Interviews with Experts, in which they Explain how they Solved Structural Failure Investigations

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Abstract - The goal of this research is to identify what topics and procedures should be taught to engineering students in order to help them work in the field of analysis of structural failures. To identify knowledge and procedures, structured, face-to-face interviews were conducted to expert engineers, with emphasis on their methodology of research and their thinking about causes of failure. The list of questions was divided into: (a) General questions about the relation between the expert and her work; (b) Questions about a specific case in which the expert was involved; (c) Questions about the methodology used in this investigation; and (d) Questions about the development of failure hypothesis in this case. One of the future outcomes expected from this research is the creation of educational tools in which the students can do and experience in a simulated environment.

Keywords: case-based reasoning, experts and novices, interviews, structural failures.

INTRODUCTION

The research reported in this paper is aimed at identifying what topics and procedures should be taught to civil engineering students in order to help them work in the field of analysis of structural failures[5]. To identify knowledge and procedures, interviews were conducted with experts, with emphasis on their methodology of research and their way of reasoning about the causes of specific failures. It is currently believed that experts become experts by doing and experiencing [10, 2, 11], so one of the desired outcomes of this research is the development of educational tools in which the students can do and experience in a simulated environment, without the dangers of having undesirable consequences to the case and to their own future [4]. Rather than emphasizing the engineering problem solved (as in the valuable work of Delatte [3]), here we investigate the knowledge and procedures used by expert engineers.

The characterization of expert knowledge in engineering has been addressed by Ahmed et al.[1], but their interest focused on design activities. Petroski [9] has linked failure with design, but his sources of evidence are the reports of famous historical collapses or engineering failures.

In order to conceptualize the kind of knowledge that an expert uses when investigating a structural failure, it is commonly accepted that there are two main sources of knowledge involved in such investigations: (i) General principles, and (ii) Lessons learned from specific previous cases. We already teach general principles at universities. (In fact, this is what we are good at, and students tend to be good at learning how to use general principles and laws in engineering, from which they can solve many problems that have been prepared to tests those principles). But a second knowledge source that an expert uses is what was learned from interventions in past cases in which she was involved. There is a discipline dedicated to study this form of reasoning, which is called "Cased-Based Reasoning", or CBR for short [8].

Structured, face-to-face interviews were conducted with expert engineers, with emphasis on their methodology of research and their reasoning about the causes of failure. Two research hypotheses are considered in this paper:

(1) Experts investigating structural failures employ case-based reasoning and adapt solutions from old cases. In a more restricted formulation, this hypothesis states that experts investigate new cases by using their experience from previous cases and from what is reported in the technical literature.

(2) Experts formulate a failure hypothesis as soon as the case is described to them and before their first visit to the site of the collapse.

ON CASE-BASED REASONING

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There are at least two links between CBR and this research. First, there is an assumption that experts in failure analysis reason and solve new cases by taking into account information from previous cases. Understanding how this type of reasoning works can help us make a better interpretation of the responses of experts in interviews. Second, when de-constructing interviews, each expert story becomes a case and the knowledge extracted from it is better framed within some structure, in this case, provided by CBR.

Fundamentals of Case-Based Reasoning

Basic concepts from this field are summarized in this section to facilitate the interpretation of our questionnaires developed to identify expert knowledge. Classical textbooks on the subject are Kolodner [8] and Schank et al. [10]. Following Kolodner [8, pp. 13]: "A case is a contextualized piece of knowledge representing an experience that teaches a lesson fundamental to achieving the goals of the reasoner".

Our remarks on this definition can be summarized as follows:

- Cases do not exist in a vacuum, and they become cases only in relation to some goal. We make cases, they are not given to us.
- Cases represent knowledge derived from specific situations and they make sense within a given context. A certain structural mechanism that occurs in a given context may be something unusual; however, the same mechanism in a different context may be what is expected. The context is crucial for understanding a case.
- There are lessons that we extract from cases. Otherwise, they will not be useful as the basis for understanding new situations. The reason why we use cases and learn from them is that we believe that situations occur with regularity because they have similar causes.
- Finally, information regarding cases is always incomplete. In cases of structural failures, this incompleteness has various sources, and arises because the mechanisms that led to the failure are (and remain) hidden to the observer. Often, there are no witnesses to tell a story, or there are no measurements of those parameters that the expert would value most. On the other hand, there are pieces of information that may not match in a consistent way.

