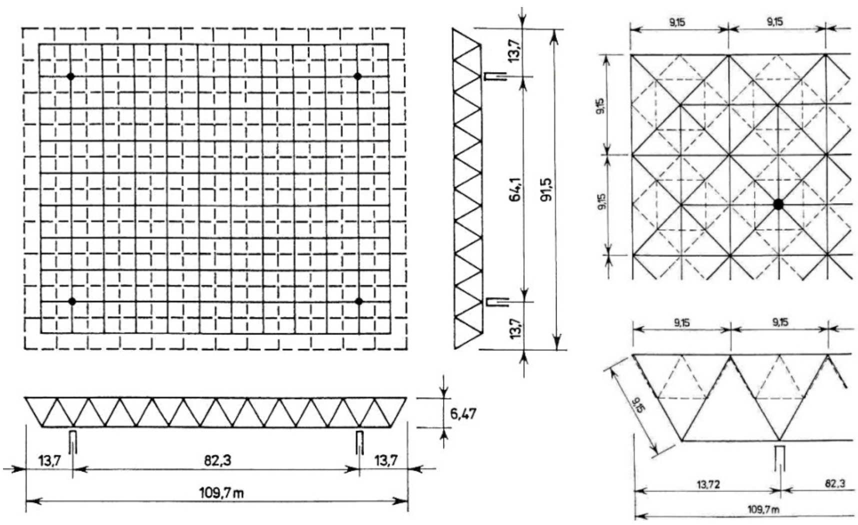

Fig. 8. – Point-supported space frame and the structure of space frame with auxiliary diagonals.

2.5. Failures During the Erection of the Structure

A typical example is the Valangin Viaduct in Switzerland (Fig. 9), which failed during the launching of the bridge deck [3].

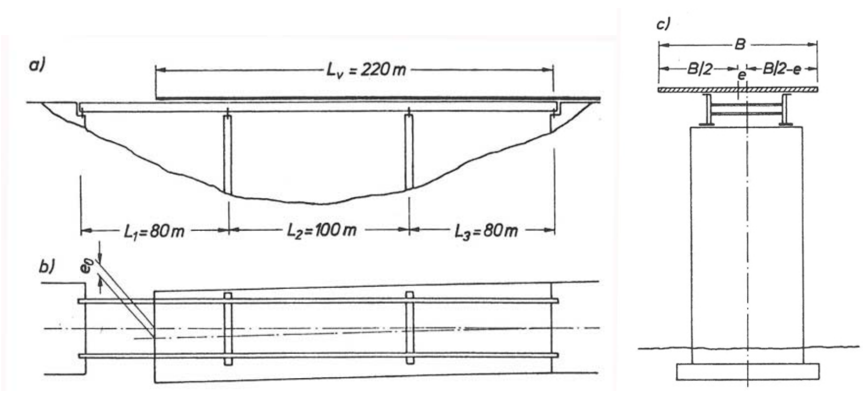

Fig. 9. – Bridge deck deviated during stage–jacking: *a* – longitudinal section, *b* – plan view, *c* – transversal cross section.

2.6. Failures due to a Lack of Maintenance

A large number of structural failures can be included in this category and an interesting case is presented in Fig. 10.

The roof of a single storey industrial building from Satu-Mare (Romania) was covered with snow. The weather changed suddenly due to an unexpected warming, and it began to rain. Realizing the danger of overloading, two workers were sent to remove the snow. When they finished removing the snow from one-half of the surface, the roof structure collapsed. The explanation is simple and it results from the unbalanced load presented in Fig. 10.

When the accidents leading to structural failures are considered, the main emphases are the mechanical problems, but also human factors can affect the safety of structures. The technical progress in the latest decades has lead to an improved maintenance and the influence of human errors is constantly decreasing.

