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Introductory Notes

Rapports préparatoires introductifs

Einführende Berichte

CONTENTS
A set of Introductory Notes – intended to outline the scope of the workshop and to stimulate discussions – was circulated to the prospective participants of the workshop in December 1982. The Scientific Committee had asked the authors to be provocative, aggressive and question the well-established. They responded – according to their spirits and professional obligations. In their present form these Introductory Notes were only slightly revised after the workshop.

CONTENU
Six rapports introductifs furent envoyés aux participants potentiels en décembre 1982. Ces rapports devaient délimiter le sujet du Workshop et suggérer des discussions. Le comité scientifique avait demandé aux auteurs d'être provocateurs, voire même agressifs et de mettre en question les points de vue conventionnels. Les réponses correspondent aux tempéraments et aux cercles d'activité professionnelle des auteurs. Dans leur présente forme, ces rapports n'ont été que très peu modifiés après le Workshop.

INHALT
Sechs, das Thema umreissende und als Stimulans gedachte einführende Beiträge wurden den vorangemeldeten Teilnehmern im Dezember 1982 zugesandt. Das Wissenschaftliche Komitee hatte die Autoren dieser Beiträge aufgefordert, provokativ, ja aggressiv zu sein und vor allem festgefahrene Meinungen in Frage zu stellen. Die Antworten entsprechen Temperament und beruflichem Wirkungskreis. In der vorliegenden Form sind die einführenden Beiträge leicht überarbeitet.

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Quality Assurance — A Paper Tiger?

Assurance de la qualité — un tigre de papier?

Qualitätssicherung — Ein Papiertiger?

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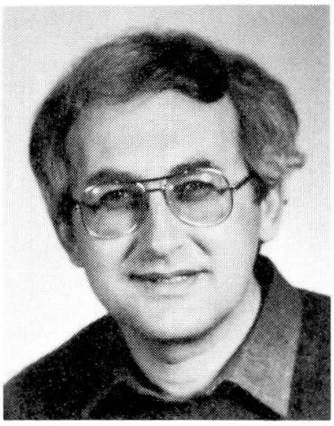

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SUMMARY
This report associates quality to the optimal conduct of someones affairs within the constraints set by society. When several egoistic subjects interact on this basis, quality is assured primarily by strategies for the rational resolution of conflicts of interest, and only secondarily by strategies against human errors.

RESUME
Ce rapport associe la qualité à la conduite optimale des affaires d'une personne ou d'une organisation dans le cadre des contraintes imposées par la société. Lorsque plusieurs sujets égoïstes agissent dans cet esprit, l'assurance de la qualité résulte primairement de la résolution rationnelle des conflits d'intérêts, et seulement secondairement d'une tentative de lutter contre les erreurs humaines.

ZUSAMMENFASSUNG
Dieser Bericht sieht Qualität verbunden mit der optimalen Führung der Geschäfte einer Person oder Organisation in den Grenzen, welche die Gesellschaft setzt. Wirken mehrere egoistische Subjekte zusammen, so besteht Qualitätssicherung in erster Linie aus Strategien zur vernünftigen Bewältigung von Interessenkonflikten, und erst in zweiter Linie aus Strategien zur Vermeidung menschlicher Fehler.

1. TERMINOLOGY

In this report, the term 'building' stands for a load-bearing structure and all systems connected to it which may affect its performance or which may be affected by its performance. This includes pavements, surface protection, cladding, bearings, expansion joints in roadways, but also water-drainage systems, thermal and accustic insulation, windows, cranes, .. .

Our interest is on the quality assurance for the load-bearing structure, but it is not possible to abstract from other systems in this context.

In most cases, buildings are custom made prototypes: one-of-a kind solutions to some owner's problem. Consider the set of all thinkable solutions to such a problem. Many of them are impossible structures because they violate natural laws such as equilibrium or material strength. In the subset of possible structures, many are inacceptable to society: they are not safe enough by standards set in technical codes, or they violate other rules set by society in the form of laws or regulations.

On the other hand, only a subset of all thinkable structures is acceptable to the owner; the rest does not conform to his wishes and convictions, which may be influenced by earlier experience.

The intersection of the set of structures acceptable to society with the set of those acceptable to the owner is the set of admissible structures. Obviously, high quality must be sought in this admissible set: Quality structures are always acceptable to society, e.g. always safe, but safe structures need not be of high quality to an owner. Quality is a subjective matter, since the owner sets the standards for the selection of the admissible set (Fig. 1).

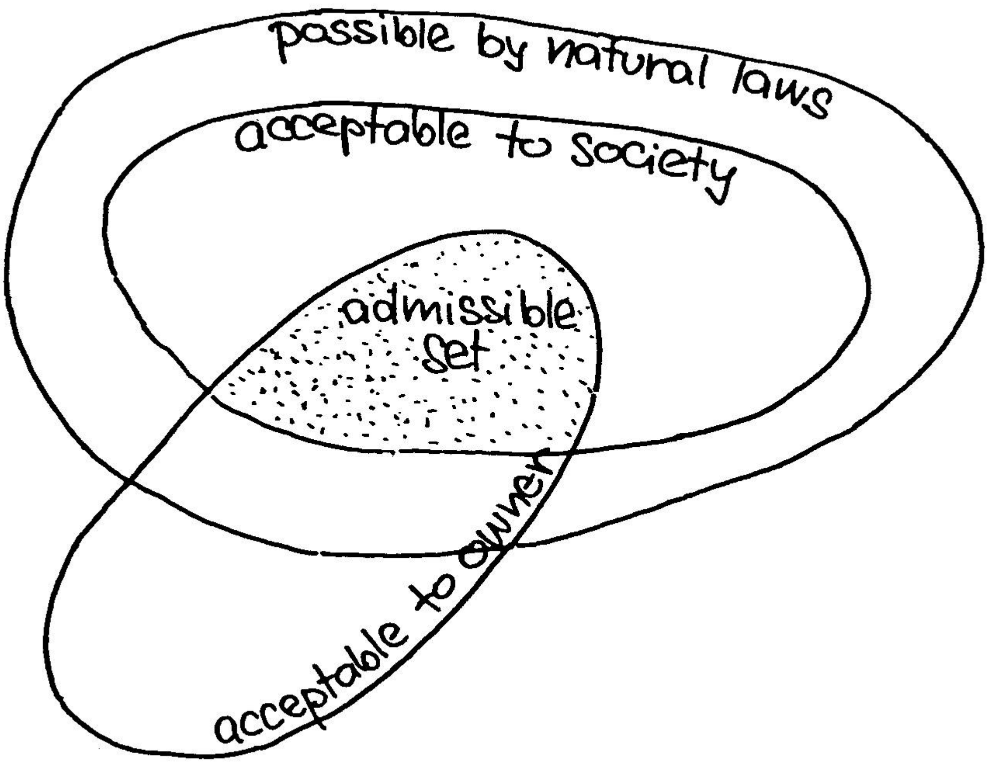

Fig. 1: The admissible set

2. QUALITY

2.1 Performance

To be useful, a building must conform to certain performance requirements. Most important performance requirements relate to safety, serviceability, and appearance. Malperformance is associated with losses. In the case of safety, losses have mainly the dimension of human life and limb. Malperformance in terms of serviceability and appearance is associated with economic losses.

Structural failure modes cannot be assigned on a general basis to safety, serviceability, or appearance. For example, tightness of a concrete tank can be a safety problem, a serviceability problem, or an appearance problem, depending on the particular situation.

In a well defined setting, loss functions associated with structural performance can be assessed. For example, Reid and Turkstra (1981) estimate the cost of creep failures of floor slabs in office buildings as follows:

$$C_f(\delta/l) = \begin{cases} 0 & \$/m^2 \qquad \delta/l \leq 0.002 \\ 4400\,\dfrac{\delta/l-0.002}{0.006} & \$/m^2 \quad 0.002 \leq \delta/l \leq 0.008 \\ 4400 & \$/m^2 \qquad \delta/l > 0.008 \end{cases}$$

δ denotes the deflection, l span. The cost of unserviceability is the sum of the non-structural repair costs and disruption costs in affected levels above and below the floor, and the structural repair cost.

Sudden structural failures result in human losses whenever people populate a building. Beside human losses, there will always be an economic cost for repair.

2.2 Utility to the owner

Under usual guarantee clauses, initial serviceability failures as the creep failure example above do not affect the owner: he buys, in principle, a building conforming to performance specifications set in a contract, at some initial cost. Repair of initial failure is covered by the producer and his insurance. More precisely: structures outside the admissible set, but in the set accepted by society, are the producer's problem by contract. Similarly, structures inacceptable to society, e.g. unsafe structures, structural failures, do not, in principle, affect the owner: the producer will be liable, and his insurance will have to pay for the dammage.

Given this legal frame, we may define quality as an optimization concept on the admissible set: Quality is what serves the owner best in the admissible set. In very simple and rather artificial cases, choices between qualitative options in the admissible set can be made on the basis of capitalized cost:

Example: Capitalized replacement costs

Let C denote the initial cost and, for simplicity, the replacement cost of a structure, and t the lifetime of each version of the structure. p is the interest rate. Then, the total cost of initial construction and replacement over a long time is

$$T = C\left[1+\frac{1}{(1+p)^t}+\frac{1}{(1+p)^{2t}}+\ldots\right] = \frac{C}{1-\dfrac{1}{(1+p)^t}}$$

Let us now compare two solutions, with initial costs $C_1 > C_2$ and lifetimes $t_1 > t_2$, respectively. Under which conditions is the more durable solution economical?

$$\frac{C_1}{1-\dfrac{1}{(1+p)^{t_1}}} < \frac{C_2}{1-\dfrac{1}{1-(1+p)^{t_2}}}$$

or

$$\frac{C_1}{C_2} < \frac{1-\dfrac{1}{(1+p)^{t_1}}}{1-\dfrac{1}{(1+p)^{t_2}}}$$

with $p = 5\%$, $t_1 = 20$ years, $t_2 = 10$ years

$$\frac{C_1}{C_2} < 1.61$$

The more durable solution may cost 60% more. With a higher interest rate of 10% and the same lifetimes

$$\frac{C_1}{C_2} < 1.39$$

The more durable solution may cost only 40% more. High interest rates on invested capital thus favor less durable solutions and waste of resources; conservation is linked to low interest rates.

The example may give us a hint at the complexity of the quality issue for a real-life owner. To him, the future lifetime of a design is - at best - a well informed guess of his technical advisors. Interest rates in the future are just plain speculation, and so is the future availability of resources. Moreover, the options in the admissible set differ from each other in many aspects not present in our simple example, such as maintenance costs, operating costs and, most important, operating revenues.

In the real world, stationary external conditions such as those normally assumed in economic models are rare.

In particular, the economic environment and the owner's existential situation may shift over periods much shorter than the buildings lifetime. This may give rise to changes in ownership, changes in maintenance policies, rebuilding, demolition, etc. In spite of the obvious complexity of the owner's real situation, decision theory (see Chernoff and Moses (1959) for an introduction) provides some well defined and useful concepts for the discussion of quality. The most important are utility, a tool for quantification of subjective preferences, and expected utility, a tool for rational subjective decisions under uncertainty.

As a rule buildings do not fail - they are maintained and repaired as long as the owner's utility dictates so, and then replaced by new buildings of greater expected utility.

2.3 Quality to the owner

Quality is what serves the owner best in the admissible set. In the language of decision theory, quality is maximum expected utility in the admissible set. For a custom-made prototype and an individual owner of just one such prototype, the definition has conceptual value only. Large institutional owners of many similar buildings may be able to go one step further and truly learn from experience.

Example

Consider the question of integral bridge abutments (Wolde-Tinsea 1983), or specifically: should bridge designs with integral abutments (Fig.2) be prefered over designs with expansion joints (Fig.3). Note that the starting point for asking a meaningful question is some standardization of structural types, as it appears in the two figures.