Next, we turn our attention to the reasoner who employs CBR. The first basic assumption in CBR may be stated as: "A reasoner remembers previous situations similar to the current one and uses them to help solve the new problem". This assumption reflects something that we all do (or think we do), and also what we expect others to do. If we could easily identify that the situation we face is similar to other situations we have gone through in the past, and recall what we learned from them, then we would not make the same mistakes twice. The main difficulties with CBR are how this simple procedure becomes operational.

Information from past cases can take various forms. First, the case in hands may be similar to another case previously solved; hence, the expert infers that similar mechanisms operated in each case, and further, that they both had the same causes. However, such simplicity is seldom true in practice. Often, some aspects show similarities whereas others differ in various degrees, so that a perfect matching does not proceed.

A second assumption is usually introduced in CBR: "Cases reflect general principles under specific situations". As such, experiences embodied in cases lead to local knowledge, which might under some circumstances be considered as a "projection" of more general knowledge affecting many cases. Some researchers in the field of CBR could argue that there is no need to employ general knowledge as a condition for using local knowledge, and they are right. However, in the field of failure of structures, in which physical systems are involved and for which structural analysis is an essential tool, it may be reasonable to understand cases as instances of more general principles underlying our conceptualization of structural analysis.

Methodology for reasoning with cases

Consider the activities needed to take CBR into practice. First, the expert needs to have (and recall) previous experiences that are relevant to the current case. This is known as the "indexing problem", meaning that the expert needs to have an efficient way to recall relevant experiences. Becoming an expert means not only (i) accumulating new cases, but also (ii) having them available as structured knowledge [8].

Second, it is not only necessary to recall previous experiences, but also to use those previous situations as a way to solve the current case. Within the context of investigating structural failure cases, this means building a hypothesis of what was the main cause or mechanism of failure.

A difficulty arises because not two cases are identical; at most, cases may have similarities and those will differ in their extent and levels. Thus, CBR would suggest that

- It is necessary to understand new situations in terms of old experiences, find what they have in common, how they differ, and what knowledge can be transferred from the old case to the new case. This belongs to the field of making analogies.
- As soon as two cases are identified as being similar (in some aspects), then it is assumed that their solutions will also have some kind of relation. However, it may be necessary to adapt a solution from an old case (or several cases) that does not quite fit into the new case.

According to CBR, the reasoner tries to adapt the old solution, that is, she attempts to fix the old case and adapt to the new case. There are two major steps in adaptation: identifying what needs to be adapted and performing the adaptation. There are various ways in which adaptations can be performed: (i) By inserting something new into the old solution. (ii) By deleting something from the old solution. (iii) By making a substitution. The outcome of this activity should be a hypothesis about what could be the cause of failure.

Third, we need to evaluate the proposed solution to the new case. This may be a simple activity: testing a hypothesis can be achieved by running a simulation, a quantitative structural model, or by testing materials or structural components in a laboratory. This is the simplest part for an engineer.

Fourth, if the evaluation is not entirely satisfactory then it may be necessary to improve the work. This is called repairing a solution, i.e. introducing modifications to the adapted model in view of the evaluation carried out. This may also require new understanding of the current problem or new adaptation of old cases.

For example, consideration of the failure of a structure during a wind storm may bring the case of another structure showing significant corrosion that failed due to low cycle fatigue under hurricane winds. The expert may postulate that fatigue is the mechanism in this new case, even though corrosion was important in the old case and is not present in the current case. The expert would adapt the hypothesis by deleting corrosion as a source of material degradation. Evaluation of the proposed scenario for a failure should be done next by performing calculations or by inspecting the fracture surfaces of the structure, or both. She needs to test if, under the load conditions to which the structure was exposed, fatigue alone can account for the failure. Let us say that the number of cycles required to reach fatigue failure is too large; then, in principle, the hypothesis has not been validated. Should she abandon the hypothesis? May be she can repair it, if she can think of some aggravating effect that was not previously considered. Investigators are not always ready to abandon their hypothesis even if the evidence obtained is contrary to it.

