Time to reflect: a strategy for reducing risk in structural design

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Introduction

The use of computers has resulted in immensely beneficial changes both, at the operational level of doing design and at the conceptual level of making us think more carefully about the processes that we use and how they should be used.

However there is much disquiet about the risks involved in their use. Hazards, that may lead to faults including disasters include:

- When relying on software, engineers' control of the design process is diminished. Much of the process may be automated requiring little input from the user. Designers become deskilled. Their understanding of design contexts is reduced.
- There is misplaced confidence in the potential of the software to produce outcomes that will be fit for purpose.
- Innovation will be stifled.

A main strategy for guarding against such risk is to use what is called the reflective approach[1]. This implies that one adopts a degree of scepticism about all received and generated information; one is open to ideas; one poses and seeks answers to questions; one makes personal assessments and reassessments and seeks advice from others, especially from experts; second or more opinions are sought if appropriate; when faults are found or improvements can be made, action is taken; an appropriate amount of resource is allocated to seek to ensure reliable outcomes.

Use of reflective thinking is fundamental to good engineering practice. Computer use does not diminish the need for it.

Cases

Two cases of failures that illustrate the risks and the potential role of reflective thinking in avoiding them are dicussed.

Large panel construction for buildings

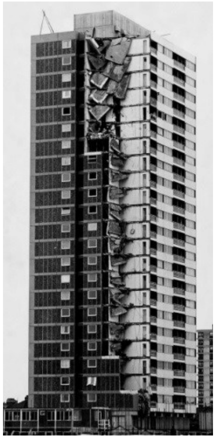
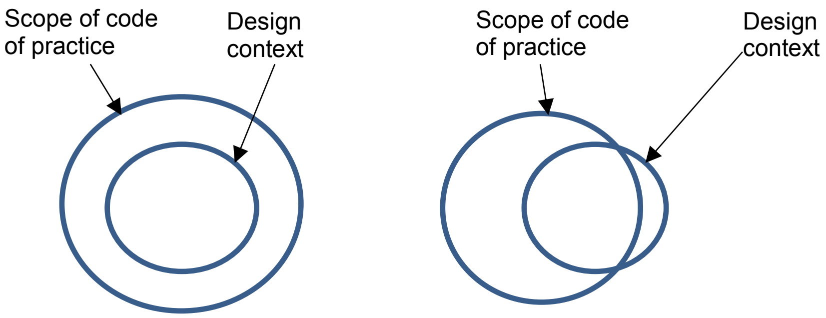


Figure 1 The failed Ronan Point Building

In the 1960s, structural designers in the UK used Code of Practice CP 114 *Design of Reinforced Concrete Buildings* for the technical assessment of large panel buildings. Many of these designers did not ask the question: "Does CP114 address all the issues that need to be considered for the design of large panel buildings that are constructed using precast wall and floor panels?" The answer to that question was a resounding "No". CP114 was written mainly for cast in situ beam and column structures; important issues for large panel buildings, particularly about how the panels should be connected, were not addressed in the code and hence in many, if not most, of the designs.

Consequences of this lack of reflective thinking included:

- A major structural failure causing 4 deaths (The Ronan Point Collapse).
- High cost of retrofitting existing buildings that were found to be unsafe.
- Long term pause in the use of a construction method that has advantages for some types of building.



(a) Standard context (b) Uncertain context

Figure 2 Applicability of codes of

In Figure 2, a ‘standard context’ can be considered as one with which the design team is wholly familiar and there is no innovation; codes of practice fully apply. An ‘uncertain context’ is one which involves any degree of innovation and/or issues that are unfamiliar to the design team. Safety-critical situations are also in the uncertain domain. The designers of large panel buildings in the 1960s did not realise that they were working in a context exemplified by Figure 2(b). They were not asking the right questions.