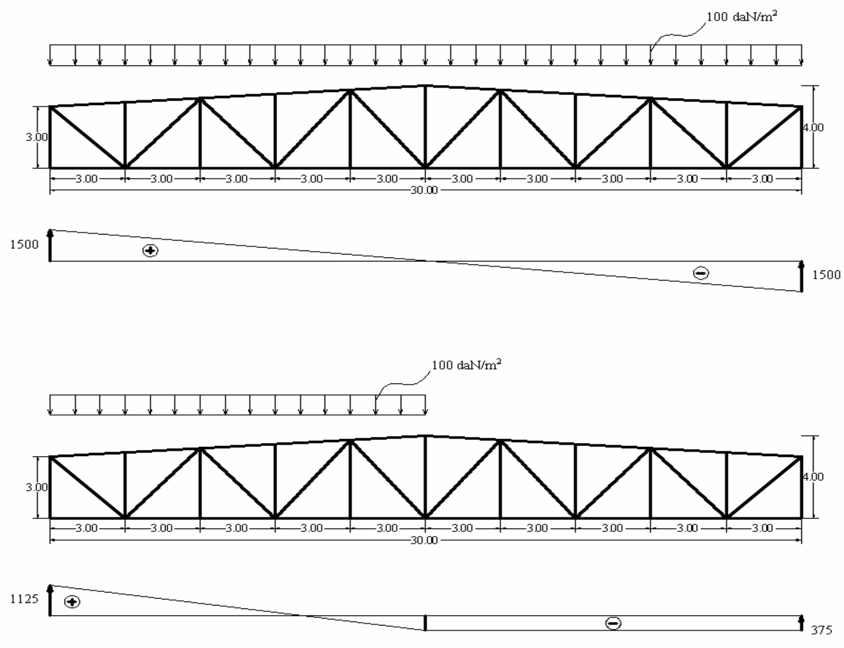

Fig. 10. – The roof of a single storey industrial building in Satu-Mare (România).

2.7. Terrorist Attacks

In the most recent times the terrorist attacks seem to be a major concern. This aspect cannot be controlled and must be separately analyzed. The collapse of the World Trade Center structures following the terrorist attacks of

September 11, 2001, was one of the worst-ever building disasters in the recorded history.

The framing systems for buildings are not specifically designed to withstand the impact of fuel-laden commercial airliners and the current codes do not require building designs to consider aircraft impact.

Buildings are not designed for fire protection and evacuation under the magnitude and scale of conditions similar to those caused by the terrorist attacks of September 11, 2001.

3. Classification of Failures

A general classification is difficult but some important studies have been performed in this area. For a better analysis of failure causes, structures can be ranged in different categories, like

k) building and bridge structures;
l) dams;
m) offshore structures;
n) pipelines;
o) nuclear power plants;
p) chemical facilities [1].

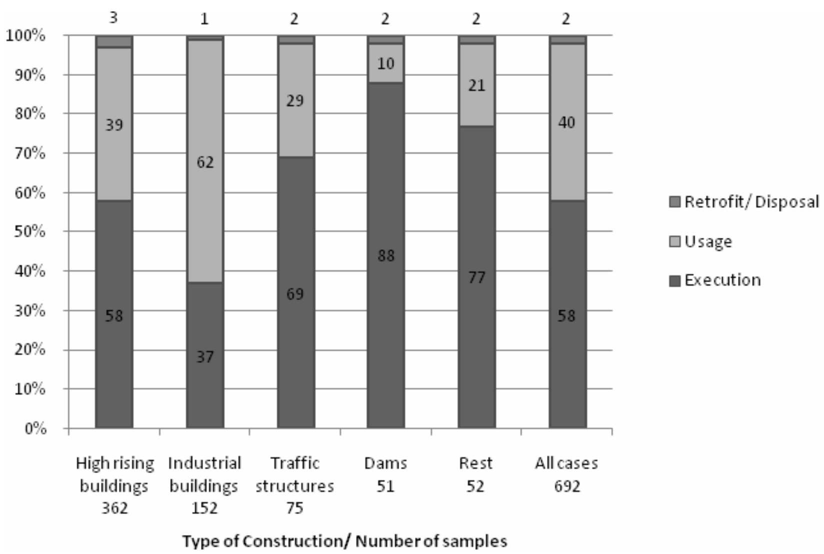

Fig. 11. – Illustration of the moment when in the course of the projects the failures and errors have been discovered [10].

In the following, the results obtained by Matousek and Schneider [10], Stewart and Melcher [8] are presented. Valorizing 800 cases, the authors have reported a detailed review of causes and errors and the possibilities to eliminate them [7].

In Fig. 11 the identification moment of different errors is illustrated.

It can be seen that on average the failures and errors were discovered more or less equally during execution and usage of structures. In Fig. 12 the primary causes of structural failures are presented.