METHOD: THE STRUCTURED QUESTIONNAIRE

Knowledge acquisition is a crucial topic in knowledge-based engineering. One of the common ways to capture knowledge from experts is by means of interviews: "The main vehicle for knowledge elicitation is face-to-face discussions between the expert who possesses the domain knowledge and the knowledge engineer who asks questions, observes the expert solving problems, and determines what knowledge is being used" [7, pp. 349].

A questionnaire was designed as part of this research to capture knowledge regarding how experts solve structural failure investigations. Due to limitations in our access to experts, the questionnaire was formulated to be completed in one session (rather than having several sessions, each with a specific goal, as recommended in the literature).

Because of this constraint, the interview contained two sets of questions in one condensed session. The first set was a kickoff part about some general experience of the expert. The aim was to understand general views of the expert regarding her field and what she considered to be more attractive and also more difficult. In the second set we asked the expert to recall one specific case and consider details of it. As mentioned in the previous section, cases make sense only in context, so that emphasis was made to understand the context of each story told by an expert. Further, it was our perspective that facilitated making a case that could be gathered with others in a coherent group. This set, which took most of the time, contained the description of the case considered. The methodology employed was the subject of the third set, and the final set of questions referred to the reasoning used in solving the case.

The list of questions was thus divided into:

I. General questions about the relation between the expert and his/her work. This part was included in order to learn about the previous experience of the person interviewed. The specific questions in this group are:

I.1. What difficult structural failure cases have you investigated yourself?

I.2. What aspects of that work do you like most?

I.3. What aspects are the most difficult part of the work?

II. Questions about a specific case in which the expert was involved. This part is important to focus on a single case and to make it as a case study.

II.1. Briefly describe a specific failure case in which you participated.

II.2. How were you contacted and who was the part interested in doing the investigation?

II.3. Why was the investigation necessary? What was the objective?

II.4. Were there any serious conflicts associated with this failure? Who were the stakeholders in the conflict?

II.5. Did you have access to all needed documents? Were there missing or unavailable documents when you requested them?

II.6. Were there previous studies about this failure, including the formulation of hypothesis? Did that influence your work?

II.7. Did you interview those who participated in the design and construction of the structure?

III. Questions about the methodology used in this investigation.

III.1. What was the sequence of activities that you followed in this investigation?

III.2. Did you visit the structure after failure? Was access to the site easy? What was the benefit of the site visit?

III.3. Did you perform structural calculations and/or lab testing? What was the objective?

III.4. Were you able to find an explanation to the failure investigated? Describe briefly.

IV. Questions about the development of a failure hypothesis in this case.

IV.1. Was this case similar to other cases in which you participated previously?

IV.2. Was this case similar to other cases that you found published in the technical literature?

IV.3. How did you formulate hypothesis about this failure?

IV.4. Did you have a hypothesis before visiting the site?

IV.5. What aspect of the investigation allowed you to think of a plausible hypothesis?

IV.6. Did you attempt to validate the hypothesis by testing or calculation?

IV.7. Were you satisfied with the validity of the hypothesis that you proposed? Did other peers provide you with feed-back or comments on them?

Questions are of open ended nature, to give the possibility of having a discussion about the question domain. The experts were told that they should not provide yes or no answers.

For the sake of comparison, we also interviewed one expert by sending the questionnaire via email, but the responses received were too short to be of any use and they were not included in this set. The rest were eight face-to-face interviews that were carried out during one year of research. All interviews were conducted by the author.

Experts were male practicing engineers, with either Ph.D. or P.E. A typical interview took one hour. Sometimes it was necessary to draw sketches to explain the case investigated, and those were added to the interview record. We never had to handle problematic experts: They all understood the importance of the research and were very happy to cooperate. As Gonzalez and Dankel [7, pp. 352] state, "experts generally enjoy the opportunity to speak openly about their domain and show how much they know".

After the interviews were conducted, we organized the answers by looking at common features in the responses.

