Reliability-Based Expertise for the Establishment of Public Liabilities

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Summary

Structural collapses imply questions of public liability and, very often, a trial is necessary for the resolution of the related problems. The persons in charge with the establishment of the responsibilities in a failure case will normally base their decision on the opinion of different experts. Therefore, these experts will have to address the safety issue either explicitly or implicitly, and will also have to communicate with their clients, e.g. owners of buildings, insurance companies or examining magistrates. A practical example, a hail load induced collapse, is presented. The application of probabilistic methods proves to be essential for the finding of satisfactory answers to the raised questions. The paper presents the corresponding analyses and discusses the reactions of the involved parties, which show that probabilistic methods can contribute to facilitate the communication between engineers and the general public, leading to a more rational treatment of safety problems.

Keywords: Hazard, hail load, accidental situation, collapse, assessment, reliability, acceptable risk, risk communication, liability.

1. Introduction

1.1 Context

Hail loads are beyond the scope of most loading codes. Therefore, in spite of the fact that every year a certain number of roofs collapse under hail loading, possible hazards due to hail remain very often unconsidered in structural design. This paper deals with the collapse of the 30 years old roof of a supermarket, situated near Seville (south of Spain), induced by hail loads (figure 1). Fortunately, the failure occurred a few minutes before the opening of the establishment so that there was no damage to life and limb. The owner was of the opinion that damages due to this kind of hazards from the natural environment were covered by the corresponding insurance policy. The insurance company, on the contrary, perceived that behind the collapse there might well exist different causes, and that the hail load could be nothing else but the apparent reason for the accident. The Institute of Construction Science, IETcc – CSIC, was asked to help with a detailed expertise, in order to clarify these doubts.

1.2 Description of the structure

The investigated duo-pitched roof covered an area of approximately 635m^2 and was supported by 7 truss girders at 3.65m centres, with a span length of 21.5m. The truss girders consisted of welded tubular elements with diameters between 26mm and 70mm, approximately, and with wall thickness ranging between 2 and 3mm. The girders were supported by battened steel columns, embedded in the walls of the building. The roof failed under the significant loads from a hailstorm of May 4th 1998.

a)  b) 

Fig. 1 a) General view of the collapsed roof; b) observed hail load on a neighbouring roof

1.3 Aim of study

Since the failure apparently was due to an accidental situation, this research not only should lead to an unequivocal conclusion about the failure mechanism and its causes. It is also to be established whether the possibility of a collapse implicitly was accepted because of representing a sufficiently small risk and, if not, why the failure did not occur earlier during the 30 years service period. The answering of all these questions implied that also the fundamental question *How safe is safe enough?* had to be tackled in some way.

2. Planning of the assessment

2.1 General remarks

When assessing the safety of an existing (non-collapsed) structure, the information is different from that available during design, because many characteristics may be measured from the structure under consideration which, at the time of its design, were just anticipated quantities. This fundamental difference between assessment and design must also be bared in mind when investigating a structural collapse. Therefore, the application of design codes does not represent an accurate way to evaluate a structure after a failure, and the assessment is most adequately be carried out by applying a staged procedure including reliability analyses [1]. Each stage of the approach involves increasing effort and leads to a more accurate assessment through the consideration of site specific data or more refined analysis methods. The key idea of this approach is that –after the establishment of the failure mode– the decision that the structure did not reach the required safety level only can be taken after all reasonable analyses have failed to demonstrate adequate performance. Indeed, in spite of its failure the structure might have reached the required safety level in a way that the collapse is to be considered as representing an unavoidable or acceptably small risk (e.g. due to a very rare hazard from the natural environment). In this sense, an over-conservative evaluation of a collapsed structure can imply important consequences from the point of view of the liabilities, e.g. for the owner of the structure.

Apart from the aforementioned circumstances, problems related to the communication of the outcome of the investigation to non-experts must duly be taken into account already at the stage of the planning of the assessment. Possibilities of successful risk communication will increase if the adopted procedure introduces order, completeness and clarity into the engineering work; if it is aimed at a balanced and unprejudiced assessment; and if it is based on objective guidelines for dealing with risks.

2.2 Staged procedure

In order to find satisfactory answers to the raised questions, the assessment is carried out in two phases. The aim of the first phase consists in the establishment of the causes of the failure and of the failure mechanism, whereas the second phase is destined to address the safety issue. Although interconnected, each of these phases is complete in itself. Furthermore, each phase is broken down in stages. Figure 2 shows the concept of the staged procedure and its relation to the collection of site data by inspection, material- and field-testing.