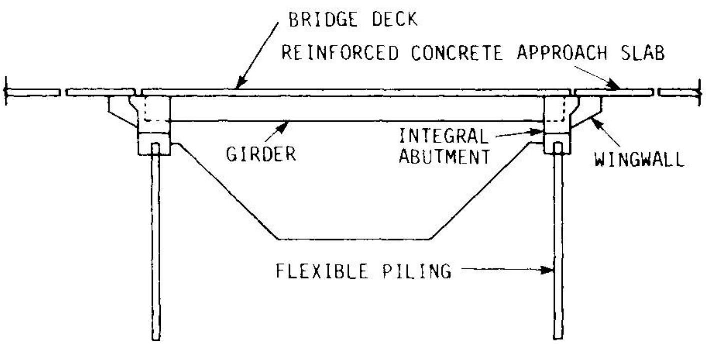

Fig. 2: Bridge with integral abutments

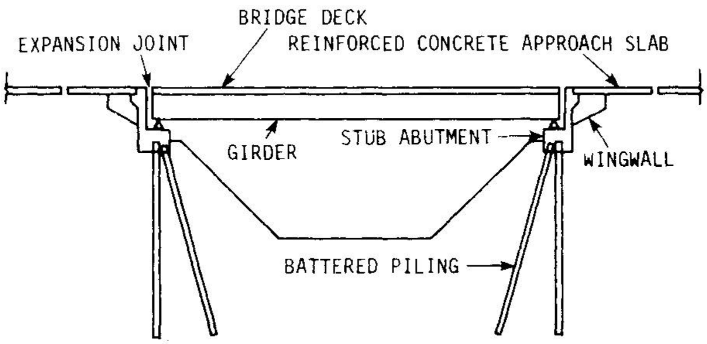

Fig. 3: Bridge with expansion joints

Structural models for the two types can help to make the question more precise, by identifying the relevant mechanical parameters: span, slenderness, abutment height and stiffness, soil properties of backfill, temperature variation, etc. On this background, a public road authority with many bridges of the two types under its control may, in the long run, gain empirical insight into the quality question-learn, in other words, which solution is optimal under which combination of parameters.

The contributions to cost (negative utility) to be monitored would be, in principle

- cost of initial construction
- cost of maintenance and repair, including cost of traffic disruption.

Simple as this may sound, the practical details of auch a monitoring program would require careful study. In particular, it would be necessary to separate initial costs relevant to our alternative from other, site-specific cost elements, and it would be necessary to refer all costs to some unit, e.g. 'costs per lane and per bridge end'.

3. QUALITY ASSURANCE?

The definition of quality proposed above identifies quality with optimal control of the building process, from the initial formulation of the owner's intention to design, construction, use, maintenance, repair, remodeling and final demolition.

What does it take to get quality for the owner? We can summarize the general requirements under four headings:

- Communication between owner and producers (planner, contractor) to identify and get across the owner's needs, values, wishes, and to make available his previous experience.

- Creation of the 'best' solution in the terms of the owner.

- Defense of that high quality concept against errors and mistakes in the subsequent building process.

- Learning from experience, along the lines sketched in the example of Section 2.3.

It must be emphasized here that quality to the owner is very much the owner's own business: unless he cares for quality himself, no one will. Nobody optimizes for someone else, and nobody steps in someone else's shoes to learn that other man's lessons .. .

We have, so far, used the word quality with the qualification 'to the owner' - of course, the other actors in the owner's game (Fig. 4) have a quality concept too, but their quality is linked to the optimal conduct of their own affairs, which are not a priori identical with the owner's building process.

What can the owner realistically do to enforce his quality requirements, and to align the producer's quality concepts behind his own? The well-established tools are competition and contractual guarantee. Competition can be used to get the best project from several competing planners, or to get the best bid from competing contractors, or both. Guarantee clauses in contracts - together with quality control - force the contractor to assure quality to the owner for his own benefit.

Learning from experience is more difficult to implement than the items on our list related to one single building. An important point probably is that learning with respect to quality is indeed the owner's business. However, it takes large institutions with a long and stable history, a large field of experience and a professionally qualified staff to learn from experience in a consistent, not just accidental way. Well-managed railroad companies or public road departments are examples of such owners.

The claims of design engineers and contractors to their experience with respect to quality should be taken with some reservation. As a rule, their attention ends with their guarantee. On the other hand, there is some kind of collective learning in the building industry: universities, technical schools, code committees and many informal channels of feedback help us to avoid the most obvious mistakes. More advanced, systemic quality questions, however, cannot be tackled without the initiative of large institutional owners - see again the example in Section 2.3.

Recent work on quality assurance for structures has been centered on strategies against human errors (JCSS 1981). In the light of the definitions proposed here, the claim of that paper to be "a description of a way to rationalize the building process" seems somewhat off target.

The most important tools of quality assurance to the owner in market economies - competition and contractual guarantee - are hardly mentioned in JCSS (1981). However, these indirect strategies are wellknown to work when used intelligently and with attention to details.

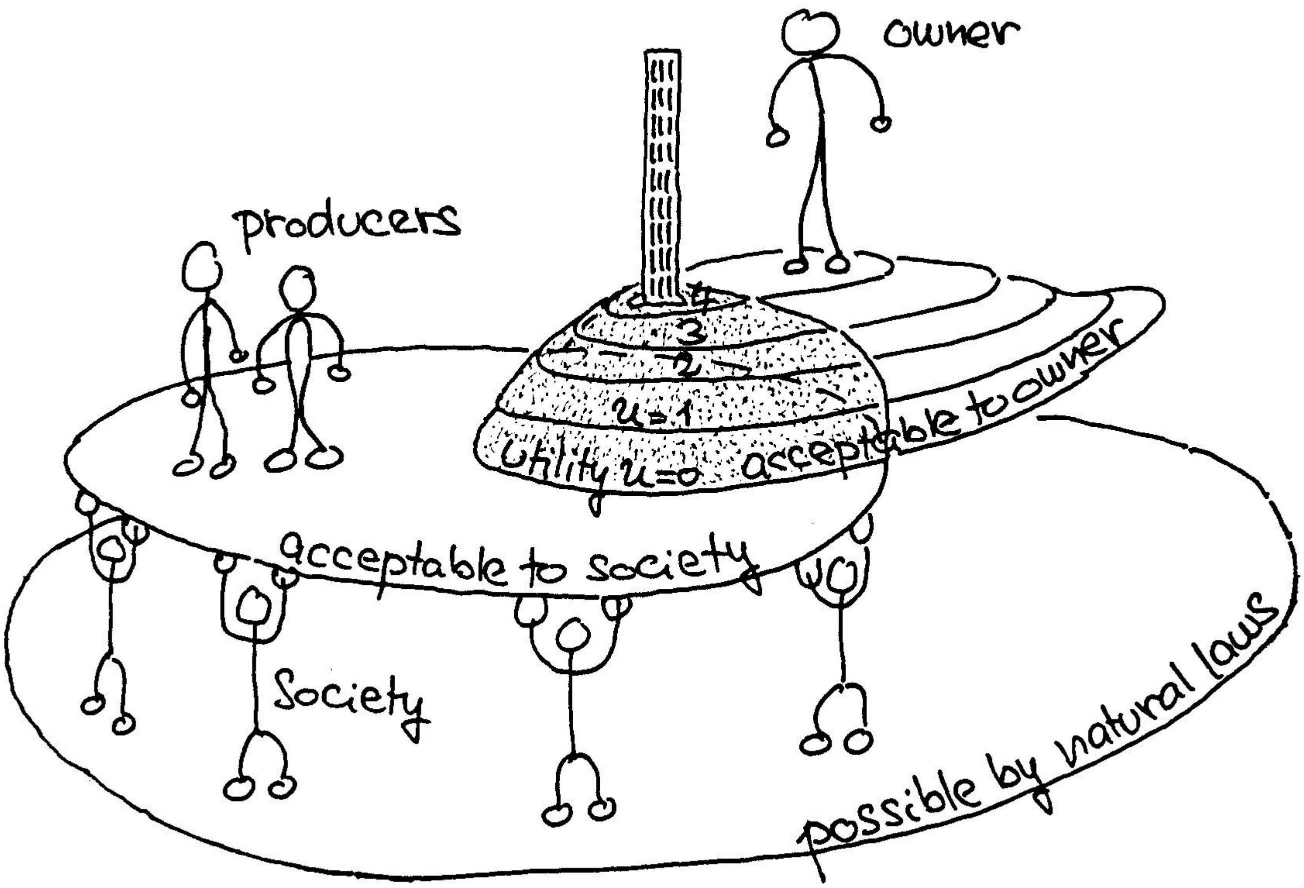

Fig. 4: The owner's game

On the other hand, strategies against human errors are primarily an issue to the producers (engineers, contractors). As such, they should be studied and implemented in the specific context of the producer's optimal conduct of his own business - in analogy to the owner, the producer has an admissible set of operational procedures, and he will choose from them in search of maximum utility to him - his 'quality' is linked to profit and success in a competitive environment. Whether those goals are always best served "by a systematic adherence to written instructions" is certainly an open question. One should keep in mind that bureaucracies, too, tend to optimize for themselves.

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Evaluation of Experience

Leçons à tirer des expériences passées

Auswertung von Erfahrung

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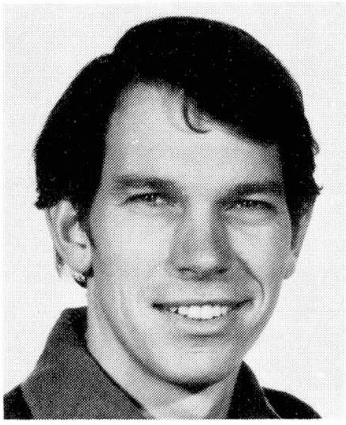

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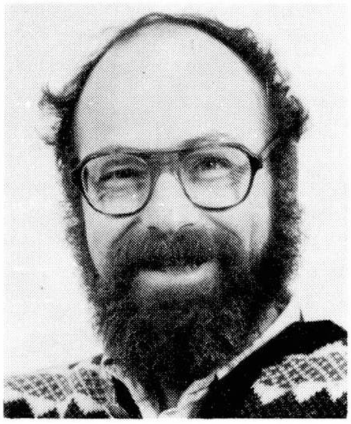

SUMMARY
This Introductory Note summarizes the experience gained from the study of structural failures and satisfactory construction and comments on the accuracy and completeness of reporting. Comparison is made of the findings of a number of investigators according to type of failure mode, structural elements affected, time of failure, prime causes of failure, reasons for their occurrence and their consequential cost. Most failures can be shown to occur because of gross human errors. The nature of these errors is discussed and the requirements for the evalutation of experience in the future is considered.

RESUME
L'article résume l'expérience acquise dans l'étude d'accidents structuraux par rapport à des comportements corrects. Des commentaires sont faits sur la précision et la méthodique des études. Divers aspects sont traités, sur la base de travaux de plusieurs chercheurs, tels que mode de rupture, éléments structuraux concernés, date de la rupture, causes premières et conséquences financières. Il apparaît que la plupart des accidents sont dus à une grossière erreur humaine. La nature de ces erreurs est passée en revue et les conditions requises pour tenir compte de ces expériences à l'avenir sont évoquées.

ZUSAMMENFASSUNG
Der Beitrag fasst die Erfahrungen zusammen, die aus Erfolg und Misserfolg im Bauwesen gezogen werden können und äussert sich zur Genauigkeit und Vollständigkeit entsprechender Berichte. Die Berichte einiger Autoren werden in bezug auf Versagensart, betroffene Bauwerkskomponenten, Zeitpunkt, Hauptursachen und deren Wurzeln sowie bezüglich Schadenkosten miteinander verglichen. Es zeigt sich, dass die meisten Schäden auf grobe Fehler zurückzuführen sind. Die Art dieser Fehler sowie die Anforderungen an eine geeignete Auswertung von Erfahrungen werden diskutiert.

1. INTRODUCTION

It is well known that as children we learned from our experiences; probably learning more quickly from our mistakes than from our victories but nevertheless learning. However, we did not all learn the same lessons. What we learned depended on our childhood environment and the prevailing level of technological achievement in that environment. Thus, today, many children have the opportunity to experience different cultures and environments as a result of the ease long-distance travel; whilst others learn how to operate and use micro-computers. In contrast, few children today learn at an early age that fire is dangerous and hot - central heating took care of that.

Just as in childhood the lessons learned from interaction with one's environment depend on that environment, so in engineering the lessons we as practising engineers learn from interacting with day-to-day engineering and with other engineers depend very largely on the environment in which we find ourselves. It is therefore relevant to ask some questions about what it is that we learn from our (collective) experiences, how relevant that experimental learning is to modern engineering and how such experimental learning can be best attained. It is to questions such as these that this introductory note is addressed.

