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Learning from failures in an emblematic building in Valencia, Spain

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ABSTRACT

On many occasions advances have been made in science and engineering thanks to the knowledge gained from failures. In the particular case of structural engineering, the study of actual failures makes it possible to advance and define new theories, concepts and designs. Some examples are the changes and improvements that appeared after some of the "classical" failures such as the Ronan Point building, Quebec Bridge, Murrah Federal Building, Tacoma Narrows Bridge and the World Trade Center. This paper describes a teaching method used with structural engineering students at the *Universitat Politècnica de València* based on the study of cases of damage to buildings in Valencia, Spain. Due to its special characteristics, one of the buildings studied is the Príncipe Felipe Science Museum. Some of its main characteristics are: 1) it is one of Valencia's emblematic buildings, 2) its considerable dimensions required huge quantities of concrete, 3) it has a complex structure and an innovative architectural design, 4) the wide variation in the type of damage detected, which make it a particularly valuable teaching aid. The most important damage detected has been classified and described during the visits to the Príncipe Felipe Science Museum. The damage mechanisms are widely diverse and include: those due to the behaviour of the concrete itself (e.g. shrinkage and early age thermal cracking), those due to the presence of damp, those whose origin can be traced back to the construction phase, and others due to corroded reinforcement and to the loads acting on the structure. The paper has a double value since on one hand it describes a highly successful teaching aid for the training of experts in structural engineering, while on the other it classifies and describes the existing damage in one of the most important modern buildings in Spain and perhaps in Europe.

1. Introduction

Since the beginning of time, the human race has been learning from its failures in all facets of life. In the field of engineering on many occasions advances have been achieved thanks to the study of actual failures, which have made it possible to produce new theories, concepts and designs. The investigation and study of actual failures is also important for the improvement of the design and construction of structures. Due to the increased interest in the study of structural failures, there has been a significant growth of the number of conferences, journals and publications dedicated to analysing actual failures in the structural field in the last few years. The study of real failures has also been used for teaching purposes in the structural engineering field, for example in the form of the excellent studies published by Professors N. Delatte [1–4] and H. Petroski [5, 6].

Within the study-analysis of what could be called "classical" cases of failure-collapse, one could point to for example those by: a) Pearson and Delatte [7] on Ronan Point; b) Pearson and Delatte [8] on the Quebec Bridge; c) King and Delatte [9] on the 2000

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Commonwealth Avenue building; d) Corley et al. [10], Kazemi-Moghaddam and Sasani [11], Mlakar Sr. et al. [12], Osteraas et al. [13], and Sozen et al. [14] on the Murrah Federal Building; e) Walshe and Wyatt [15], Wyatt [16], Matsumoto et al. [17], and Plaut [18] on the Tacoma Narrows Bridge; and f) Corley [19], Omika et al. [20], Wang et al. [21], Irfanoglu and Hoffman [22], and Miamis et al. [23] on the World Trade Center. All these "classical" failures made the headlines in their day and the subsequent study of the events that led up to them helped to improve subsequent designs.

The studies published on failed structures are very wide-ranging, including for example: masonry walls [24, 25], the aftermath of earthquakes in buildings [26, 27], problems in bell towers due to the effect of ringing bells [28], the effect of marine environment on buildings [29], damage to industrial masonry chimneys [30], water tank failures [31], the collapse of long-span roof structures [32], failures in old buildings [33], failures of building structures during construction [34], and damage to masonry domes [35].

At the present time, two of the leading journals that specialise in publishing papers on case studies of structural failures are *Engineering Failure Analysis* (published by Elsevier) and the *Journal of Performance of Constructed Facilities* (published by the ASCE). Some of the most important of the recent papers published in *Engineering Failure Analysis* include: Bayuaji et al. [36], Mosoarca et al. [37], Otunninyi et al. [38], Vatansever et al. [39], and Krentoswki et al. [40]. While some of those published in the *Journal of Performance of Constructed Facilities* include those by: Stark et al. [41], Shrestha and Hao [42], Bilcik et al. [43], Wang et al. [44], and Yamin et al. [45].

This paper deals with part of the work done by authors using the "Learning from Failures" philosophy both in their research and in their teaching duties at the *Universitat Politècnica de València* (UPV). The authors created a series of teaching routes for their students in which they could learn from failures and damage to buildings in the city of Valencia (Spain). This paper describes the work carried out during visits to one of Valencia's most emblematic buildings: the Príncipe Felipe Science Museum designed by architect Santiago Calatrava. The paper's principal novelty and contribution is due to its combining a description of one of the authors' teaching methods based on "Learning from Failures" with an analysis of the defects found in one of the city's, if not the world's, best known modern buildings.

After this Introduction, Section 2 describes the teaching method based on the study of actual failures used by the authors in some of their courses. Section 3 describes the special characteristics of the Príncipe Felipe Science Museum, while Section 4 analyses the main damages found to be present and the paper ends with the main conclusions drawn from the work in Section 5.

2. Learning from structural failures at the Universitat Politècnica de València

At the present time, the UPV's Civil Engineering School includes in its syllabus two courses that deal with the analysis of structural failures: Pathology and Rehabilitation, and Maintenance and Conservation of Structures. The Department of Construction Engineering offers Pathology and Rehabilitation to students of the Master's Degree in Concrete Engineering. These three subjects are designed to achieve the following objectives:

- Train students in the field of structural failures, diagnosis and remedial actions.
- Use the study of failures to consolidate the knowledge acquired in structural engineering.
- Teach techniques of management, maintenance and conservation of existing structures.
- Instil students with ethical aspects of the profession.

Within the "Learning from Failures" teaching method, in the three preceding courses the students will already be familiar with the teaching routes in which visits are made to a series of buildings in the city of Valencia to inspect existing damage.

Field visits are organised immediately after the corresponding theoretical concepts of damage mechanisms have been dealt with in lectures. Besides consolidating these concepts, the visits are designed to familiarise students with the inspection protocols of damaged structures. Before the visit, the professor explains the route the students will follow and the location of the structures they will inspect. These groups are composed of 15–20 students, who are further sub-divided into smaller groups of three or four. Damage is inspected in situ, photos are taken to locate the damage on a plan of the building, and the students then draw up a brief report on the main types of damage observed, indicating probable causes and its further evolution. This report is marked by the lecturer and contributes to the final grade achieved in the subject. After handing in the reports, the students debate the experience in class assisted by slides of the damage observed and are encouraged to give their ideas on its origin and evolution. The lecturers' feedback is highly satisfactory since the debates are usually quite intense with the enthusiastic participation of the whole class. There is no doubt that these activities motivate the students and help them to construct their own self-learning programs.

The routes followed are quite near the university campus and in fact one is within the campus itself and involves buildings with which the students are already familiar. Another is through one of Valencia's most emblematic districts, the City of Arts and Sciences. Fig. 1 shows a map of Valencia with an outline of both routes.

Fig. 2 shows the first route in the UPV campus. The buildings visited are: *Department of Construction Engineering Laboratory*, *Students' Building*, and the *Sports Centre* car park. Fig. 3 shows the route followed in the City of Arts and Sciences. The buildings visited are some of the city's most emblematic and include: the *Palau de les Arts*, the *Hemisfèric*, the *Príncipe Felipe Science Museum*, and the *Àgora*.

3. General description of the Príncipe Felipe Science Museum

Based on the work carried out with the students on the teaching routes, this paper describes the principal damage observed in the