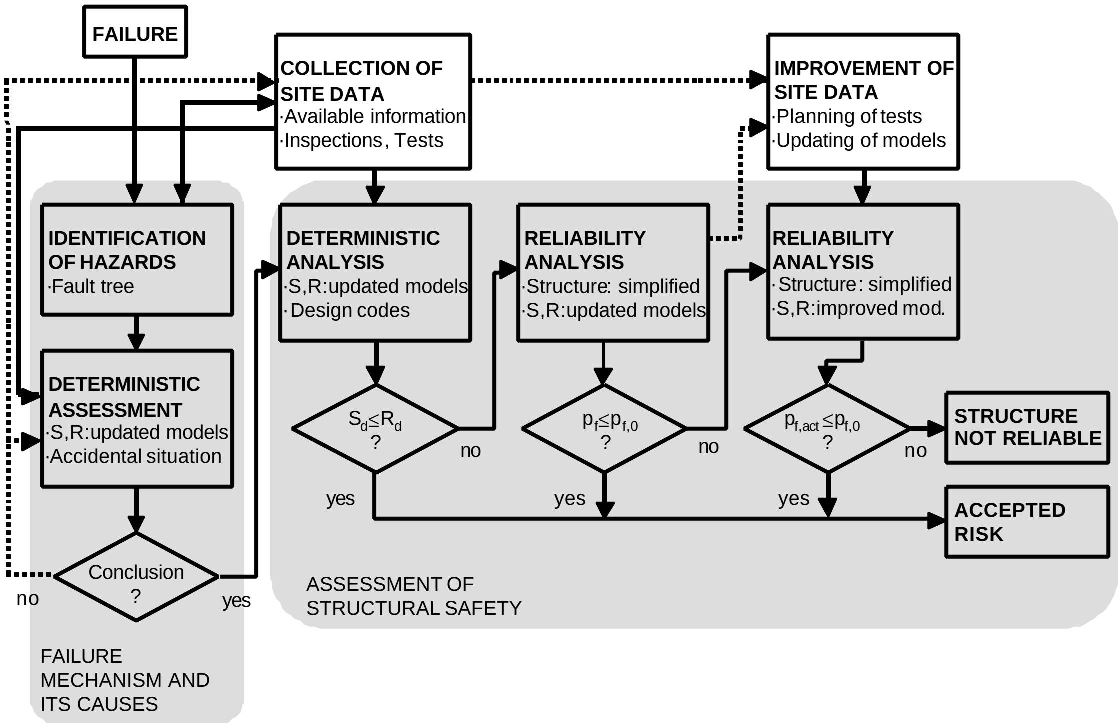


Fig. 2 Staged procedure for the assessment and its relation to the collection of site data

Phase I: Failure mechanism and its causes

In a first step, possible combinations of influences or hazards that can be in the origin of the failure event are represented in a logical diagram. The so-called *fault tree* constitutes an efficient tool for the identification of independent variables entering the problem at hand, and also aids the planning of site data collection. Taking into account the available information about the structure, it can be deduced for which of these variables the parameters are to be updated. Fault trees are a useful tool not only for the engineer. An important advantage in the present context is that they are very easy to understand. Therefore, they are extremely helpful for communication purposes with non-experts.

For the most likely of the possible failure scenarios, identified in the first step, an assessment by the partial factor method (also called *deterministic assessment*) is carried out using the verification criteria defined in a consistent set of current design codes [2, 3, 4]. No further evaluation is required in this first phase if an unequivocal identification of the failure mechanism is possible.

Phase II: Assessment of structural safety

In a first step, a deterministic assessment is carried out according to a consistent set of design codes, e.g. [2, 3, 4]. Not as like as in Phase I, where only the failure scenario is analysed, all significant design situations are to be considered according to the applied codes. The calculation models are based on, respectively, the available and the updated information about the structure, and the deterministic models from the codes. If structural safety is verified for all members and connections, particularly also for those in the origin of the failure (identified in Phase I), the collapse has to be considered as corresponding to an implicitly accepted risk. Otherwise, the evaluation has to be continued by carrying out a reliability analysis using updated or, where site data is not available, default probabilistic models of action effects and resistance (2^{nd} step). If structural safety is not verified for all elements, further evaluation is possible based on improved load and resistance models. It seems reasonable to conclude that the structure did not reach the required safety level, if adequate performance can not be demonstrated in this third step.

