ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

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FORENSIC ENGINEERING

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ABSTRACT

Forensic Engineering is a subject that is introduced relatively recently in universities as a separate course. The present paper introduces the subject with respect to structural failures and investigates one such failure of a steel roof covering the archaeological site of Santorin/Greece. With this motive, remarks of general consideration are made.

1. Introduction and Definitions

Damages and local or global structural failures, up to collapse, may occur in Civil Engineering projects. Main reasons range from overloading, fire, strong earthquakes, explosions or due to inappropriate design, erection or service. They refer to roofs, buildings, bridges, as illustrated in Fig. 1, but also to tanks, silos, towers, masts, chimneys, racks or other type of construction. The investigation and study of failures is the objective of Forensic Engineering.

According to the definition of the American Society of Civil Engineers (ASCE):

"Forensic engineering is the application of engineering principles to the investigation of failures or other performance problems. Forensic engineering also involves testimony on the findings of these investigations before a court of law".

Forensic Engineering may be studied in universities, especially in UK or USA, in specifically dedicated MSc Programmes. Graduates may find jobs in companies offering services in this specific sector that exist in many countries. Services may go beyond structural failure and refer to Product failure, Materials Engineering, Construction Claims, Fire & Explosion, Geotechnical, Road/rail safety, Photovoltaic Arrays or other Civil Engineering

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failure. However, the subject extends also to other Engineering disciplines, such as Electrical, Mechanical, Mining, etc.

Forensic Engineering is not only associated to practice, but also to research and is supported by specific scientific Journals, such as the International Journal of Forensic Engineering or the *Proceedings of the Institution of Civil Engineers – Forensic Engineering.*

In the following, one case of partial structural collapse is presented and conclusions are drawn.

a)

b)

c)

Figure 1. Examples of structural failure due to a) overloading, b) explosion, c) fire

2. Collapse of the Roof of the Archaeological Site in Santorini, Greece

2.1. Description of the Case

In 1970 an ancient settlement dating back in the Minoan time, 1500 BC, was discovered on the Island of Santorin, Greece. The settlement is situated in the southern part of the Island and remained nearly intact due to the fact that it was covered with lava during the huge volcano explosion. The excavation is a proof of the high artistic and technological level of that period in the Cycladic Islands. Fig. 2 shows wall paintings in the buildings that were up to three (3) floors and remained in perfect condition.

Figure 2. Wall paintings and photos inside the excavations

Since the excavation was fairly below ground, it was decided to cover it for protection with a steel roof and to plant the roof in order not to disturb the landscape.

The steel structure of the roof covered a total area of approximately 12 000 m^2 and consisted of a space frame (Fig. 3) composed of tubular bars that were connected to nodes by means of bolts.

The structure was divided into 13 panels with various spans. On 23 September 2005 at 13:50 the panel No. 7 with span 16,5 m collapsed (Fig. 1a). This was during watering operations of this panel, while panels No. 1 to 6 have been watered during the previous days. The sequence of events was as follows:

a) Early in the morning: Start of watering panel No. 7;

b) 8:30: Failure of a tension bar of a bottom chord and replacement by another bar;

c) 11:00: Leakage of water in panel 7. Provisional stop of watering and replacements of thermal insulation;

d) Failure and replacement of other bars;

e) Consecutive bangs from failure of bars leading to progressive collapse.

Subsequently, a commission was set up by the Ministry of Culture, the owner of the structure, in order to investigate the reasons for the collapse. The author was one of the Commission members.