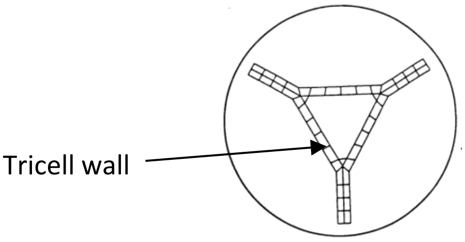
The Sleipner Platform Collapse

In 1991 a large concrete oil recovery platform - Figure 3(a) - was close to completion in a Norwegian Fjord when a loud bang was heard and the structure sank to the sea floor – a total loss. The fault was traced to shear failure in a ‘tricell’ wall - Figure 3(b) - at a the bottom of the structure. The system had been modelled using 3D finite elements (FE) - Figure 3(c) - the results from which were used for assessment of the shear strength of the wall. Questions that could/should have been asked include:

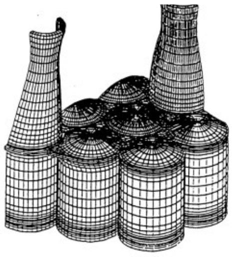
- *Is the model that I am using more complex than is appropriate?* The designers of the Slepiner Platform assumed that that because they were using a complex model that it would necessarily give adequate predictions. In the case of the tricell wall, bending theory would have resulted in much better predictions of bending moment and shear force than from the model used.
- *Is the mesh of elements used adequate for the purpose?* A review of the FE mesh in the area that triggered the collapse - Figure 3(c) - by a person experienced in FE modelling could have prompted an investigation of the accuracy of the mesh for predicting bending actions.
- *Can I do a simple check calculation?* Figure 3(d) shows a calculation, on the back of an envelope, based on treating a 1m depth of the tricell wall as a beam withstanding a 67m hydrostatic pressure head. The predicted shear is 3 times the allowable.

The consequence of failing to ask and respond to such questions was a financial loss of over $700m

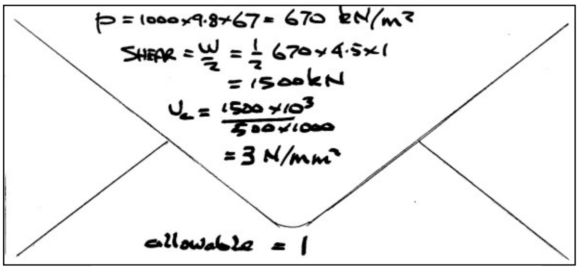
(a) The platform prior to collapse



(b) Plan of part of the FE mesh



(c) The FE model of the system



(d) Back of an envelope calculation

Figure 3 The Sleipner Platform collapse

The Design Process

At its most basic level, the design process includes the following activities/stages:

- *Inception* Where information about the context is gathered and the requirements are established.
- *Conception* Where a set of conceptual designs/options are identified and assessed against the requirements leading to a decision about the design solution
- *Production* Where the information needed to create the entity is established.
- *Review* This is the reflective activity that is pervasive in the process

In structural engineering this process can be applied to the structural system as a whole or to a part or to details.

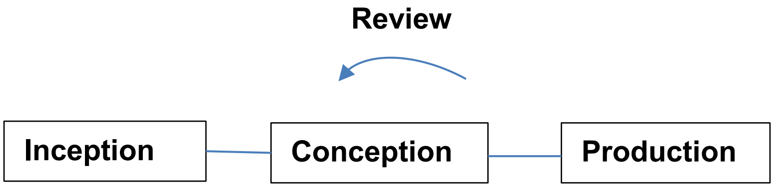


Figure 4 Basic design process

While the process may be mainly linear as shown in Figure 1, it can be deeply iterative, e.g. in product design, a prototype may be manufactured, tested, modified, re-tested and so on.

Traditionally 'structural design' meant the use of code of practice rules to ensure that the system and its parts would perform satisfactorily. The term is now used for the process of synthesising and assessing the whole of the design information for a structure. It is better to refer to assessment using codes etc. as *technical assessment*. Technical assessment is sometimes required at the concept design stage to assess options but it is mainly used in the production stage of design.

It is said that if bad decisions are made at the concept stage, no amount of good detailing can rescue the situation. The need for reflective thinking at all stages of the design process is therefore evident. However it is errors in technical assessment that have the greatest potential to result in major failures/disasters. Therefore this area is of the greatest concern in seeking to ensure that computer use is satisfactory.

Technical Assessment

Main processes in technical assessment are:

- *Model development process* Here the 'model' is the set of rules that need to be addressed (normally code of practice rules). The main reflective question at the model development stage is "Have all the relevant issues been addressed and are the rules used adequate for this purpose?" This is the *validation* question. In standard design contexts not much resource needs to be applied to model development but with innovation, posing the validation question is a key issue. It was here that the designers of large panel buildings in the 1960s made their main errors. The fault that caused the collapse of the Sleipner Platform lay in the decision about what analysis model to use.
- *Solution Process* i.e. doing the calculations. Reflective questions here include: Is the software reliable?' 'Are the input values correct?'
- *Output assessment* Here the main reflective question is: "Has the model been correctly implemented?" This is the *verification* question.