3. Site data

3.1 Available information and planning of data collection

Valuable information about the structure and the weather conditions during the period previous to the accident was obtained on the occasion of a first contact with the owner. Particularly, it can be mentioned that, originally, the building had been used as a cinema and only 12 years before the accident it has been transformed into a supermarket. From this conversation it was not clear, however, whether this change of use was linked or not to any changes of the structural system, or addition of dead loads. It is worth mentioning that no written information was available, neither about the original structure nor the aforementioned change of use.

Since the available data in the present case was very scarce, an extensive programme for data collection had to be put into practice at a very early stage of the assessment (figure 2). The information to be updated included the geometry of the structure, data concerning the employed steel and the welded connections, signs of damage the structure might have suffered before the accident for example due to corrosion, and finally, the data relative to permanent and variable (such as wind and hail) loads on the occasion of the accident.

3.2 Main findings

From the obtained information the following data can be emphasised:

– The nominal value of the hail load is estimated to $q_{hail} = 0.8$ kN/m^2, which can be compared to the snow load that must be taken into account in structural design. It is found that the hail load corresponds to 3.3 times the design value of the snow load according to the Eurocode [5].
– On the occasion of the change of use, dead loads –ceiling, installations– of the order of 28% of the estimated hail load were added. Apparently, on that occasion no safety evaluation for these new conditions or strengthening of the structure was carried out.
– Tests showed a very low strength of the Heat Affected Zones (HAZ) of the welded joints, compared to the strength of the base material (table 1).
– No signs of corrosion or other deterioration mechanisms or damages previous to the accident could be observed.

Table 1 Evaluation of test results: Characteristic value (for deterministic assessment) and parameters (for reliability analysis) of the yield strength of the employed steel and the HAZ

		Base Material	Heat Affected Zones
Characteristic value	f_{yk} [N/mm^2]	331.4	240.8
Mean value	μ_{fy} [N/mm^2]	368.1	249.9
Standard deviation	σ_{fy} [N/mm^2]	23.5	5.6
Distribution function		Lognormal	Lognormal

4. Failure mode

Performance of several structural members and welded connections was not sufficient in order to withstand the internal forces and moments corresponding to the assumed failure scenario with the hail load as accidental action, which was established according to the procedure described in section 2.2. The analysis showed that a poor conceptual design was in the origin of a significant stress concentration in the structural elements adjacent to the supports of the truss girders. Due to its low strength, the HAZ of the welded connection between the bottom chord and the end post of one truss girder failed first. The failure of one girder implied load redistribution towards the adjacent trusses, which failed immediately.

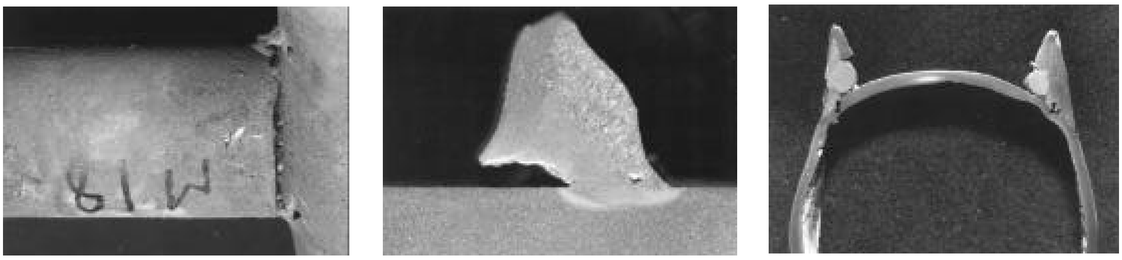
This failure mechanism was confirmed on site. In spite of the very poor quality of the welds (figure 3), it was observed that the fracture took place in the HAZ of all failed connections. Therefore, there was coincidence between tests showing the aforementioned, very low strength of the HAZ, visual inspections and calculations.

5. Structural safety

5.1 Introduction

Since the change of use, a new generation of design standards, the Eurocodes, came into force. This circumstance is to be taken into account when deciding whether the structure reached the required safety level, respectively after the change of use and at the time of the accident.