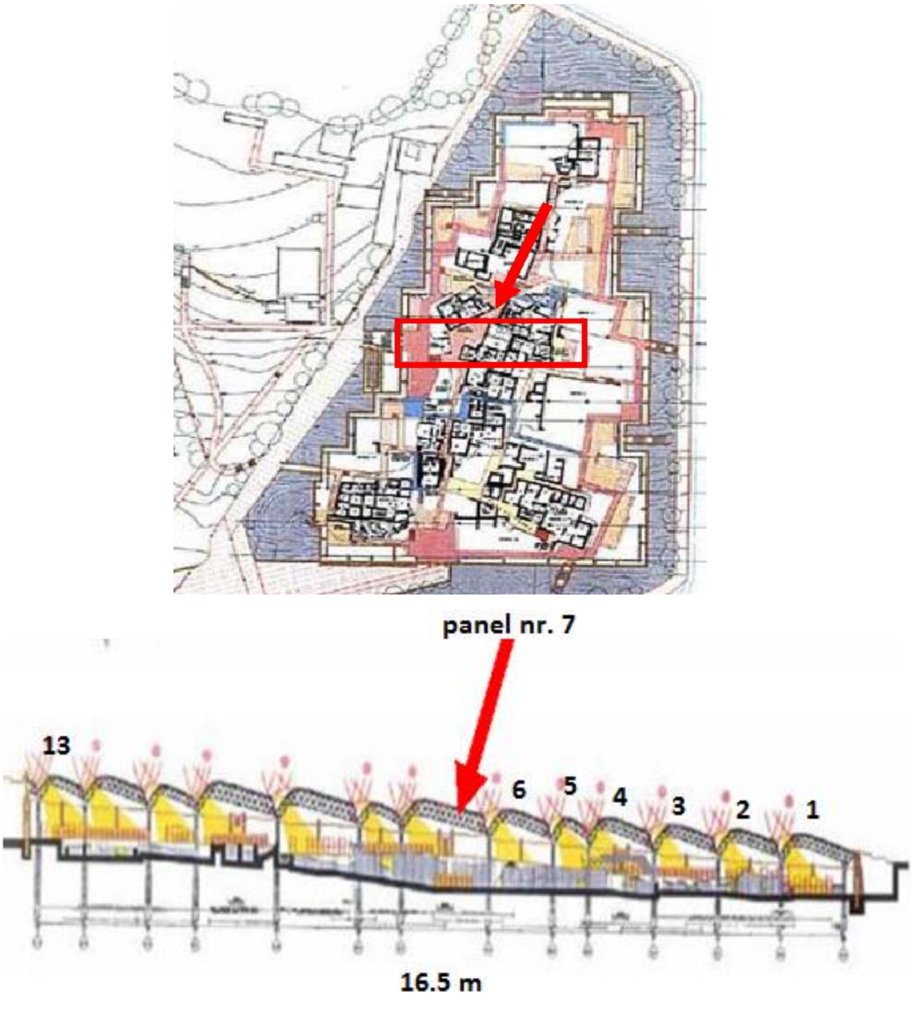


Figure 3. Plan view and section of the roof

2.2. Investigation of the Loads and the Structure

In order to investigate the case, the actual loads on the roof were determined. They were composed of the, known, self-weights of the structure and the covering panels, as well as of the self-weight of the soil that was determined by measuring its depth (Fig. 4) and its density in fully saturated conditions.

Figure 4. Measuring the depth of the soil

The measurements showed that the actual weight of the soil was much higher than its nominal design values, assumed in the structural design (Fig. 5). This was due to the fact that both its depth and its specific weight were much higher than those anticipated in the design phase.