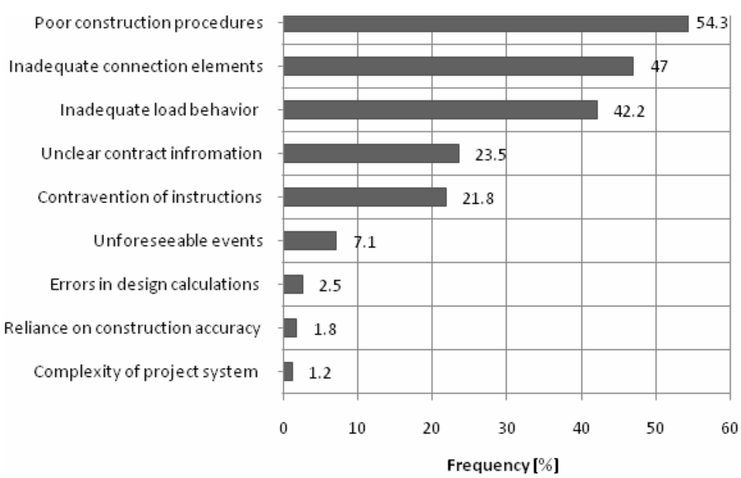

Fig. 12. – Illustration of primary causes of structural failures [8].

The major causes depend mostly on the first three factors: poor construction procedures, inadequate connecting elements, inadequate load behavior. In Fig. 13 the relative distribution of reasons for failures and errors is illustrated [7].

The neglected risks and risks treated with inadequate and insufficient measures are the major causes for failures. If we analyze when in the life-phases of buildings and bridge structures risks where not adequately treated, it can be noticed that a large majority are in the planning and execution phases (Fig. 14), leading in many cases to loss of lives and injuries [4].

This conclusion is confirmed by the results of Stewart and Melcher who processed a large number of different studies (Fig. 15) [8].

However, a difference between buildings and bridges must be observed, since the damages in bridges are relatively more frequent that in other structures.

If failures and damages are related to the time (design=1/100, fabrication and erection 1/50) of the structures design life, a high density in the design phase can be remarked in Fig. 16 [5].

The best solution for risks mitigation is the careful analysis of the design phase, where errors can be influenced (Fig. 17).

Short construction terms and some spectacular architectural solutions are the main sources for different errors, especially during the erection time [6].

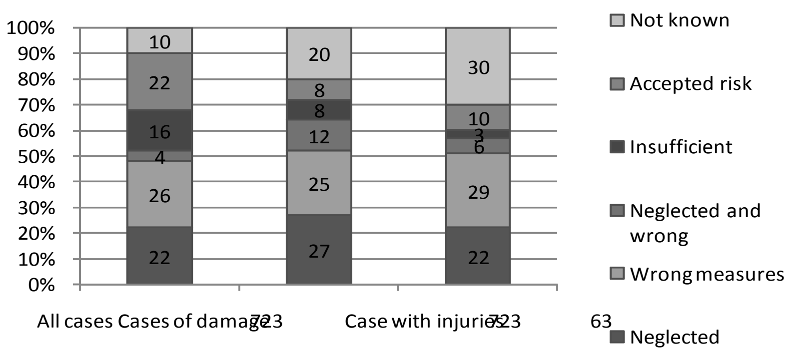

Fig. 13. – Illustration of the relative distribution of causes of failures and errors [10].

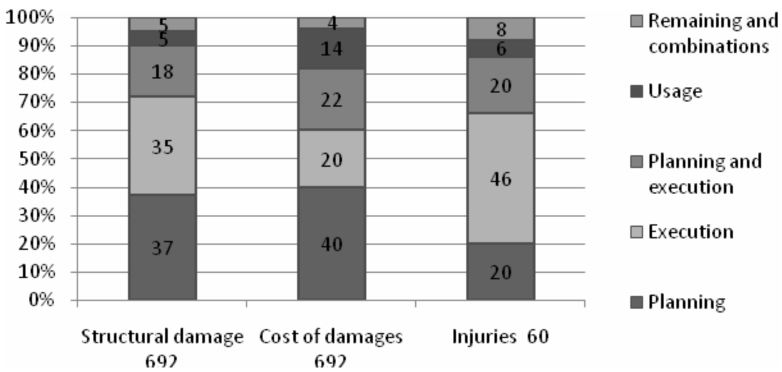

Fig. 14 – Relative distribution of the moment when in the phases of the projects failures and errors originate in inadequate treatment of risks [10].