Figure 5 is a diagram of the predictive modelling process. Technical assessment rules are predictive in the sense that they are used to assess future performance of the structure. In this diagram the rectangular boxes are sub-processes and the oval boxes can be considered to be states. The system model is the full set of information about the entity being designed. The engineering model is that part of the system model that requires technical assessment.

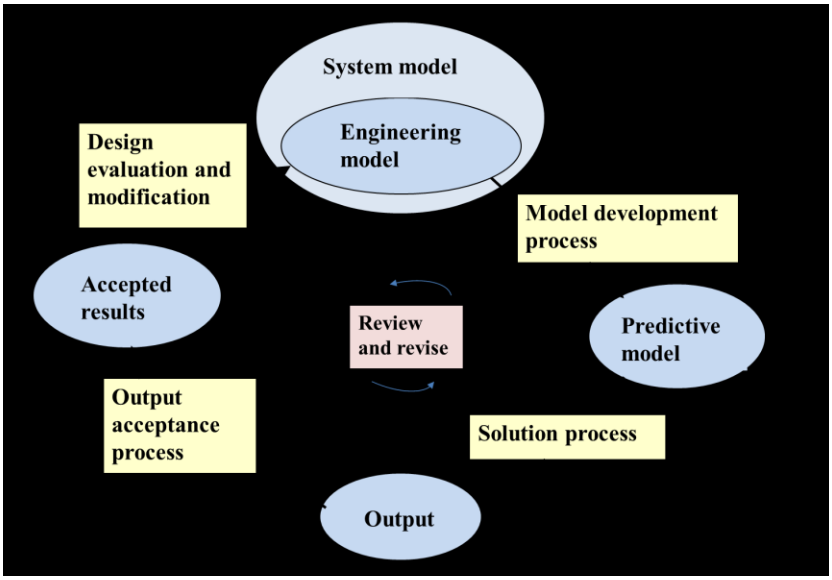


Figure 5 The modelling process

There is concern in the profession that for the implementation of many Eurocode provisions, such as complex combinations of loadcases, computer processing is the only feasible strategy. Some people see this necessity as leading to a dangerous 'black box' mode of operation where designers become dissociated from the calculations. Such a mode of operation is unacceptable. A reflective ethos must be adopted. Rather than see computational power as a threat, it must be harnessed to support improved design in, for example, answering 'what if?' questions and better support in the investigation of options

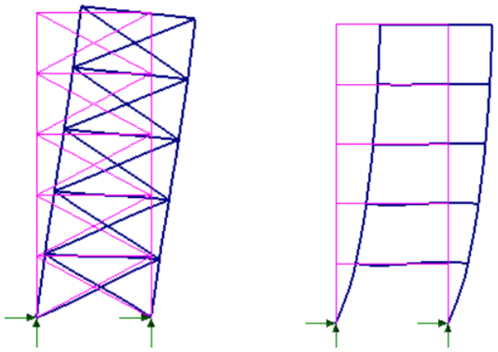
Analysis modelling

The analysis model is the mathematical representation of the behaviour of the structure. The analysis modelling process[1,2,3,4] has the same form as illustrated for technical assessment in Figure 5. It is a sub process of technical assessment. The validation question is: “Is the analysis model capable of satisfying the requirements?”

In traditional engineering education, analysis modelling, i.e. structural analysis, was treated as a dominant issue. Students learned to do time consuming calculations by hand. Now engineers do not do complex hand calculations. Some people are of the opinion that this results in a decline in understanding of behaviour but the accuracy and efficiency of computer processing means that complex hand calculations are in the past. We must therefore look to other sources for understanding of structural behaviour. Computer use is seen as the problem; in reality it is the solution. Responding to reflective questions using analysis software can significantly enhance understanding of behaviour.