RESULTS: RESPONSES TO SELECTED QUESTIONS

Because the main interest in this investigation was to understand how experts reason and formulate hypothesis, in this section we review only examples of the answers that are related to this interest.

IV.1. Was this case similar to other cases in which you participated previously?

Expert A. "No, this was a special case that was not similar to anything I had seen before. In most cases, structures like the one we investigated do not have such problems. However, in this particular case, the beams were fabricated by a firm that was in business for a short time, produced components with low levels of quality control, even with inadequate materials, which is not a common practice to see."

Expert B. "Yes, in the sense that the deflected shape observed in this structure is one of the typical buckling modes that occur under wind loads. We had seen this mode in tests and in theoretical studies of cantilever cylinders under wind, and the shape at collapse is due to the lack of restraints at the top. But the failure loads in the real case were very different from what was initially found in the analysis."

Expert C. "No, this case was not similar to any other case that I have seen before. Perhaps the closest was the failure of other large reinforced concrete shells, but even those failures were not due to the same cause."

Expert D. "The type of structure was similar to other pipelines that I investigated, but this one had unique features that made a huge difference in the behavior."

Expert E. "No. But there is a recurring factor that bothers me; it is that those who design a structure consider all the members in the completed structure. However, during the construction not all members are there, and the decision about how to secure the structure becomes the responsibility of the constructor. He may have experience but it is also true that his judgment may not be adequate for the case."

Expert F. "I had seen cases of foundation settlement leading to cracks and even failure of a structure, but never caused by a tunnel excavation, as in this case."

Expert G: "No, because I had never been in a structural collapse in which the collapse was strictly due to structural causes. I mean, there was nothing else important but the structure. Under normal loads, this bridge collapsed by itself. For a number of years, this was the largest bridge in the country, an engineering achievement."

Expert H: "No, this was the first case in which I participated in the investigation of the collapse of a structure that failed while it was being built."

Common features:

- Most cases were not similar to other cases previously investigated by the expert.
- The experts had investigated cases of similar or related structural types, but not with the characteristics of the one they reported here.
- The structural behavior identified in previous cases was different and could not be used to identify causes of failure in the new case.
- There are local features that make that each case is a special one.

IV.2. Was this case similar to other cases that you found published in the technical literature?

Expert A. "No, this case had no clear similarities with others. In most cases of structural pathologies it is common to use analogies (there are even pathologies that are specific to certain geographical areas, to specific soils, types of buildings or types of construction), but it was not like that in this case. Here I was not able to think in terms of analogy."

Expert B. "I could not find references to collapse during the construction stages. The buckling mode is the one expected in cantilever cylinders under wind, for which there are many references in the literature, but the critical loads were very different because this structure failed while it was still under construction."

Expert C. "No, I could not find information on similar cases in the literature. Just the general design codes were helpful to check the original structural design. Cases of inverted pressures are not common situations. With time, I found some papers published on related topics, but those were published after my report was handed to the client."

Expert D. "No, but I notice that books recommend that one should not have a pipeline crossing a thin layer of different soil, and in this case there was a sand layer that cut the tubes across."

Expert E. "It was already known that if there is any problem with this type of structure, it usually occurs during its construction."

Expert F. "I read a lot about forensic cases, but cases concerning tunnel excavations I never found."

Expert G: "No, but after we completed the investigation we learned that tied arches were considered with certain suspicion in some places in the US."

Expert H: "I think not. Each collapse case occurs under very specific circumstances. And I would not attempt to search for a similar case, because that would condition my own search for the reasons of the collapse. This would become a prejudice and would guide me to search in a direction in which I would probably be wrong. What I try to do is, with basic knowledge, I try to build my hypothesis."

Common features:

- Most investigators could not recall having seen a similar case in the literature.
- Existing information was useful only in indirect ways.
- No one used analogy to construct a hypothesis.
- The experts may find common features with other cases in the literature once the case is solved (sometimes years after the case finished).
- Some experts stated that it would not be convenient to read about similar cases in the literature.

IV.3. How did you formulate a hypothesis about this failure?

Expert A. "The hypothesis of what could have happened came from looking at the deflected shape of the roof. Roofs of this kind have an initial upwards curvature to compensate deflections due to loads, whereas in this case the deflections were downwards."