In what follows, we shall attempt to review the types of past experience from which engineers have typicaly made evaluations, to review how such evaluations have been made, and to consider the validity or otherwise of the conclusions that have been drawn. We shall use these findings to make some suggestions concerning the Quality and Safety of Structures and the implications for Quality Assurance matters. In so doing we shall touch on the importance of human error and measures to reduce it, and consider organizational matters briefly. These topics will be taken up more fully in later Introductory Reports. Finally we propose a number of matters for consideration for future evaluations of engineering experience. Not only should we learn from past experience, but we should learn from past attempts at the evaluation of experience.

Summaries of a number of case histories of structural failures are given in an Appendix. These are not for consideration in their own right, but are intended as examples of circumstances which can arise in practice, and against which quality assurance measures must be designed to be effective.

2. PAST EXPERIENCE

2.1 General Remarks

It is readily evident that past experience comes in a continuum; the vast majority of experience is middle-of-the-road, mainly good, positive experience, generally reinforcing the status quo of accepted theory and practice, with minor excursions into problem areas. Seldom are major problems encountered; but when such negative experience does occur it seems to be largely in the form of individual events - there rarely appears to be much warning of a build-up to the problem experienced. Examples here include (i) Ronan Point, where problems of connectivity under blast loadings were not obvious before the event; (ii) Quebec Bridge, buckling of curved members; (iii) Westgate Bridge (and others at about the same time) with stiffened-plate buckling problems.

When thinking of these examples, it must be remembered that the interpretations noted are rather subjective, and are a function of the time at which the events occurred. The interpretation of experience will be considered in more detail in the next section.

It is important to note that both positive and negative reinforcement is required to defined experience properly; merely knowing that a particular technique has worked in the past under certain circumstances does not help very much in extrapolating to a new situation. Negative reinforcement, that is, also knowing when something did not work, can be extremely useful is setting bounds [1].

Unlike data gathered in a scientifically controlled experiment, the "data" represented by a continuum of experience, both "good" and "bad", is seldom truly comparable. The circumstances surrounding each structure are generally unique; whether this be in a contractual sense, a political sense, an industrial relations sense or an economic one. Similarly, the design concept and its realisation in design and construction is often quite different even for nominally similar structures. Hence, in no sense can one imagine that a structure is a sample from a real homogeneous population, but rather it is a special case of generically similar, but not identical structures. Comparison between such structures therefore requires rather more care than might otherwise be the case. Nevertheless, various attempts have been made to use the behaviour of structures as raw statistical data for rather formalised evaluation of structural performance. Such evaluations have generally focussed on "bad" experience, while unformalized, unstructured evaluation is the norm for evaluation of "good" experience.

2.2 Evaluation of past experience

As noted, the formalization of past structural engineering experience of a positive nature (good or satisfactory experiences) takes place in a relatively informal way. The successful completion and operation of a structure is the expected norm, at least in relatively modern times, and hence informal surveys by individuals or organizations of structures similar to that which is being proposed is usually taken to be an adequate procedure. This may be supplemented by formal reports of successful construction and operation, such as published in learned institution journals. Some aspects of the experience so gained may ultimately find its way into codes of good practice and text books, and so become available to future engineers.

The formalization of structural engineering experience of a negative nature (bad experience) takes place in a greater range of ways. The more important of these are summarised in Table 1 together with an estimate of the reliability of the evaluation and the possible effect of the results on the engineering profession. Except for the last item, the methods employed are arranged in order of increasing frequency, and also, incidentally in approximately the order of decreasing reliability of information on which evaluations are based. Probably the most outstanding misfit is that of newspaper reports - a rather unreliable source of information.

In all the methods of evaluating experience, the results of the evaluation must reflect the quality of the data used and the biases affecting the evaluations, conscious or otherwise. For this reason, it is to be expected that a formal enquiry, such as a Royal Commission, will yield a much more precisely detailed and qualified evaluation than would be expected from a more limited enquiry. However, such formal enquiries are usually only instituted in the case of grave accidents, where it is also politically expedient to do so. It is not unlikely, therefore, that evaluations based on such formal enquiries, while admirable in themselves, also introduce bias into attempts to obtain more generally based evaluations [2]. A simple example is that serviceability-type problems are extremely under-represented in formal enquiries, in "in-house" reports and newspaper reports, and even in technical papers, but constitute a considerable proportion, if not the major part, of negative experiences in structural engineering, as assessed by individual and generally unreported observations.

Several attempts have been made to improve the collection, and hence the possibility for evaluation of past experience. Probably the more ambitious of these is the EPIC (Information Centre on Structural Performance) program, which is meant to function as a system of university-based data banks. More than 100 case summaries have been used to test the system and many cases are in the process of being prepared for computer processing. A similar system has been proposed within the CEB.

Some early accounts of failure of modern engineering structures include Thompson's description of American Railway bridges [3], Lossier's study of concrete structures [4] and Pugsley's description of bridge failures [5]. Rather more systematic accounts have been published since then [6-14], including the well-known study by Matousek and Schneider [9] and the first results from a BRE/CIRIA survey [14]. Data from these studies will be used in the next section to review the principal findings.

3. OBSERVATIONS FROM PAST EXPERIENCE

3.1 Modes of Failure

It is not possible, within the confines of the present report, to present an exhaustive overview of the many observations which have been made as a result of analysing past experience. What can be done, however, is to present some selected material, with a view to indicating trends. It will also become evident in so doing that there are considerable differences in the data that have been presented and that this complicates simple analyses. But analyses of the present type must rely on diverse points of view in order to avoid the real possibility that observation in obscured by preconceived ideas.

Table 2 shows a simple breakdown of the types of failure observed by various analysts. Although agreement is quite astonishing, it is felt that "serviceability" type failures are distinctly under-represented in these statistics (see above) [14].

There is also some evidence [14] to suggest that isolated failure events and progressive failures are about equal in number (Table 5) and that for ultimate strength failure modes (Table 4) rupture of the critical section, with or without formation of a mechanism, predominates. Curiously the British BRE/CIRIA [14] study found that instability problems accounted for 20-30% of cases, yet the European (Matousek & Schneider) [9] study found this mode to be negligible, with loss of equilibrium being an important factor. This type of inconsistency may well reflect classification difficulties rather than being the result of regional structural engineering practices; there appears at present no other relevant data.

For serviceability failure, the figures shown in Table 3 must be taken as a rough guide only since categorization here differs considerably between the studies reported. Some further interpretation has been done to arrive at Table 3. Nevertheless, it is clear that cracking in concrete structures, and excessive deformation generally are the most severe problems encountered.

The types of structural elements for which failures have been reported depend, of course, on the type and form of construction. An overview is given in Table 6. It should be noted that there are significant differences in the columns of figures, with the European study [9] listing many combined cases, and excluding foundation failures. The figures should not, therefore, be compared horizontally. If foundation problems are excluded, it is seen that slabs and walls are the elements most commonly involved in failure with beams and columns about half as often. The reasons for this rather suprising observation are not clear from the available data. In view of the high inherent safety (due to redundancy) and and overload capacity of 2-way slabs, one might expect that they would not figure large in failures. Review of Allen's [11] list of errors in concrete structures (in Canada) suggest that construction errors feature at least as often as design errors. Slabs-in-ground are included in his figures and some slabs might, therefore, be considered under the foundation category.

The results for the time of occurrence of failure, given in Table 7 show some inconsistencies between data sources. The European study [9], which consisted of 52% office buildings, and less than 12% bridges, suggests that on aggregate of those structures that fail about 60% fail during construction, with a gradual reduction of failures with time after construction. These results are not significantly changed by isolating office buildings, but differ somewhat from the British study [14], which has rather fewer (31%) of buildings failing during construction, and another 30+% within 5 years of completion. This latter breakdown agrees better with the European figures [9] for factories alone. The greater failure rate for factories during service life is, of course, to be expected, since factories are more likely to be exposed to unforeseen loadings and misuse than office buildings.

If bridges are considered, the inconsistency in statistics is even greater. It is commonly held that because of the low live load/dead load ratio for bridges, the selfweight of the bridge provides a certain amount of proof loading, so that failure during construction should be relatively high. This accords with the small samples (75) of bridges in the European study (c. 70% failure during construction) but is in stark contrast to that report by Smith [8], who has only 16% failure during construction. Part of the reason for this difference is that Smith's study reports that about 50% of failures were caused by flooding (see Table 8). This included two cases of floods in which nearly one-third of his total sample failed. If these cases of simple bridges are removed, his figures fall more closely in line with the others.

3.2 Causes of Failure

The various reports on the reasons for structural failure are not easy to compare directly although the messages contained in the reports are much the same, even if not always spelt out. Smith's summary [8] of prime causes (Table 8) has already been mentioned. The British study [14] again lists prime causes (Table 9). "Inadequate appreciation of loading conditions or real behaviour of structures" stands out as the major problem area, with "grossly inadequate execution of erection procedure" as next in importance. Somewhat similar conclusions were reached in the European study [9], as is shown in Table 10, which lists the types of errors, assessed by the study group, to have been committed in the cases studied. This represents an attempt to move from prime causes to underlying causes, although it is self-evident that such a progression cannot be bounded. Nevertheless, it shows that human error is a principal problem and that "insufficient knowledge" together with "under-estimation, neglect, error and ignorance, thoughtlessness and negligence" constitute by far the most important components. The European study [9] went into considerable detail about the further breakdown of the figures in Table 10; however, this need not be of concern here. What is of interest here, and for the later Introductory Reports, is the estimation of how effective additional control measures in the building process might be in order to discover errors (Table 11). Although these results are subjective, they do have a certain commonality with the results from the ACI survey [12] (which includes the results of Allen's Canadian study [11]) and which indicate that of the errors which were detected, a significant proportion were detected by succeeding people in the design-construction sequence. It is also of interest in this context to note that in the British study [14], it was found that in about 50% of cases studied, it was felt that the "absence of a person with authority" or lack of an effective "project leader" was a major factor contributing to structural failure. Such a person would offer not only leadership but control as well. A related finding is given by Bentley [15] in his assessment of building site quality control.

3.3 Costs of Failure

The data on the costs involved in structural failure are not particularly compatible. Table 12 shows estimated total economic costs of failure relative to original costs; it is clear that generally this is about 10% with only very occasional greater costs. The European study [9] has a lot of data on cost, injuries and fatalities. However, it does not appear possible to present this information in the form of Table 12. It can be derived that in the majority of cases (>90%) there are no deaths or injuries, and that for about 95% of failures the failure costs are less than 5% of original construction costs.

4. IMPLICATIONS FOR QUALITY ASSURANCE

The collected data and evaluations of the previous section lead to a number of topical conclusions. These are of interest in themselves. More generally, however, some overall implications can be drawn from the data and a number of tentative conclusions about their importance for quality assurance can be made. These will now be discussed.

4.1 Relationship between Reliability Theory and Quality Assurance

If it is accepted that the above data are reasonably representative, although probably biased towards major accidents rather than serviceability problems, it is reasonable to conclude that the majority of failures occur because of unexpected combinations of circumstances, and because of gross numerical or conceptual errors in the processes of design and construction. Failures rarely occur (in modes for which the structure has been designed) because of the chance combination of "low strengths" and "high loads"; but this is to be expected, since the deterministic design codes used in most countries have sufficiently high safety factors (or partial coefficients) to ensure that both the theoretical failure probabilities and the actual relative frequencies experienced in practice (in these modes) are extremely small.

Structural reliability theory has been used to a significant extent in the development of deterministic structural codes e.g. [16] and in the rationalization of partial coefficients (partial safety factors), and it should therefore be questioned whether these applications are meaningful if most failures occur as a result of circumstances which are not normally considered in any formal analysis.

Studies have shown, however, (e.g. see chapter 13 of [17]) that in many cases, the choice of partial coefficients, which in effect govern the amounts of materials used in a structure, can be made independently of the choice of the measures adopted, and the resources spent on, checking for the occurrence of gross (human) errors. Some other work in this direction by Allen [18] suggests a trade-off between control procedures and notional reliability. This has long been an accepted approach to the design of structures such as cranes under fatigue loading.

4.2 The Importance of Gross Human Errors

From the early, rather intuitive work of Pugsley, it was already evident that various aspects of human errors had played an important part in the occurrence of a number of quite spectacular engineering failures. Objective backing for this thesis has been provided by the work of Matousek and Schneider [9], Allen [11], Sibly and Walker [13], Walker [14] and others, and it is not generally accepted that gross human error plays a critical part in the malperformance or failure of structures. Similar conclusions [19] have been reached in other industries.