For example suppose, if you were accustomed to analysing braced frames for buildings you may observe that a frame of this type, under uniformly distributed lateral load, tends to deflect as in Figure 6(a). Then you solve for a similar, but moment resisting, frame with no diagonal bracing and find that the lateral deflection is as in Figure 6(b). A natural reaction is to think that you have made an error. To respond to this reflective question, you do some experimentation by varying the stiffnesses of the members of the frame. This leads to the conclusion that there is a fundamental difference in how the two types of frame resist lateral load. You find out what characterises the difference. Your learning about behaviour improves significantly. Using such knowledge then informs improvement in design decisions.

People say that in modern practice there is little time for such reflection. But if a structural designer is operating outside the standard envelope (Figure 2(b)), the risk in not being reflective is unacceptable.



(a) With diagonal bracing

(b) No bracing

Figure 6 Lateral displacement of frames

Structural Failures

While the scope of what we define as structural design is, as it should be, much wider than in the past , the risk of failure is still a dominant issues. The track record for preventing major failures in the UK is very good but the risk will always be present. Reflective thinking is a key strategy in controlling such risk. Table 1 lists seven major failures and their root causes. None of the causes listed are related to errors in doing the calculations. The faults all occurred at the model development stage of design; in each case the validation question was not properly addressed. Very few major failures are attributable to errors of the doing calculations. This does not mean that errors in calculations are not made nor that improvements in methods for identifying them should not be sought.

Table 1 Root causes of some major failures

Incident	**Reason for failure**
Tay Rail Bridge collapse 1879	Inadequate provisions for wind loading, neglect of known good practice for detailing of connections
Cleddau (Milford Haven) Bridge collapse 1970	Buckling of diaphragms not included in theanalysis model
Ronan Point building collapse 1968	Code of practice used did not address important issues for the type of structure
Hartford Connecticut Civic Centre collapse 1978	Analysis model neglected buckling and eccentricities
Hyatt Regency Hotel collapse 1981	Error in assumption about how loads were distributed.
Ramsgate Walkway collapse 1994	Error in assumption about moment on stub axle
Sleipner oil recovery platform collapse 1991	Inadequate FE mesh

While we are very aware that structural calculations need to be carefully checked, the lesson to be learned from Table 1 and other major failures is that all the sub-processes of the modelling process (Figure 5) need to be assessed in a reflective way.

BIM

Building Information Modelling (BIM) is leading to automation in structural design. More importantly, it is an enabling technology for interdisciplinary working. A fundamental aim is that each design discipline will be able to access the models of the other disciplines involved (BIM 2) or that all parties will access a central model (BIM 3). In doing this, difficulties must arise, for example, in controlling revisions to the design. The brain has special ability to make associations and identify anomalies that is not replicable by software. While seeking to use software in managing the processes, the brain must continue to be used as a main source for controlling uncertainty. The same reflective ethos as outlined in this paper needs to be applied to all processes whether or not the work is in a BIM environment. BIM software must be such that it is possible for designers to get answers to questions such as “What assumptions were made for the analysis model?“ “What is the deflected shape?” “ What is the bending moment diagram for that beam?”

Conclusion

A computer can do calculations and repeat them much more efficiently and accurately than is possible using brain power. Computer power also beats brain power at processing logic especially when the rule set is complex.

On the other hand, the deep associativity of knowledge and other features of the brain allows us to: identify patterns, make subtle inferences, understand, have hunches, ask penetrating questions, generate ideas, etc. Computer technology is a long way from replicating the phenomenal power of the brain to ‘think’.

If a process can be defined as a formal algorithm, to implement it on a computer is the sensible approach. Software should seek to help us in our thinking – for example it would have been possible that the software used for the Sleipner Platform model (Figure 5) had an embedded rule that flagged up the fault that led to the collapse – but harnessing the thinking ability of the brain must remain a central activity in the design process. This should work in partnership with formal quality management systems – as discussed in the paper on page xx

The low incidence of major structural failures in the UK indicates that we do have good checks and balances to prevent them. But the key strategy of reflective thinking, that is at the core of good engineering practice and is very important in controlling risk, tends not to be explicitly addressed in education and training. Failure of structures is, of course, just one of the risks that need to be controlled by such thinking.

I believe that that the ethos in which one operates, i.e. the thought processes that guide our thinking and actions[5,6], is as important as technical knowledge in the pursuit of successful engineering outcomes.

Structural engineers who have not developed a reflective ethos in their work must seek to move in this direction. In education, teachers must seek to instil a reflective ethos in student project work.

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