Expert B. "By looking at the shape of the structure when it failed. This was a clear case of shell buckling. But the failure mechanism was not clear and we had to use different support and welding conditions and each of them was a hypothesis in itself."

Expert C. "I had to think of two aspects: one was the load configuration and the other one was a structural weakness that could help in triggering the collapse. The load configuration at the time of the collapse was very unusual: an inverted pressure from overfilling the tank. The structural weakness was there because the steel mesh had been located close to the bottom surface of the concrete shell, thus only working well for self weight loads."

Expert D. "There were not one but several hypotheses. The key was given by the lack of support due to the washing away of the layer of fine sand in the longitudinal direction of the pipeline. In the transverse direction, a clue was given by the inadequate steel reinforcement to support internal pressures."

Expert E. "The hypothesis was formulated after we modeled the complete structure, modeled the structure with the elements that were present at the moment of collapse. We applied small forces to the last case and found that this could have produced the collapse."

Expert F. "The hypothesis was formulated by the client, who argued that all damage was caused by the excavation of the tunnel."

Expert G: "I formulated the hypothesis when I visited the structure, observed the parts exposed by the collapse and found unexpected prior damage. Looking at the parts of the bridge after the collapse, the segment in which failure occurred was supported on one end and had failed on the other end. The segment was deflected, but this was not the reason of the collapse. It was very helpful to study the location of each part. We paid attention to the end that had failed, and discovered that some of the steel cables were recently broken during the collapse, but about 2/3 of the steel was already cut in a process of degradation during perhaps 20 years: the ends of those steel cables were already rounded. This indicated that there was corrosion present and acting during a long time. Then we searched for possible water paths, found cracks and identified the source of water."

Expert H: "This was a process of formulating hypothesis and discarding them based on the evidence found on site. After eliminating many possible causes, we found that there were two main sources of problems in the structure (design errors in the location of steel reinforcing bars and improper consolidation at the foundation) but there is uncertainty regarding the exact cause of failure."

Common features:

- Often, several hypotheses are formulated, although they may be associated with the same failure mode.
- Each hypothesis considers specific aspects of the mechanism and the conditions that would make it the most probable cause.
- Often, the deflected shape provides sufficient information on the failure mode. The researcher finds that there is something unusual about the deflections.

- In some cases, the hypothesis was formulated only after considering the computer results.

IV.4. Did you have a hypothesis before visiting the site?

Expert A. "Before the first visit we had no idea of what happened (or could happen in a near future). The client was completely mistaken about what the problem was."

Expert C. "At the time of my first visit I had an initial hypothesis that was not useful after seeing the collapsed structure. The client wanted the cause to be xx, but this was not something related to the collapse."

Expert D. "When we visited the structure for the first time we had no idea of the cause of failure. However, the client had a hypothesis that this was a problem of soil failure due to settlement, and this was not the actual cause."

Expert E. "No, I did not think about the case until I saw the collapsed structure."

Expert F. "As said before, the client had a hypothesis that he wanted to prove. So there was an hypothesis already formulated when we started the investigation even before the first visit. We had to perform the investigation to see if the hypothesis was right or wrong. It was wrong."

Expert G: "Not in this case."

Expert H: "We arrived to the construction site without any preconceived ideas, we saw the failure and were very impressed by the size of the structure: we had never seen such large steel structures of this class."

Common features:

- Experts do not make a plausible hypothesis before visiting the structure for the first time.
- Hypotheses provided by the client are often misguiding and loaded with their own expectations and needs.
- Some experts did not even consider formulating a hypothesis before visiting the site.

IV.5. What aspect of the investigation allowed you to think of a plausible hypothesis?

Expert A. "We postulated the hypothesis during the first visit to the structure, because this case was structurally simple."

Expert B. "From the structural analysis. The indication that we were in the right track came when we included (in the model) the possibility of a shell lift at the joint between shell and bottom plate. Both the wind speed and the post-buckling mode were consistent with what was observed in this case. The required model was nonlinear incremental analysis. As we included the bottom plate as part of the model and allowed for shell uplift, the results became closer to reality."