The term gross human error is used here as a substitute for the terms "human error" and "gross error" often found in the literature on this subject. The two latter terms are not entirely appropriate; "human error" because all errors are directly or indirectly caused by defective human behaviour, and "gross errors" because this implies that the errors are necessarily very large. By gross human error we mean an error of concept, of calculation, of design, of construction, or of maintenance which gives rise to a gross misunderstanding of how a structure will behave at some or all stages of its life, or how it would behave under hypothetical loads of different magnitudes.

However, although the acceptance of these ideas has been rapid and widespread, and despite the studies mentioned above, it is reasonable to conclude that there is still not very much objective information about the nature of gross human errors and their occurrence. A number of relevant questions are as follows:
(a) What percentage of errors committed in design and construction actually lead to failure of the structure (however failure is defined)?
(b) What percentage of errors are not detected and are built into the structure as a consequence? What effect does this have on the structure?
(c) What percentage of errors which are detected are then satisfactorily corrected?

Answers to questions such as these are essential if procedures to control gross human errors are to be established in the rational way; several suggestions for such procedures have been made [20-23]. However, all suffer from lack of data in defining critical parameters. Although this matter is discussed in more detail in Introductory Reports 4 and 5, it is worth noting here that although it has been suggested [22] that (i) education, (ii) personnel selection, (iii) task complexity reduction, (iv) quality control procedures, and (v) the legal framework, are all important in reducing human error, not all are equally effective. In fact, it is not unreasonable to state that there is virtually no objective data on the effectiveness of any of these activities or procedures, since, apart from the status quo in each country, there is an almost total lack of experience in changing any parameter.

About the only recent experience which exists is that relating to human error and control measures, as reflected in the Matousek-Schneider [9] study. This showed that lack of control can lead to structural failure, but the converse, that greater control reduced the incidence of failure, is not so easily deduced. For that type of evidence, one has to look back to the reasons for the introduction of material quality control, for the reasons for requiring design checking, etc. Interestingly, the motivation in each case can be found in ensuring a level of protection for society, rather than for individual designers or contractors or clients (c.f. Melchers [24]).

Similarly, the necessity for education, and in particular, continuing education, of engineers is usually accepted without question. In view of the studies by Sibly and Walker [13] for example, this is wholly reasonable. However, our experience does not yet lead us to be able to suggest how the continuing education of engineers might best be achieved in terms of obtaining more reliable structures. Greater emphasis on, or skill in, say, engineering mathematics may be quite counter-productive in this setting.

Finally, the experiences summarized in the previous section make little reference to quality assurance techniques in other industries, perhaps with different levels of technology. It is inconceivable that the human error problems in structural engineering are unique and further comparisons of experience in different industries in the future are almost certain to be of value.

4.3 Organizational Effects

The importance of the organizational structure of a project is recognized as an important parameter in quality assurance of structures (c.f. Introductory Reports No. 1 and 5). However, it is equally true that there have been only very preliminary efforts to evaluate experience in this area (c.f. Melchers [25]).

Matters of importance for quality assurance in an organizational framework include the contractual and actual relationships between organizations, the managerial competence and managerial aspirations of each organization as well as professional jealousies, personalities and pride. Other matters of importance may include industrial relations matters and the availability of proprietary technologies to individual organizations.

To complicate matters, any investigation of organizational effects must take into account national systems of contract and legal liability. This may well invalidate comparisons between countries with Anglo-Saxon based legal systems and those with other systems.

4.4 Unimaginables

It is often suggested that ultimately the quality assurance of structures is hampered by co-called "unimaginables", events or oversights leading to disastrous consequences which cannot be imagined beforehand. Such events may include a previusly unforeseen loading condition, or an unrecognized mode of structural behaviour. There certainly appears to be evidence to support such a notion (e.g. Tay Bridge - wind loading; Tacoma Narrows Bridge - wind oscillations...). However, closer examination of cases such as these has revealed that in nearly all circumstances there were known antecedents for the observed loading or behaviour (e.g. Sibly & Walker [13]). Unfortunately, such antecedents were not always recognized by the designers, or were consciously set aside as being of insignificant importance. The available evidence suggests very strongly that so-called "unimaginables" constitute a negligible proportion of all structural failures. Hence, it would appear reasonable to ignore them in the first instance as factors in quality assurance considerations.

4.5 Costs of Structural Failure

Despite considerable preoccupation by structural engineers with the safety of their structures, it is evident from the figures now available that very few structures fail in an ultimate strength sense and that more, but still relatively few, show serviceability failures. It is tempting, therefore, to suggest that fear of failure for structural engineers is not so much based on monetary loss as on loss of prestige and livelihood, and that a case might be advanced that the profession is already achieving a sufficiently low level of structural damage cost taken in aggregate, without needing to be unduly worried about matters such as human error. Alternatively, the balance between quality control procedures and statistical variability could be altered so as to lower traditional safety factors and recover the concomitant increase in rsk of failure through increased control of structural quality (i.e. human error related problems). Techniques for developing such a new balance are becoming available (e.g. Allen [18]); the desirability of such a stance should be a matter for considerable discussion in the profession.

5. FUTURE EXPERIENCE EVALUATION

The evaluation of future experience, may be considered to consist of two parts: that of evaluating the experience itself and that concerned with assessment of the evaluation techniques. Both of these matters ought to be given attention by the profession.

Up to the present time, little attention has been given to the differences that are almost certain to exist between failure rates and types of failure in structures and structural components associated with different levels of technology. Benefits could be gained by studying past experience, both now and in the future according the level of technology. Three levels would probably be sufficient:

- high level technology e.g. nuclear plants
- medium level technology, e.g. bridges, offshore structures, important buildings, etc.

- low level technology, e.g. small structures, domestic housing, etc.

In the past, there have been different levels of control applied to each technology and we now need to know its separate effectiveness.

In addition to the above and the various detailed matters raised in this report, the additional requirements for future experience evaluations seem to be as follows:

(a) determination of appropriate procedures for analysing structural failures, whether this be at ultimate load level or at service load level; the EPIC program is one possible approach, reruns of studies of the type conducted by Matousek and Schneider is another. However, other approaches may exist and ought to be examined;

(b) determination of appropriate procedures for drawing together structural failure analyses such that soundly based conclusions can be derived; the present report is in part one such effort. However, a formalized procedure might be more appropriate once a regular flow of information is available;

(c) procedures for minimizing the influences of national legal systems and local legal constraints on the study of structural failures;

(d) similarly, procedures to isolate organizational differences in projects involving structural failure, and hence attempting to make various cases comparable;

(e) procedures which will allow the effectiveness or otherwise of particular quality assurance schemes to be objectively assessed; thus, for example, allowing the effectiveness of the French 10-year legal liability scheme for buildings, as is being studied for introduction into the U.K., to be objectively assessed against conventional U.K. procedures; and

(f) development of appropriate feedback systems and trend warnings mechanisms such that the profession can get sufficient and timely warning of unfavourable trends in structural engineering practice or theory.

Of the greatest importance, however, is the need for a means of assessing the effectiveness of changes in control on both the design and construction processes on the occurrence of gross human errors of the various types.

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APPENDIX: CASE HISTORIES

This appendix includes the summaries of four case histories of structural failures. Full details are not given but further information can be obtained from references [26-29]. The purpose of these summaries is to give examples of circumstances which can arise in practice and against which quality assurance measures must be designed to be effective. The case histories are of failures which have occurred in recent years and involve a variety of consequences, some simple and some complex.

A.1 Falsework collapse, Chicago, U.S.A. - April, 1982 [26]

On 15 April 1982, two spans of a partially completed post-tensioned concrete bridge, being constructed at Riley Road interchange in East Chicago, collapsed during the casting of the deck, killing 13 men. The bridge was of in situ pre-stressed concrete box-girder construction and was to an alternative design put forward by the contractor.

At the time of failure, three of the spans had been completed and post-tensioned, and the bottom and sides of the box-girder for the fourth span has been cast. Until the completion of the post-tensioning operations in each span, virtually all the loads (both permanent and temporary) were supported by the temporary falsework consisting of pairs of isolated high-capacity shoring towers close to the permanent concrete piers and at 1/3 points in each of the 54.9 m spans.

The failure occurred during the casting of the deck slab for the fourth span when about 100 m length of the partly finished bridge and its supporting false-work collapsed. On investigation it was found that the falsework as built was substantially different in several vital details from that envisaged in the design. The collapse was probably triggered by the excessive settlement of one of the temporary foundation pads of one of the shoring towers at the 1/3 span position. This caused an increase in the reactions provided by the other pads which were under-designed and thus cracked. The differential settlement of the foundations caused an estimated increase in the loads in the diagonal bracing members of the tower to about 40 kN which was grossly in excess of the average value of about 28 kN for the buckling strength of the tubes, determined from later tests. This partial tower failure induced a slight sway at the top of the tower causing the main cross-members supporting the bridge to be eccentrically loaded. The welds holding these in place fractured and one cross-beam fell away imposing an eccentric load on the tower which then buckled and collapsed, precipitating collapse of the two partially-completed spans.

On subsequent investigation it was found that:

- the temporary foundations pads for the towers had been constructed on top of about 3 m of compacted fill, but this overlay 300-600 mm deep pockets of highly compressible black organic silt.
- the temporary foundation pads were only 300 mm thick, whereas ACI Standard 318 would have required a thickenss of at least 530 mm.
- the external guys originally designed to prevent sway of the falsework towers had been replaced by internal X-braced cables.
- the main cross-beams at the top of the towers were initially eccentrically loaded because wedges had been omitted.
- some cracks in the foundation pads had been noted by the site surveyor a few days before the collapse, but their significance had not been appreciated.

A.2 Walkway collapse, Kansas City, U.S.A. - July 1981 [27]

On 17 July 1981, two suspended walkways in the Hyatt Regency Hotel, Kansas City, collapsed without warning killing 13 people and injuring 186 others attending a dance. The two walkways which collapsed were two of three which spanned the hotel foyer and linked the hotel's newly opened guest block to its convention centre. At the time of the collapse about 60 couples were dancing on the second floor walkway, about 40 on the one at the fourth floor level, and others in the foyer below. Each spanning 40 m, the 2.2 m wide steel/concrete composite walkways were hung from the ceiling by three pairs of 30 mm diameter asbestos clad suspension rods. The two walkways which collapsed (those at the second and fourth floor levels) were vertically above each other and were hung from the same suspension rods. The third floor walkway which did not collapse was suspended independently and to one side of the others.

Each walkway comprised a steel frame resembling a horizontal ladder with 460 mm x 305 mm longitudinal I beams and 200 mm x 100 mm cross beams at 2.5 m intervals, supporting a 75 mm thick concrete deck laid on permanent steel shuttering. At the three suspension positions on each walkway, the designer had provided a transverse box beam fabricated from two channels welded toe-to-toe. The suspension rods passed through holes drilled close to the ends of each box beam and the loads from the walkways were transmitted to the rods by the provision of washers and nuts threaded onto the rods.

It had been deduced that failure was initiated at mid-span on the fourth floor walkway by the suspension rods and nut pulling up through the box beam. The load it had been carrying was immediately redistributed to the five remaining suspension points which were then overloaded and failed in rapid succession.

On investigation it was found that the walkways had not been fabricated as originally designed. In particular, the suspension rods were made discontinuous at the fourth floor level instead of running continuously from the roof to the second floor. This changes meant that the loads from the second floor walkway were transmitted to the fourth floor walkway, effectively doubling the load at the fourth floor connections. Laboratory tests, however, showed that the connections were capable of withstanding only 27% of load which they should have been able to carry with the modified arrangement of suspension rods. Thus failure would have occurred at loads far less than the design loads, even if the walkways had been fabricated as originally designed. Other points of relevance are:

- the walkways' self weights were found to exceed the nominal self weight by about 8%.
- an estimated 63 people were on the walkways at the time of failure but the dynamic contribution to the loading was considered to be small.
- the connection failure mode was ductile involving upward rotation of the bottom flanges of the channel members of the box beams and extensive local yielding in the webs; nevertheless the overall failure was rapid with negligible warning.
- severe local yielding was found at the suspension points of the walkway which did not collapse.