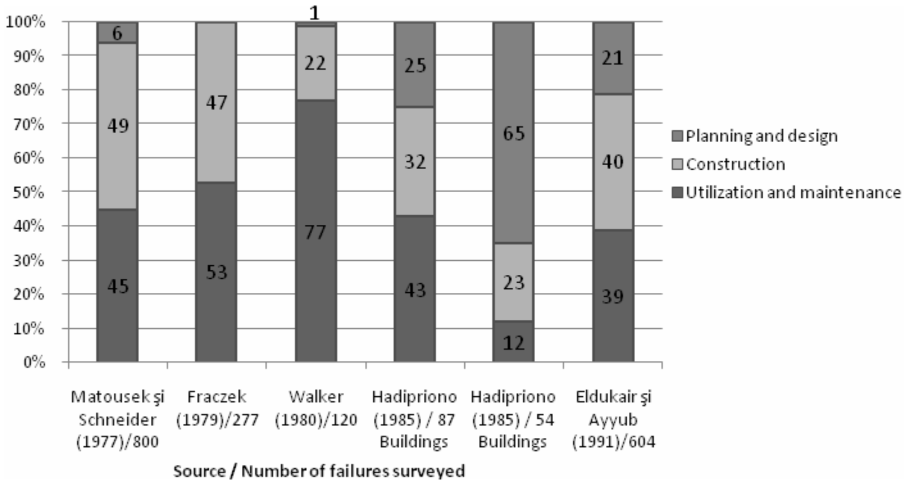

Fig. 15. – Relative distribution of failures and errors in the life-phases of building and bridge structures [8].

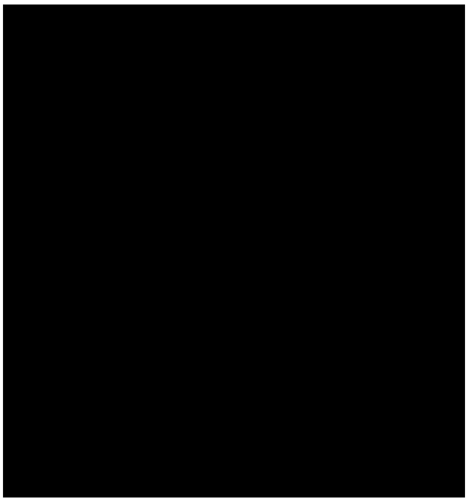

Fig. 16. – Failures and damages in buildings and bridges.

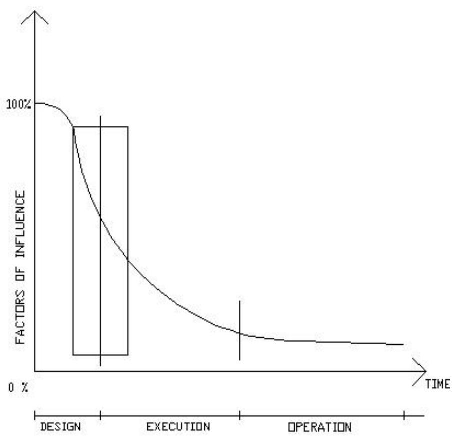

Fig. 17. – Analysis of the design phase.

4. Conclusions

Finding the methods to deal with unknown hazards/ disturbances in order to quantify robustness of a system, as an intrinsic property, is a major issue for the structural designers.

With respect to unexpected disturbances it seems more appropriate to work with robustness concepts related to the structural system as such and not in a wider sense.

An essential condition is to find out the main potential types of failures and their causes.

One way to proceed in a design situation should be to predict the response and consequences by systematic investigations of possible failure scenarios associated with assumed weaknesses in different elements of the system.

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ÎNȚELEGEREA CEDĂRILOR STRUCTURALE, O CALE UTILĂ DE EVALUARE A ROBUSTEȚII STRUCTURALE

(Rezumat)

Cunoaşterea şi înțelegerea tipurilor şi mecanismelor de cedare ale construcțiilor existente reprezintă o componentă esențială a proiectării unei structuri robuste, cu rezistență şi rigiditate adecvate la diverse solicitări.

Obiectivul esențial al acestei lucrări îl reprezintă colectarea, sistematizarea şi sintetizarea informațiilor privitoare la deteriorările/ cedările/ colapsul unor structuri cu destinații diferite produse în diverse țări. Se prezintă mai multe tipuri de cedări, clasificate pe baza cauzelor care le-au generat şi genuri de structuri. Învățămintele formulate din acest studiu vor fi valorificate la proiectarea unor structuri robuste cu un grad superior de asigurare.