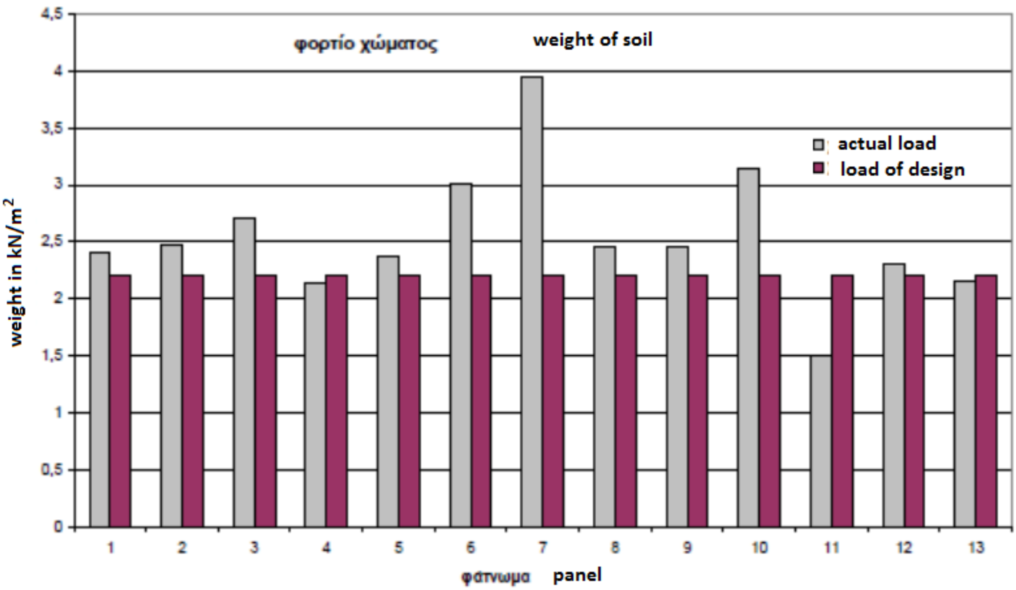


Figure 5. Comparison of actual vs. assumed in design soil weight

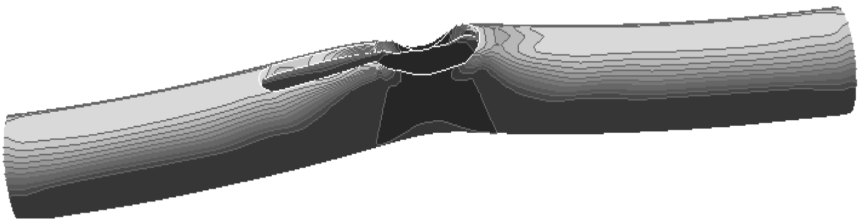
In addition, specimens were taken from bars, bolts and nodes to determine the actual material properties and to investigate the behaviour of the bars under compression and tension (Fig. 6). It was found out that the material was in accordance with the specifications assumed in the structural design.

Figure 6. Buckled bars of the structure

3. Numerical Simulation

3.1. Numerical Models for Structural Members

a)



b)

Figure 7. Bars in the actual structure (a) and their models (b)

The behaviour of bars in compression and tension has been studied numerically. The tubular bars were accurately modelled by FEM by means of shell elements in the ABAQUS software (Fig. 7). Subsequently, a geometrically and materially nonlinear analysis including imperfections (GMNIA) was performed. Numerical results compared well with the results of the experimental tests carried out in the Laboratory for both tension and compression bars (Fig. 8). Similar results were derived for compression bars.

a)

b)