A.3. Complete collapse of apartment block, Cocoa Beach, Florida, U.S.A. [28]

On 27 March 1981, a five-storey apartment block collapsed to the ground in Cocoa Beach, Florida killing 11 workers and injuring 23 others, during the casting of the roof slab. The building was a five-storey flat-plate concrete structure supported on 254 mm x 457 mm internal columns and 254 mm x 305 mm columns at each end of the 75 m long building. Many of the columns were left standing after the collapse indicating that the 203 mm thick slabs failed in punching shear around the columns. The vertical stacking of the slabs indicated that no sidesway occurred.

It was concluded that the collapse was intiated by the punching shear failure of the slab at an internal column, on the fifth floor. This propagated to other slab/column connections on the fifth floor which then fell, causing failure of all the floors below.

The low punching shear capacity at the slab/column connections was the result of two factors:

- the punching shear requirements of ACI Standard 318 which would have controlled the slab thickness were not considered in the design of the building. This was the code applicable under the local building regulations. In consequence the slabs were 76 mm less thick than they should have been (203 mm instead of 279 mm).
- the two-way top reinforcement in the slabs in the column strips was placed (or ended up) about 25 mm lower on average than specified in the drawings. This reduced the effective depth and the corresponding punching shear capacity of the slabs.

It is considered that both errors contributed about equally in bringing about the collapse and if either had not been made, the failure would probably not have occurred.

A.4 Partial collapse of Kongresshalle, Berlin - May 1980 [29]

In May 1980, a large section of the prestressed shell roof of the Kongresshalle in West Berlin collapsed 23 years after completion. Although the building was crowded at the time only one man was killed. The roof which was elliptical in plan, failed between its inner ring beam and the southern arch edge beam.

Although the structure was designed and built in accordance with standards which applied at the time, a number of faults were discovered which in combination led to the failure:

- the structure was sensitive to the action of extreme temperatures which led to large cyclic displacements and weakening of the concrete and prestressing steel.
- due to cracking of the concrete, the tendon stresses had in places increased by up to 100%, and so increased the risks of stress corrosion.
- eight prestressing tendons at the junction between the roof and the ring beam had not been grouted over a 200 mm length and had been misplaced by about 20 mm in position.
- bad detailing at the roof's junction with the ring beam aided the access of rainwater to the unprotected tendons. The decomposition of the water led to hydrogen embrittlement of the high strength steel.
- chlorides in the grout and zinc paint on the tendons hastened the above effects.
- the nature of the structure was such that even regular inspection of the hall would probably not have led to a prediction of the impending collapse.

Prime Source	Evaluators	Estimated Reliability of Evaluation	Effect on Profession
Formal Reports (e.g. Royal Commission)	Engineers & Lawyers	very high	high
"In-house" Reports not published widely) (e.g. for insurance purposes)	Engineers	high	medium
Newspaper reports	Non-engineers	unreliable	very low
Individual observation (Formally reported)	Engineer/ non-engineer	medium	medium
Individual observation (Not formally reported)	Engineers	medium	sporadic uneven
Formalized Data Banks (e.g. EPIC program)	Engineers (with non-engineers	medium-high	very low as yet, potentially high

Table 1 Evaluation of Negative Past Experience

Type of Failure	%	%	%
Collapse	25	63 (Ultimate: Collapse + Loss of Safety)	20
(Ultimate)			
Loss of Safety (distress)	35		40
Loss of Serviceability	40*	37	40
References	[14]	[9]	[11]**

* considered to be under-represented
** concrete structures only

Table 2 Type of Failure

Failure Mode	%	%	%
Excessive deformation	26	52	30
Cracking	50	38	60
Local Damage (Clearance, gap holes)	7	5	5
Oscillation & Vibration	15	-	-
Water Penetration, Deterioration	2	5	5
References	[14]	[11]+	[9]*

\+ concrete structures only (small sample)
* approximate values

Table 3 Serviceability Failure Modes

Failure Mode	Sudden Collapse %	Ductile Collapse %	%
Loss of equilibrium	18	10	-
Instability	1	30	20
Rupture & Mechanism	42	15	-
Rupture (no collapse)	15	45	80
Other	24	-	-
References	[9]	[14]	[14]

Table 4 Ultimate Failure Modes

Failure Mode	Ultimate %	Serviceability %
Isolated Failure	42	53
Progressive Collapse	40	40
Load Shedding	18	7
References	[14]	[14]

Table 5 Isolated and Progressive Failure Modes

Types of Element	%	%	%
Foundations	16	-	7
Columns	7	}	}
		3	14
Slender Strut	<1	}	}
Wall	16	10	17
Bracing	1	-	-
Other	4	-	-
Beams	4	}	}
		8	12
Roof Beams	7	}	}
Trusses	6	-	-
Seating	5	-	}
			15
Brackets	4	<1	}
Flat Slabs	1	}	}
		17	27
Other Slabs	8	}	}
Arches	2	6	-
Other	8	54++	6
References	[14]*	[9]	[11]**

* Buildings Only - (derived)   ** Concrete Structures only
++ include combinations

Table 6 Types of Failed Structural Elements

Building Phase	%	%	%	%	%	%
Preparations Foundations			4	6	4	8
Substructure	31	16	16 (69)	3 (57)	1 (37)	7 (58)
Superstructure			48	39	28	37
During handover			2	9	3	6
Year 1-2		5	5	13	10	11
	32					
Year 3-5			0	4	11	4
After year 5			9	11	24	12
	37					
Year 1 →∞		79	16	11	17	12
During demolition or renovation	-		1	3	1	3
References	[14]*	[8]**	[9]**	[9]+	[9]¶	[9]

* Buildings only
** Bridges only
\+ Office Buildings only
¶ Factories only

Table 7 Time of Failure

Cause of Failure	%
Inadequate or unsuitable temporary works or erection procedures	8
Inadequate design in permanent material	3
Unsuitable or defective permanent material or workmanship	15
Wind	3
Earthquake	8
Flood and foundation movement	49
Fatigue	3
Corrosion	1
Overload or accident	10

Table 8 Prime Causes (Bridges) [8]

PRIME CAUSES OF WHICH SAFETY AND SERVICEABILITY DESIGN FACTORS DO NOT RELATE (Gross errors which could be reduced by checking and supervision)	Weighted %
Grossly inadequate appreciation of loading conditions or real behaviour of structure	36
Grossly inadequate appreciation of loading conditions or real behaviour of connections	7
Grossly excessive reliance on construction accuracy	2
Serious mistakes in calculations or drawings	7
Grossly inadequate information in contract documents and instruction	4
Gross contravention of requirements of contract documents and instructions	9
Grossly inadequate execution of erection procedure	13
Gross, but unforeseeable, misuse, abuse and/or sabotage, natural catastrophe, deterioration	7
Others	5
Subtotal	90
PRIME CAUSES TO WHICH SAFETY AND SERVICEABILITY DESIGN FACTORS DO RELATE (Stochastic variations which, singly, should not lead to failure but of which a combination of two or more may form an unfavourable situation leading to failure)	
Unfavourable load variation or combination (foreseeable, relating to γ_{S1} γ_{S2})	0
Inaccuracies in design assumptions of support conditions hinges etc., neglect or environmental effects (relating to γ_{S3})	3
Deficiencies in materials (γ_{m1}-related)	1
Deficiencies in workmanship (γ_{m2}-related)	3
Unforeseen, but foreseeable deterioration	3
Others	0
Subtotal	10

Table 9 Prime Causes [14]

Type of Error	% in the 212 cases with engineer involved	% in the 261 cases with contractor involved
Insufficient knowledge	36	14
Unclear definitions of competencies, error in information path	1	3
Reliance on others	9	5
Choice of poor quality for economical reasons	1	2
Underestimation of influence	16	11
Neglect, error	13	4
Ignorance, thoughtlessness, negligence	14	54
Objectively unknown situations	7	3
Other reasons	3	4

Table 10 Causes [9]

Possibilities of discovery	
Discovery probable with additional checking in phase of:	
Planning	33
Construction	17
Occupation	5
Discovery impossible	13
Discovery probable without any additional checking	32

Table 11 Possiblity of Error Discovery [9]

Economic Consequences as Percentage of Original Cost	Collapse (%)	Loss of Safety or Serviceability (%)
0 - 10%	48	60
11 - 20%	2	8
21 - 30%	8	8
31 - 40%	2	-
41 - 50%	8	4
51 - 100%	8	13
101 - 150%	8	4
151 - 500%	12	3
501 - 1000%	4	-
Total	100	100

Table 12 Cost of Failure [14]

Data Control, Supervision and Checking

Contrôle et supervision

Kontrolle und Überwachung

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SUMMARY
Means and methods of control are different at the various stages of the building process. Several parties are involved in the quality control, e.g. designers, producers of components, contractors, clients and owners as well as users of buildings and authorities. The control should as far as possible be related to the production process. An interaction between self-control by the producer and supervision by an independent body is normally suitable in order to establish adequate control procedures. An important part of the control is to minimize the risks of gross errors.

RESUME
Les moyens et méthodes de contrôle varient au cours des différentes phases de la construction. Plusieurs partis sont impliqués dans le contrôle de la qualité, tels que les projeteurs, les producteurs d'éléments de construction, les entrepreneurs, les clients, les propriétaires et utilisateurs des bâtiments, et les autorités. Le contrôle devrait autant que possible être en rapport avec le procédé de production. Une action réciproque entre le contrôle par le fabricant lui-même et la surveillance par un organisme indépendant convient normalement pour atteindre un niveau de contrôle suffisant. Un des objectifs du contrôle est de réduire les risques d'erreurs graves.

ZUSAMMENFASSUNG
Mittel und Methoden der Kontrolle wechseln in den verschiedenen Phasen des Bauprozesses. Mehrere Parteien sind an der Qualitätskontrolle beteiligt, z.B. Konstrukteure, Hersteller von Bauteilen, Bauunternehmer, Bauherr, Besitzer und Benützer von Gebäuden sowie auch Behörden. Die Kontrolle soll so gut als möglich mit dem Bauprozess verbunden sein. Die Wechselwirkung zwischen Eigenkontrolle des Herstellers und Überwachung durch eine unabhängige Organisation führt normalerweise zu zweckmässigen Kontrollprozessen. Eine wichtige Aufgabe der Kontrolle ist die Reduktion des Risikos von schweren Fehlern.

1. PHASES AND OBJECTS

1.1 Introduction

For the user of a building it is evident that the quality of the finished building is of vital importance. Several properties of a building can in some way be determined when the building is finished, for example the air quality and the sound level. Also the safety of a structure can, of course, be tested when the building is finished - this mode of procedure is in fact often applied as a final check of bridges, before they are opened for traffic. But all important aspects on the quality can not be determined in such a simple way at the final stage, for example the durability of a concrete structure.

In most countries the authorities endeavour nowadays to give quantitative requirements in the building regulations. As far as it is practical the requirements are related to the completed product and connected to verification methods. Also the client or builder as well as the future owner of the building are usually more interested in the ultimate functions of the building than in the details of the structure or the methods of producing the building.

There are, however, several reasons to check the quality step by step during the entire building process including the design of components and the structural framework etc. and the manufacturing of materials and components as well as the management and maintenance of the building in use. It is very important to define adequate control steps and to use economical control methods.

1.2 Stages in the building process

The building process starts with the planning and design of the building, based on the requirements of the client (owner) and the authorities. This phase of the process will result in drawings and descriptions which constitute the quality of the building as well as the costs.

Before the construction of the building can start, the client must normally apply for and be granted a building permit by a building authority. Building products aimed for general use are to-day often produced industrially in long runs. In several countries such products can be type approved in relation to requirements in the building regulations by a central body vested with the necessary authority. One condition in the type approval certificate is normally that the approved product shall be tested and inspected according to a programme for quality assurance or a control programme. Prefabricated products whose properties are specified in regulations or standards, e.g. cement, reinforcing steel and structural timber, can directly be subject to production control.

The design documents, including possible type approval certificates, form the base for the construction stage in the building process. Depending on several circumstances, e.g. the type and the complexity of the building, sub-stages may be defined in order to find out strategical opportunities for testing and inspection. The control steps ("check-points") should be chosen with regard to inter alia the possibility of verifying requirements in the regulations or in the contract. Consideration may also be taken to the prerequisites for correcting possible mistakes. Such control steps should also be laid down at points where responsibility is transferred from one party to another.

When the construction work is finished and the building accepted, the entity of the building is a fact. According to instructions the use of the building and later on the maintenance can start. But there still remain some check-points in relation to the responsibility of the producer and the guarantee given by him.