Once the failure mechanism is identified (sect. 4), it is clear that there is no significant system redundancy. Therefore, the failure of the most critical element, the welded connection between the bottom chord and the end post of the truss girders, leads to the failure of the system. Consequently, the failure probability for the system is governed by the failure probability of the most critical element. For this reason, structural safety is assessed for the aforementioned connection.



a) b) c)

Fig. 3 Examples of detected imperfections in the welded connections: a) incomplete weld; b) partial penetration and porosity; c) fill up of gaps with embedded electrodes (Pictures: Courtesy of CENIM – CSIC)

5.2 Deterministic assessment

According to section 5.1, the safety issue is to be addressed for two sets of design standards: respectively, the Spanish codes in force on the occasion of the change of use of the structure [6, 7], and the Eurocodes in force when the structure collapsed [2, 3, 4, 5]. In both cases, since the roof is accessible for maintenance only, *snow* is the leading variable action in the governing design situation. For both of the two sets of codes considered, the design value of the action effects, S_d, is greater than the design value of the corresponding resistance, R_d. Therefore, structural safety is not verified and there is a need to perform a more accurate evaluation (figure 2).

5.3 Probabilistic assessment

Based on the *axiom* that the correct application of a consistent set of codes produces a reliable structure within the framework of these codes, the assessment of the safety of an existing structure can be carried out following a procedure described in [8]. This procedure allows the calculation of the failure probability, p_f, related to the actual structure under consideration, as well as the failure probability representing the safety level of the considered codes, $p_{f,0}$, thus the target probability of failure. The structure may be considered safe if the condition $p_f < p_{f,0}$ is fulfilled. As in the deterministic assessment, the analysis is carried out for the simplified structural model described in section 5.1, and by considering a scenario with *snow* as variable action.

The failure probability, p_f, related to the actual structure is calculated by introducing carefully updated parameters of the variables. Only for the parameters of the snow load model it is necessary to adopt default values. The same values, taken from the literature [9], are assumed as those used in determining the target value, $p_{f,0}$, representing the safety level of Eurocodes [2, 3, 4, 5] (bias = 0.33; coefficient of variation = 1.0; lognormal distribution function),.

By using the computer programme [10], a failure probability of 189 times the target value is obtained ($p_f = 1770 \cdot 10^{-5}$; $p_{f,0} = 9.36 \cdot 10^{-5}$). Therefore, according to the aforementioned condition, the investigated connection, and thus the whole structure may not be considered safe. It can also be concluded that further updating for dominant variables (sect. 2.2) would only marginally improve the accuracy of the evaluation. Indeed, except for snow loads, parameters of all load and resistance variables have been updated before (sect. 3). And in the case of the snow loads the same model has been adopted for determining p_f and $p_{f,0}$, respectively.

6. Communication of the results and consequences

If the goal should be reached that the insurance company *and* the owner accept the result of the analysis, it might not be sufficient to simply communicate to the interested parties the final outcome of the assessment. Some additional effort seems required. To this end, general acceptance is assumed of the fact that complete freedom from risk is an unattainable goal in areas such as public health, but also in science and technology. The basic idea of comparative analysis based on failure probabilities will therefore be understood by professionals and also by the general public. This is exactly what reliability analysis is used for in the present study, where the numerical values are not interpreted as absolute values. Some of the obtained results are summed up in the following:

– Considering the self-weight of the structure and the dead loads only, the calculated failure probabilities are smaller than the corresponding target values.
– In the case of a snow event, the calculated failure probability exceeds the target value for a snow layer on the roof with a nominal depth of 26mm. The resulting snow load corresponds to 24% of the characteristic snow load to be considered according to the Eurocode [5].
– For a hail event, p_f exceeds the target value, $p_{f,0}$, for a nominal depth of the hail layer of 5mm.

Although the hail load that induced the collapse is to be considered an accidental action, the results show that the structure could have failed even for insignificant variable loads. The structure did not fail during its previous 30 years service period (particularly during the 12 years after the increase of dead loads) due to the absence of significant hail or snow events. By consulting the relevant meteorological data, this fact can be confirmed. In this way, the reasons are explained why the structure did not fail earlier. A convincing answer to this question is essential for creating confidence towards the whole analysis. Credibility, on the other hand, is a main requirement for a successful communication with non-experts. Finally, it can also be demonstrated that the structure most likely would not have failed if, on the occasion of the change of use, it would have been strengthened in order to reach the required safety level according to the codes then in force [6, 7].

Based on the results of the assessment, the owner of the supermarket understood that the failure probability of the roof was much larger than the acceptable value, and that therefore the hail load only was the apparent reason for the collapse. Consequently, the involved parties reached an agreement concerning their responsibilities without any trial. Due to the fact that no safety evaluation was carried out on the occasion of the change of use, the owner accepted that he would pay the major part of the damage cost. The example shows that, although a highly complex subject, communication between experts and the general public about matters like risks, probabilities or frequencies can be successful if some basic rules are followed [11].

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