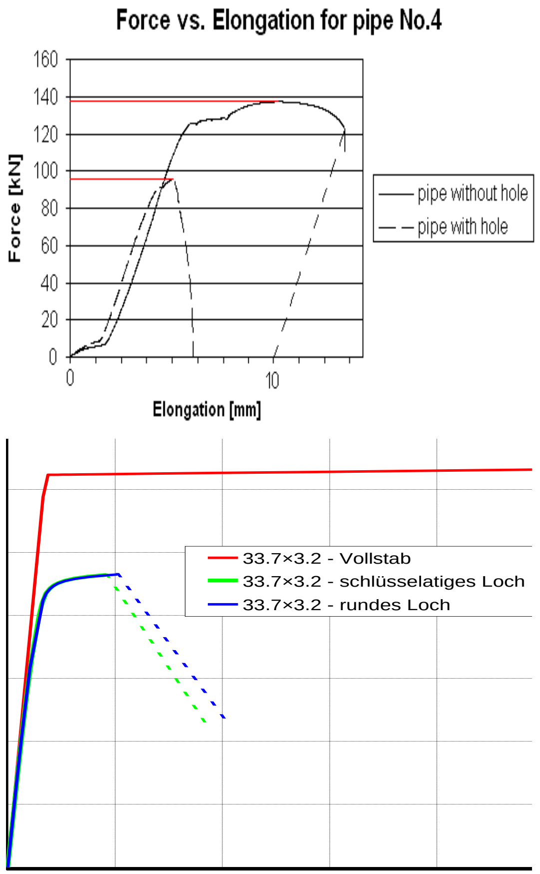


Figure 8. Experimental (a) vs. numerical results (b) for tension bars

3.2. Global Analysis and Global Model

Global analysis was performed for the complete structure. The global model included the bars and the nodes of the complete structure as well as the columns on which the roof was supported. The bars of the space frame were modelled as compression/tension elements, while the columns as beam-column elements. The global model included 53 908 truss bars, 13 613 nodes and 95 columns and is presented in Fig. 9.

Global analysis was performed using the SOFISTIK program and was linear elastic due to the large size of the model. By comparison of the actual forces with the corresponding resistances, the safety factors for the individual bars could be determined. It was found that the safety factor was for a tension bar below 1,0, indicating failure of this bar. By repetition of the analysis with this bar missing, safety factors below 1,0 were determined for other bars, indicating progressive collapse. This was promoted also by the fact that the bars had no ductility due to the provision of large holes opened in order to pass the connection bolts through them (Fig. 7). More information is provided in [1].

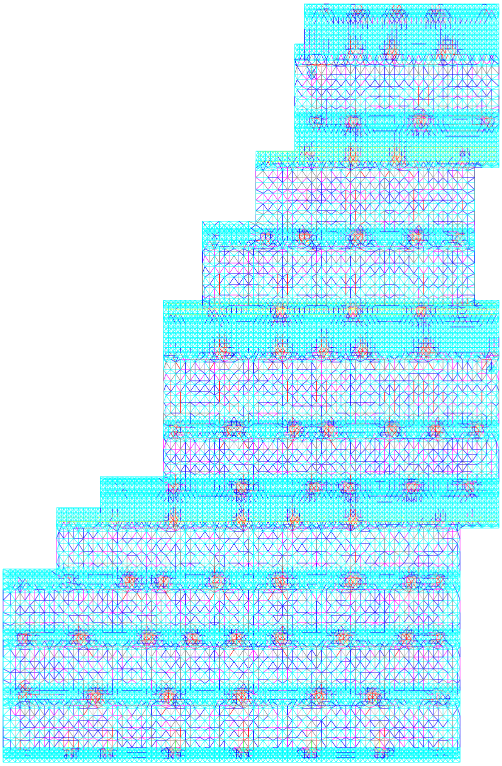


Figure 9. Plan view of the global model

Finally, the reasons of failure are summarized as following:
1. Severe overloading due to higher depth and higher density of soil;
2. Development of substantial restraint forces due to structural imperfections;
3. Reduction of resistance due to slotted holes;
4. Reduction of ductility due to large holes and small material overstrength.

4. List of Actions and Lessons

The list of actions when performing forensic research on structural failures may be recommended as follows:

- **On-site documentation**: Visit the site, take photos and observe closely the debris;
- **Historical data**: History of the structure during the construction and operation period;

- **Event**: Information, preferably by eyewitnesses, on the conditions at the time of the event and possibly the failure progress;
- **Survey of existing design and construction documents**;
- **Performance of experimental tests for materials and components;**
- **Loads**: Environmental conditions, live loads and other actions at the time of the event;
- **New design**: Independent structural design with the loads at the time of the event. Focus on the area and elements of collapse;
- **Technical report**: Includes all documentation, tests and calculations and concludes with the causes of failure not forgetting that they are in most cases more than one.

The examination of a number of cases by the author leads to following lessons in order to avoid structural failure:

1. Structures must be properly designed, executed, operated and maintained;
2. Structural designs must be appropriately checked and certified;
3. Fabrication and erection must be appropriately checked and certified according to the quality control plan.

5. Ethics

When performing Forensic Engineering services some ethical considerations should be followed that might be summarized as follows:

- Perform services only in areas of competence. Call other specialists if necessary;
- Never compromise your personal integrity;
- Treat information given by your client confidentially;
- Be objective in your reports or oral statements and make a distinction between facts and opinions.

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