1.3 Conclusions

Summing up, the quality of a building can be considered and determined with respect to various objects in the course of the following different phases:

a) Design process

- Specifications, calculations, drawings and descriptions for 1) materials and prefabricated components and 2) the structure to be erected at the building site.

b) Production of materials and components.

c) Erection at the building site.

d) Use.

Means and methods applied in order to control the quality at these four phases of the creation and entity of a building are quite different with respect to the objects of the control. For this reason the problems regarding the control means and methods must be delt with in various ways.

2. MEANS AND METHODS

2.1 Requirements and control

There is generally an interaction between requirements and control. Fundamentally the requirements, concerning for example properties of materials, are based on what is necessary in order that the structure shall serve its purpose. The aim of the control is to verify that the requirements are fulfilled. In certain cases, however, it is not possible to verify, in an operative way, that the requirements are fulfilled. That is, for example, the case if a requirement concerns durability and if it is formulated in a general way which implies that a structure shall be durable for a specified time. In these cases the requirements have to be changed to some substitutes which can be verified by means of control. For the example above the requirement on durability has to be changed to a requirement concerning the composition of the material or something similar. Thus, it is not always easy to find out if requirement or control is primary in reality. They are, however, almost always closely connected and at least formally the requirement is primary.

2.2 Design

The control of the design can be divided into the following phases:

- checking the assumptions for the design
- checking the design calculations
- checking that drawings and other documents are in accordance with the calculations
- checking that the structure, as shown in the drawings, is in accordance with regulations and good practice.

The control concerning the calculations (the three first items above) can be made in different ways. One way is just to follow the designers´calculations and check that they are correct. Another way is to make a new calculation (simplified) and to compare the results. These two ways can be regarded as extremes, many procedures between them are possible. A disadvantage with the first way is the fact that the person who makes the checking will be more or less guided by the designer and the risk of overlooking an error is not so small. A disadvantage with the other way is the fact that the method is laborious and that it is difficult to find the reason, if there is a disagreement.

Special problems occur in those cases when the design calculations are made with the aid of a computer, as it is not easy to follow computer calculations. In the near future, however, they will be the dominating methods for calculations. For this reason the computer program should include the control aspects in order that it shall be possible to control the calculations. The program ought to be made so that they account for part results with relatively small intervals which makes it easier to follow and to check the calculations. The program should also have special control moments included, for example comparison with results from calculations made in a different way.

For prefabricated products for general use in different buildings it is often justified to execute the calculations very carefully and to prepare the drawings with the utmost exactitude. As a consequence the checking of the calculations and the drawings can be done rather rationally.

2.3 Production of materials and components

In this section that case is treated when materials and components are produced in a factory separated from the building site. Particularly for type approved products, manufactured industrially in long runs, it is convenient to control the products according to a programme for quality assurance. The control system may in that case be very flexible depending on inter alia the complexity of the product and the production process.

One of the main questions is what should be controlled: the production process or the completed products. It is, of course, important that the internal control (self-control) includes the production process in order to steer the process. As regards those who shall use the products for a structure it is in principle most important to control directly the properties of the completed products. According to section 2.1, however, it is not always possible to control a required property of the products. Then it could be necessary, as a substitute, to control the basic material for the production, the production process or something else.

Another question is if the control of the completed products should be made in the factory at the end of the production process or if it should be made when the products have been delivered at the building site. In most cases it is advantageous to execute the control at the factory as an internal control (compare section 4.3). Then one will obtain a continuous control of relatively uniform products which gives the best information about the quality. If the control is mainly executed at the building site, it has often a disturbing influence on the erection process and therefore it is sometimes regarded as something that is negative. The most ideal would be that the control of material and components at the building site only consist of checking that the right products have been delivered and that they have been controlled and approved at the factory.

A system for production control of prefabricated products based on self-control by the producer is normally connected with inspection and spot checks by an external body. It is of interest to study the relation between the self-control and the supervision in order to establish an adequate quality control system.

2.4 Erection at the building site

If the properties of materials and components are controlled at the factory according to the discussion in section 2.3, the control at the building site can be concentrated on the erection problems, i.e.

- that the materials and components are placed in the right place
- that the connections are properly made
- that the measures of the structure are correct within given tolerance limits

- that the components have not been damaged during the erection.

This control implies that the structure must be checked continuously during the erection. It is not possible to execute the control for the completed structure only.

The control mainly consists of visual inspections, measurements and perhaps testing of non-destructive material (to verify that the material properties have not changed during transport and erection). The results of the control shall be recorded.

The erection at the building site is probably that stage of the building process, when there is the greatest risk for the occurrence of gross errors. Therefore the control at this stage is extremely important.

2.5 Use

The control during use may concern

- the way the structure is used, for example the loads it is subjected to
- the condition of the structure with regard to its load bearing function.

The possibilities of control during the use of a structure differ very much from one structure to another depending on, among other things, if the structure is easily accessible for inspection or not. There is also a difference from one country to another with regard to legal rules.

There are many questions concerning control during the use, for example the following:

- should there be legal requirements for the owner to make periodical inspections of the structure (or to engage an expert to make them) and to report the results to some authority?
- should there be a legal right for some authority to make periodical inspections of a structure?
- are there any possibilities of using automatic systems in order to indicate the need of maintenance, repair or substitution?

3. PARTIES - OBLIGATIONS AND WAYS OF ACTING

3.1 Parties involved

There are many parties involved in the building process and the management of a building. Responsibilities and duties of the different parties in relation to contracts and legislation are delt with in session 3. In this section some questions and problems regarding the tasks and obligations of the parties involved in quality control systems should be discussed.

Normally, the control is carried out as a consequence of an agreement (a contract), based on civil law and in accordance with public law and mandatory regulations. It is of interest to discuss in which way the different parties involved may co-operate and co-ordinate their efforts in order to rationalize the control procedures and to reduce the control costs.

Based on the contract and the relevant regulations, adequate measures and routines can be compiled in a programme for quality assurance in order to secure the proper quality of a building. In such a programme the different parties involved in the quality control procedure should be settled and their obligations should be defined. In this connexion several problems can be discussed. How far in detail should such a programme be precised? The relation between persons engaged in the prefabrication of materials and components on one side and persons at the building site? The role of the designer? Separate from the quality assurance programme - or perhaps included in it - there is also a need to define the obligation and the right of "third party persons", e.g.consultants and building inspectors.

3.2 Ways of acting

The parties involved in a private agreement (according to civil law) are on one hand the person, who orders the erection of a building (the client) - usually also the future owner - and on the other hand consultants, contractors, suppliers of components, credit grantors and insurance companies as well as tenants or other "users" of the building.

When an agreement is at hand concerning the conditions of delivery of a certain achievement or product, such as design or erection of a building, the receiver of the "supply" normally arranges some kind of control by a person or body engaged and paid by the client (external control). According to the agreement the "supplier" can often be imposed to check or to test the "delivery" by means of internal control (self control).

Several building components - composed of several materials or parts - are produced at factories, which are subject to some kind of production control. In which way and how far should the producer of such components arrange for control of delivered products?

Public laws usually affect, in the first place, the relation between the client (the future owner) and the proper authorities. Also designers, contractors and producers of components can sometimes be subject to some kind of public supervision. Is it reasonable to require that e.g. designers are authorized? And by whom? Is it more appropriate to judge the result of a designer - by means of self control, spot checks (or other measures) - instead of forming an opinion of a person´s skill?

The control, executed by the authorities, always implies to be impartial and according to public law. The extent of this control varies in view of several factors. It is often presupposed that self control, specified in advance, shall take place and be documented (see section 4). The supervision by the authorities can under such circumstances be rather restricted - how far? Which measures and steps may be taken in order to establish a fruitful interaction between self control, involved as far as possible in the production process, and supervision by impartial control bodies?

The parties involved in the use, management and maintenance of a building are in the first place the owner and the user. Also the authorities have normally to some extent a legal right to inspect the building, but the responsibility to keep the building safe rests exclusively with the owner (see 2.5). A question to discuss is: which obligations should the designer have to prepare instructions for periodical inspections and maintenance of the structure?

3.3 Parties involved in international co-operation

From the point of view of international trade it is of great value if the quality control procedures, applied by national approval and control bodies in the country of manufacture, can in some way be accepted by the corresponding bodies in the country of destination. Even if the requirements in the regulations are not yet harmonized, barriers to trade will be reduced, if national control bodies co-operate in order to avoid duplication of testing and inspection.

Several international governmental and non-governmental organizations are more or less involved in negotiations and studies aimed at international harmonization of approval and control systems and mutual recognition of test results. Basic rules of general nature are given in the GATT Agreement on Technical Barriers to Trade, in force since 1 January 1980. Furthermore, the Working Party on Building within the United Nations Economic Commission for Europe (ECE) has stressed the need of co-operation between national approval and control bodies. ILAC (International Laboratory Accreditation Conference) has paid considerable attention to problems regarding international recognition of test results. Other organizations, such as RILEM, CIB, CEB, ECCS and ISO, are involved in the preparation of unified test methods.

However, an operative action programme is still lacking for an international system for approval and quality control of building products. It may therefore be discussed which steps should be taken in order to facilitate the introduction of products from one country into another.

Lack of harmonization of approval and control rules is not the only barrier to trade. The difficulty in obtaining immediate and clear information about the specific rules and systems in a foreign country often causes considerable problems for a producer, who tries to market his product in a country with a different pattern of approval and control. Which bodies and organizations are suitable and ready to provide for such information?

4. EXTENT, EFFECTIVENESS AND COSTS

4.1 Does control always lead to better results?

The presence of control has an influence on the work which is subject to the control. This may occur in different ways. The following two possibilities are to be regarded as extreme cases.

One of these possibilities means that the person doing the work may think in the following way, if there is no control: "No one but me will look at this and therefore I had better watch the result of the work to make sure that it is well done". If there is a control, he may think: "Someone else will look at this work and will find out if anything is wrong so therefore I can leave it as it is". If this corresponds to reality, it is better to have no control at all than to have a badly functioning control.

The other possibility means that the person, doing his job, thinks in the following way, if there is a control: "I know that someone will look at this and therefore, if I shall not be blamed, I had better to do a good work". If there is no control, the thinking may be: "I know that nobody will look at this and therefore my work is not so important and a great care is unnecessary".

The question is: Does control have a favourable effect on the quality of a work whether the control is efficient or not or is an unefficient control even worse than no control?

4.2 Do several control steps always give better results?

It is a common opinion that a control consisting of several independant control steps, for example internal control, control by an independant consultant and control by authorities, is favourable with regard to the quality of the project. This is probably true, if the different control steps are really independent of each other in a statistical sense. However, in principle the same points of view that were given in section 4.1 could be applied here, if control is regarded as a work included in the total process. This means that each one of the persons, executing control, is aware of the fact that there are other persons entrusted with control tasks. Perhaps each one of them trusts the efficiency of the others to such an extent that he considers his own part of the control as unimportant, uninteresting and unnecessary. Thus, in the worst case the total effect of several control steps could be less than the effect of a control, concentrated to one step and one person.

4.3 Internal control, external control or a combination?

If one intends to concentrate the control mainly to one of the organizations which take part in the building process, the question arises which is the most efficient control, internal control or external control. The internal control is executed by persons from the same organization which has the responsibility for the performance of the work, which can be design, production of material or components or erection at the building site. The external control can be executed by persons from the client's organization, by an independant consultant or by the authority.

The external control has the advantage of being less dependent on such factors as the conditions of the work, the actual working situation, the economic result of the work etc. The external control is generally considered as more neutral than the internal control.

The internal control has the advantage of being executed by persons who often have a great knowledge of the character of the work, which is subject to the control, and who are aware of what kind of problems that can be expected.

A possible way to obtain the advantages of both the internal and external control could be to combine them. This could be done in such a way that the work is directly subject to an internal control which benefits by the knowledge of the persons executing the control. The external control is mainly directed to an evaluation and a judgement of the efficiency of the internal control. Thus, the tasks of the persons executing the external control are different from the tasks of those who execute the internal control, i.e. they do not control the same things which may be an advatnage (compare section 4.2).

4.4 Should the control be directed to reach an acceptable quality level or to discover gross errors?

In most cases collapses and other severe failures of load bearing structures seem to be caused by some kind of gross error. That does not mean that the general quality level is of minor importance. If the quality level becomes too low - however, not so low that this is to be regarded as a consequence of a gross error - the consequences are often unsatisfactory behaviour during normal use, unsufficient durability and abnormal costs for maintenance. It is therefore important to direct the control to reach an acceptable quality level as well as to discover gross errors.