Expert C. "As soon as I visited the collapsed dome and saw that the reinforcing steel mesh was significantly displaced with respect to the mid-surface of the shell."

Expert D. "Regarding the transverse model, we thought our hypothesis after we observed the plans and drawings of changes adopted in the project. About the longitudinal model, our idea came from the site visit, in which cracks were detected in the lower part of the tube. This location was in coincidence with the largest positive bending. Cracks were also found at the ends of the tubes, where the maximum negative bending would be. A global view of the events was then obtained, in which all pieces came together, including the differential settlements between consecutive tubes. There was testing of the materials."

Expert E. "The calculations allowed us to think of the hypothesis."

Expert F: "After we built the computer models and made the calculations, everything fell in place."

Expert G: "The mode of failure that we saw in the first visit was almost telling its own story of the collapse."

Expert H: "This was a team work, in which we discussed possible hypothesis and tested them one at the time. During the internal discussions that followed, each one tried to show that the hypothesis of other group members were wrong. Computations were brought to the table in support of hypothesis. In the end, we converged to a reasonable scenario to explain the failure."

Common features:

- The timing varies: in many cases the hypothesis are formulated at the site visit; in other cases, it was after the structural analysis; in other cases it was triggered by the evidence obtained from design documents.

- Often, researchers accept a hypothesis because, when introduced into a model, it is consistent with the observed collapsed structure.

IV.6. Did you attempt to validate the hypothesis by testing or calculation?

Expert A. "We performed structural calculations. A model for this structure was simple. We had access to all design documents that were needed."

Expert B. "Structural calculations were done using finite elements. There is evidence in papers that finite element models for problems like this one compare well with wind tunnel tests. No testing was done."

Expert C. "The structural analysis confirmed that the proposed scenario could explain the structural failure, at least, at the onset of failure. Testing of material properties was not done."

Expert D. "The failure hypothesis was calibrated and validated with the longitudinal model. Failure did not occur in the worst segment, but precisely in the best one, in which the quality of concrete was not a triggering factor. Testing was only useful to confirm the poor quality of the material."

Expert E. "Yes, we did structural computations."

Expert F. "In this case we were able to show that the claims against the part that I represented were not valid. This we did by observations, documentation analysis, and calculations."

Expert G: "Yes, we did a large number of computations and also testing in the bridge, in the parts remaining that did not collapse."

Expert H: "Various models were tested in computer simulations, in an attempt to represent the construction process and its equilibrium. Tests of steel coupons were also done."

Common features:

- Structural computations are always a decisive element in hypothesis validation.
- Testing is used to confirm aspects of the investigation, but they are not the most important part of the investigation. Notice that what is considered here is structural failures, not material failures.

CONCLUSIONS

This paper is a first attempt to gather information about the reasoning and methodology followed by experts in the field of structural failure investigations. Not all questionnaires have been completed yet, but from the eight cases already completed (which are 75% of the target number) it seems that it is possible to postulate clear trends and common aspects in the responses of experts.

Unlike what is commonly believed, experts do not find cases that are entirely similar to the one that they described. Perhaps this is why the expert chose to speak about this case and not about others which he thought were less original. Thus, what they can use are general ideas about the structure that failed and general concepts on failure investigation, but not an analogy with previous cases that would lead to the solution of the new case. The idea of solving a puzzle seems to be closer to the work done by this group of experts, in which some of the activities (structural analysis) plays an important role in making sense of the puzzle.

During the site visit, an expert can imagine possible ways and mechanisms through which the structure may have collapsed. This capacity of constructing a mental model is crucial in solving a failure case.

It is often stated that structural calculations are performed to confirm or reject hypothesis; however, some of the experts state that they were able to formulate a hypothesis only after looking at the results of calculations.

The lessons learned from this investigation would indicate that not only narrated cases of engineering failures are important, but also (i) the application of structural analysis to real structures to visualize how the structure can sustain loads, and (ii) the identification of failure mechanisms for a given collapsed situation.

The knowledge summarized from the interviews is now being used by the author to create educational tools in the form of active learning in a simulated environment [6].

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