However, these two aims can generally not be reached by the same control methods. It is often convenient, and in most cases sufficient, to use random checking for the control of the general quality level. The gross errors, however, are relatively rare and therefore it is generally not possible to discover them by a random checking. The checking ought to be almost total. On the other hand, in this case, it is not necessary that the results of the checking are very accurate, in most cases it is sufficient with just an estimation.

What is said above does not mean that control shall always have two different aims. Gross errors occur with a relatively small probability. In those cases when a failure causes mainly economic losses, it is often more economic to accept a probability of failure, which is of a similar order as the probability of the occurrence of a severe gross error, than to arrange an extensive control. Thus, a control directed to discover gross errors is necessary in those cases mainly when a failure has very severe consequences including loss of human lives.

4.5 Should the objects which shall be controlled be chosen randomly or according to a control program

In many cases it is not possible or justifiable from an economic point of view to let the control include all parts and all details of a structure, especially if the control contains measuring and testing. Thus, a choice has to be made in some way. This choice can be made by the person who executes the control and according to his judgement or according to some random method. The objects which shall be controlled may also be chosen according to a control program drawn up beforehand and based, for example, on points of view given by the designer.

There are many advantages of a control program. A program makes it possible to balance the control efforts for the different objects against each other in a reasonable way. It also makes it possible to direct the control activities to the most important and sensitive parts of the structure, for which an error could lead to severe consequences (compare section 4.4). Thus, for given control resources, a control program may contribute to improve the result of the control.

A control program has also some disadvantages. If the objects which shall be controlled are specified in a program, the consequence will be that also the objects which shall not be controlled can to some extent be regarded as specified. According to the discussion in section 4.1 this may in some cases lead to an undesirable differentiation of the quality level between the structural parts.

4.6 Economic aspects

What is written in sections 4.1 to 4.5 is more or less valid for the whole process consisting of design, production of material or components, erection at the building site and use. The control activities should be regarded as part of this process and the costs of control as part of the costs for the building. As for the other parts of the costs, the costs of control should give some gain which may ideally be expressed in economic terms. This gain could, for example, consist of increased quality, less maintenance, smaller consumption of materials etc.

To some extent control and other measures, taken for the purpose of increasing the quality, are interchangeable. The relation between the amount of control and the amount of other measures should ideally be determined by an economic optimization. However, this is possible only if there is a sufficient knowledge about the effect (expressed by means of some numbers) of different control activities. To-day the existing knowledge about these matters is unsufficient and therefore it is only possible to make formal optimizations using, for example, formal relations between the number of tests and the degree of utilization of the strength of a material.

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Planning for Quality — Concepts and Numerical Tools

Planification de la qualité — Concepts et méthodes numériques

Qualitätsplanung — Konzepte und numerische Methoden

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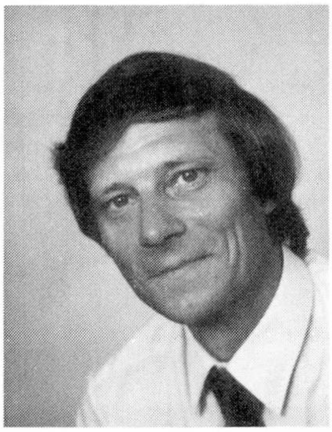

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SUMMARY
Planning for quality plays an important part in quality assurance of buildings. Yet, it has been to a large extent a rather pragmatic subject since no formal feasible tools to arrive at optimal solutions were available. In the paper an attempt is made to structure the problem and model its ingredients, particularly the occurence and detection of human errors throughout the building process.

RESUME
La planification de la qualité joue un rôle important dans l'assurance de la qualité des constructions. Cependant, le sujet est souvent traité de façon assez pragmatique, puisque des méthodes formelles et pratiques en vue d'une solution optimum ne sont pas à disposition. Dans ce travail, on a essayé de structurer le problème et de quantifier ses composantes, surtout l'existence et la découverte des erreurs humaines dans le processus de construction.

ZUSAMMENFASSUNG
Qualitätsplanung spielt eine wichtige Rolle bei der Qualitätssicherung von Bauwerken. Sie läuft vielfach jedoch ziemlich pragmatisch ab, da keine formalen, praktikablen Methoden für optimale Lösungen zur Verfügung stehen. In der Arbeit wurde versucht, das Problem zu strukturieren und die Einzelheiten zu modellieren, insbesondere das Auftreten und Entdecken von menschlichen Fehlern während des Bauprozesses.

1. INTRODUCTION

The most ambitious definition of *quality* of a technical facility is that it is at its optimum utility to its user possibly under external constraints with respect to the probability of reaching certain adverse high consequence states. A fairly modest interpretation of *quality assurance* is assurance, in the sense of documentation, that a given set of pre-selected specifications has been met by pre-defined compliance rules with a reasonable degree of confidence. In the following we shall adhere to the first view on a definition of quality with all its consequences for its assurance. If utility is measured in monetary terms (in what else?) quality assurance, therefore, should optimally balance costs and benefits or at least minimize costs. These may include costs for pre-investigations and siting studies, for design, construction and their control, for inspection and maintenance during use resp. for non-possible use during repair, possibly for demolition and removal after the anticipated time of use or when the structure becomes obsolete but, most important, for failures of the system in their different forms. From experience it appears essential that the whole life-cycle of a constructed facility is covered. Planning for quality thus is not only the assessment of the various means to achieve quality, the organization of the verification of the various measures, the creation of an appropriate professional, psychological and financial climate and a reasonable time-schedule; it is also the optimal allocation of the available resources in the various quality relevant measures. Accordingly, the subject of "Planning for Quality" might be split into two areas.

I. the phenomenological description of the ingredients of quality assurance in the wide sense

II. the mathematical formulation and numerical solution of aims, tools and bases of quality assurance for sound decision-making.

Yet, at least for the building sector, only a few studies are available in both areas.

Practice of quality assurance appears to be widely based on intuition and speculation and only occasionally as in the control of the production of materials on more or less carefully assembled and evaluated experience. General systematic approaches apparently do not exist. Perhaps most revealing, the subject but particularly planning for quality is hardly teachable at present. This is what the author wishes to make clear before attempting to elaborate on a few aspects selected out of a much larger group of elements constituting the overall problem.

2. BASIC STRUCTURING OF THE PROBLEM

Once the "infra-structure" of quality assurance for a given job is known and settled the remaining steps are to assess the logical structure of the overall system and, then, allocate the efforts in the most optimal way. It is to be underlined that the first qualitative and the second quantitative step are highly interactive. The second step results in decisions about the final setting of the specific quality assurance measures which then may be up-dated during the course of the work.

In order to get hold of the problem the concept of *hazard scenarios* is introduced (1). This concept is not the only one possible and, in fact, appears unfit for certain complex problems.

It is used here merely to demonstrate the potential of a discrete consideration. A *hazard scenario* will be understood as a more or less complex "scenario" of events one or a few of which play the role of defining it but also guide its probabilistic formulation. Such leading events could, for example, be a critical construction phase, the structure under normal service conditions, extreme values of one or several types of external or internal actions upon the structure with due consideration of the other simultaneously acting forces, the presence of abnormal environmental conditions as, for example, clay lenses in the soil, but also the existence of one or more types of errors, flaws or omissions during planning, design, construction, use and, possibly, demolition of the structural facility. Because a definition of what is an error, blunder, flaw, omission or just negligence has many facettes and appears hardly clear cut we will assume it undirected and avoidable under the circumstances, i.e. with due regard to the type and amount of skill and effort appropriate for the work. What is important for our purpose is that this understanding of a hazard scenario as effective upon a structure can be displayed in terms of the well-known event - or fault (failure) trees and, thus, also allows for straight - forward mathematical treatment and numerical manipulations. It is a discrete representation of reality in most cases but might be as such the only one feasible for numerical treatment. We shall call the set of hazard scenarios complete if it contains the scenarios which are reasonably imaginable. "Unimaginables" are not and principally cannot be handled. Conversely, not considering a relevant scenario during planning and design may already be interpreted as an error. We shall not discuss this case further but it will be clear from the following how to deal with it.

Formally, failure of the system due to failure in any of the hazard scenarios is failure of a series system, i.e. a system fails once any of its links fails or it fails in any of the scenarios considered. Let the index r count the number of hazard scenarios for which the leading event is an human error. Also, index with s the hazard scenarios with other leading events. Then, the failure probability with F_n denoting the failure event of the n-th scenario

$$P_f = P\,(\bigcup_{\{N\}} F_n) \leq \sum_{\{N\}} P\,(F_n) \tag{1}$$

in which the union operation runs over all subsets $\{N\} \subset \{0,1,...,s,...,S,0,1,...r,...,R\}$. For convenience, let s=r=0 denote the case of some normal service condition and no error existing. Damage statistics indicate that it is generally important to consider hazard scenarios where the leading event is a combination of events. Although the occurence event of such a combined event may be associated with much smaller probabilities than any single event the probability of structural failure given their joint occurence can be large and, therefore, the contribution to eq. (1) can also be large. The upper probability bound in eq. (1) is exact, if the events F_n are or are made disjoint. In the contrary case one may wish to improve it. Such an improvement will be given later on.

Fortunately, the failure event F_n associated with the n-th hazard scenario can be broken down further because these events appear to have a similar structure in almost all cases. In fact, for system failure we now have the intersection of various events. The first of those events is the occurence event. The last event clearly is failure of the structural system. In between these events the failure of some protective apparatus usually is placed. For system failure all these failure events must take place. In other words, they form a parallel system. For example, assume that a certain design error occurs. Then the events necessary for system failure are {(Occurence of the error <u>and</u> non-detection during some checking <u>and</u> structural failure) <u>or</u> (Occurence of the error <u>and</u> detection <u>and</u> non-correction of error <u>and</u> structural failure)}. We have:

$$F_n = \{O_n \cap \bar{D}_n \cap V_n\} \cup \{O_n \cap D_n \cap \bar{R}_n \cap V_n\} \tag{2}$$

with an obvious short-hand notation. "$\cap$" stands for an "and"-connection (intersection) whereas "$\cup$" denotes an "or"-connection (union of events).

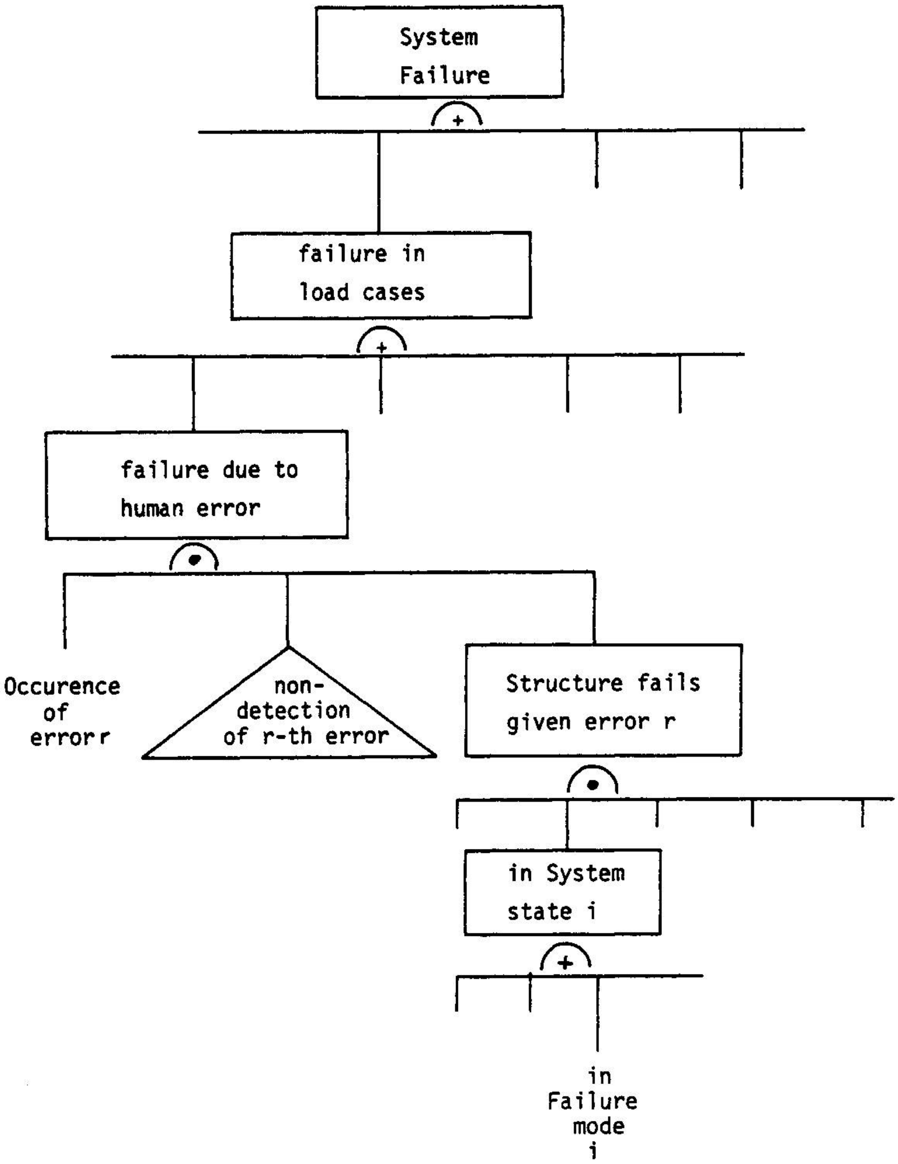

Figure 1: Fault (failure) tree of overall system

Both the detection event and the structural failure event given the error can be split down further. For the moment this is done here only for the structural system which typically can be modelled by a tie set of failure events (series systems in parallel) where in the subsequent formula the failure modes in any redundant system state are indexed by j while the system states are indexed by i.

$$V_n = \bigcap_i \bigcup_j V_{n,\, ij} \tag{3}$$

If, for simplicity, we neglect the second event in the union of eq. (2), eq. (1) can be written after insertion of eq. (3) as:

$$P_f = P\,(\bigcup_{\{N\}} (O_n \cap \bar{D}_n \cap (\bigcap_i \bigcup_j V_{n,ij}\,)))$$

$$\leq \sum_{\{N\}} P\,(\,O_n \cap \bar{D}_n \cap (\bigcap_i \bigcup_j V_{n,ij}\,)) \tag{4}$$

in which the inequality does not only hold with respect to the upper bound approximation already introduced in eq. (1) but also since the redundant system states i usually are limited to a few interesting ones and hence, its failure probability is overestimated. This "system" is represented by its fault tree in figure 1. The corresponding block diagram is easily constructed from the fault tree. Very much the same structure of a fault tree is obtained for exceptional loading situations. As an example take the hazard of a ship colliding with a bridge pier. In this case the protective element could be either ship-owned devices to prevent the ship veering out of course or a jetty securing the piles. Those protective elements if fulfilling their intended function can be used to diminish the occurence probability or at least the magnitude of the loads.

Similarly, the investigation of the logical structure of the overall system could have been done by the use of event-tree methodology, if one considers all sets in {N} as "initiating" events which ultimately could lead to failure. For both types of analysis the formal reduction to minimal cut sets of failure events facilitates their numerical evaluation (see [2] for a suitable algorithm).

3. COMPUTATION OF FAILURE PROBABILITIES

We now turn to the determination of the probabilities in eq. (4). Due to interesting developments in so-called first-order reliability methods in the very past, the computational part is no more a serious problem and further developments are expected both with respect to simplifications and advanced numerical techniques. The idea of first-order reliability methods is surprisingly simple and will be scetched for the computation of the failure probability of a structural component. Let $V = \{g\,(\underline{X}\,,\underline{\pi}) \leq 0\}$ define the failure domain of a component in the space of uncertainty variables $\underline{X}=(X_1,\ldots,X_n)^T$ such as strength of materials, loads, geometrical dimensions or (randomized) agreed-upon prediction errors of the physical model in use. π is a vector of parameters collecting, for example, structural dimensions, material grades or certain parameters describing the effort of quality assurance measures. For convenience of notation it is dropped in the sequel. Transform the vector $\underline{X}$ into an independent standard normal vector $\underline{U}$ such that $P\,(g\,(\underline{X}) \leq 0) = P\,(g(\underline{U}) \leq 0)$ [3]. If the failure surface $G \equiv g\,(\underline{U}) = 0$ is linearized by a plane whose normal vector is pointing to the coordinate origin and fits the surface in a point closest to the origin (or, alternatively where the multinormal density $\varphi_n(\underline{u})$ obtains its maximum on G), the failure probability is

$$P_f \approx \Phi(-\beta) \tag{5}$$

where β (=safety index) is this distance of the most likely failure point (β-point) to the origin and Φ the univariate standard normal integral. This estimate can be further improved and be made asymptotically correct, if the curvatures of G in the β-point are taken into account. [4,5]

If, on the other hand, the probability of a parallel system with m components is to be computed one has [6]:

$$P_{f,p} \approx \Phi_m(-\underline{\beta}; \underline{\underline{R}}) \tag{6}$$

where Φ_m is the m-variate normal distribution function, $\underline{\beta}$ the vector of componental safety indices and

$$\underline{\underline{R}} = \{\rho_{ij}\} = \{\underline{\alpha}_i^T \underline{\alpha}_j\}$$

the matrix of correlation coefficients between the componental state variables with $\underline{\alpha}_i$ the vector of direction cosines of the i-th approximating hyperplane.
If the system is given as a cut set of failure events which always can be achieved by appropriate set operations we have [6,7]:

$$P_f = P(\cup\cap F_{ij})$$
$$\begin{cases} \leq P_1 + \sum_{i=2}^{n} \left(P_i - \max_{j<i} \{P_{ij}\} \right) \\ \geq P_1 + \sum_{i=2}^{n} \left(\max\left\{0, P_i - \sum_{j<i} P_{ij}\right\} \right) \end{cases} \tag{7}$$

with $P_i = \Phi_{n_i}(-\underline{\beta}_i; \underline{\underline{R}}_i)$ and $P_{ij} = \Phi_{n_i + n_j}(-\underline{\beta}_i; -\underline{\beta}_j; \underline{\underline{R}}_{ij})$

In this case, $\underline{\underline{R}}_{ij}$ collects the correlation coefficients between any two components i and j of the parallel systems.
The crucial question in applying this methodology to the general system formulation as expressed in eq. (1) is to model both the occurence event and the detection event appropriately and particularly such that dependencies among the different redundant failure events are properly taken into account. Remember that the trivial bounds for redundant systems, i.e. the lower bound as the product of the individual probabilities and the upper bound as the smallest componental probability are almost useless for our purpose. The upper bound ignores any redundancy. The lower bound dramatically overestimates the effect of redundancy in most cases.

4. EFFECT OF "NORMAL" QUALITY ASSURANCE MEASURES

The spectrum of quality assurance measures is too wide to be exhaustively considered herein. Therefore, a few examples of frequent quality assurance measure may suffice to demonstrate how to model their effect on component or system probabilities with emphasis to cases which have been considered by the author elsewhere. For the moment, we exclude those measures aiming at error detection and removal. These will be dealt with in the next section.

The remaining measures include, for example, previous investigations to update usually relatively diffuse prior information on uncertain quantities such as loads or strength of materials or to identify and locate anomalies, normal quality procedures and, perhaps, some type of proof-testing. And, of course, the selection of safety elements in normal design procedures belongs to this category. Specifically, the parameter vector π may include partial safety factors $\underline{\gamma} = (\gamma_1,\dots,\gamma_q)$ which, given the loads, define the safety margin between loads resp. load-effects and the resistances. Formally, this can be written as

$$P_f = P\,(g(\underline{X};\ \underline{\gamma},\ \underline{d}) \leq 0) \qquad (8)$$

$\underline{d}$ is a vector of design parameters such that the design failure probability achieves a certain prescribed value, i.e.

$$P_{f,t} = P\,(g(\underline{X};\ \underline{x}^*,\ \underline{d}) \leq 0) \qquad (9)$$

in which according to [8]

$$x_i^* = \gamma_i\ x_{iN} \qquad (10)$$

with x_{iN} some nominal value of X_i. P_f generally is increasing (decreasing) for decreasing (increasing) γ_i's.

The majority of the other quality assurance measures modifies the stochastic nature of one or more uncertain variables. For example, let the variable X, e.g. a climatical load, have density f_X but depend on a parameter (mean yearly maximum) λ which varies from location to location. Prior to any specific inestigation the predictive density of X is

$$f_X\,(x) = \int_{\lambda} f_X\,(x|\lambda) f'_\Lambda\,(\lambda)\,d\lambda \qquad (11)$$

where f'_Λ is the prior distribution on the uncertain parameter. Most likely, the nominal value specified in loading codes is defined in this distribution as a certain fractile. However, a near-by weather station can provide specific local data and via Bayes rule, the posterior density of λ given the observations $\underline{z} = (z_1,\dots,z_n)$ is

$$f''\,(\lambda|\underline{z}) \propto l\,(\underline{z}|\lambda)\ f'\,(\lambda) \qquad (12)$$

where $l(z|\lambda)$ is the likelihood of z given λ. Many special but useful results for eq. (12) resp. (11) can be found in the books on Bayesian statistics. With increasing effort parameter, here the sample size n, one can narrow down the variability of X to its natural local uncertainty.

If active control measures are specified for the production of materials, this "natural" uncertainty arising from the unavoidable variations in the raw materials and in the manufacturing process itself can be substantially diminished. As a first example, take a production process whose outcome is modelled as an (autocorrelated) random sequence. If the process is observed at any k-th value at which it is adjusted to the target, it is clear that the variability of the production outcome is smaller than for the uncontrolled case and decreases for decreasing k. Generalisations and modifications of this simple scheme are the subject of the rich theory of (stochastic) control where many useful results can be found.

As another example consider the inspection of flaws in welding of length L. Flaw occurence can be modelled by a Poisson process. The residual strength at the location of a flaw is X with distribution $F_X(x)$. It depends on the flaw size in a certain manner. Hence, if the distribution of flaw size is known so is that of X and for known stresses in the flaws the failure probability of the weld-line. Assume a certain inspection method. The probability of flaw detection increases with flaw-size, e.g. according to $P(D|X \leq x) = F_D(x)$. It follows that after inspection the flaw size distribution is

$$F_{X,D}(x) = F_X(x) \frac{\bar{F}_D(x)}{\int \bar{F}_D(x)dx} \qquad (13)$$

and the occurence rate of flaws is reduced from ν to $\nu\,(1-\int \bar{F}_D(x)dx)$ (see figure 2). The arguments are very similar if the material to be used is selected by continuous grading (see [9]) and also with respect to the effect of normal compliance control [10]. In particular, let the qualities offered be described by a vector of distribution parameters Θ whose prior (before compliance control) distribution is $f''(\Theta)$ and assume a certain compliance rule, i.e. acceptance for $z_n \in A$ where A is the acceptance region and z_n some function of the control sample. Then, the posterior distribution of $\underline{\Theta}$ is given by

$$f''(\underline{\Theta}) = \frac{L(\underline{\Theta})\, f'(\underline{\Theta})}{L(\underline{\Theta})\, f'(\underline{\Theta})d\underline{\Theta}} \qquad (14)$$

reflecting the filtering effect of such activities. L is the acceptance probability given $\underline{\Theta}$. Clearly, the amount of filtering depends on the type of acceptance criterion and the sample size.
In some cases, prototype or proof-testing may be chosen. If prototype testing serves to collect specific information the mathematical scheme for the description of its effects is exactly the same as for the previous investigations mentioned before. For proof-testing, one has to distinguish whether its purpose is to truncate the distribution of resistances [11] (e.g. when setting and prestressing earth anchors with overloading) or whether its purpose is similar to prototype testing with or without the up-dating of design and/or construction strategies. Some further interesting results may be found in [12] and [13].
There is no reason here to extend the list of examples of models for the effect of "normal" quality assurance measures. What was to be shown is the general concept which with few exceptions relies heavily on Bayes' theorem. Depending on the specific problem at hand one or the other or some joint measures can be most

appropriate. All of the foregoing formulations fit into the general framework set out in section 2 and are numerically amenable with the aid of the reliability methods scetched in section 3. The situation is somewhat different if human errors have to be considered.

5. SOME ERROR OCCURENCE AND DETECTION MODELS

It is useful to distinguish between at least three different types of errors depending on the effect they would have

i. Inadequate physical model: Suppose there is a "correct" or generally agreed physical model for the problem at hand and a corresponding failure surface $g_o(\underline{X})=0$ can be formulated. Any other model, denoted by $g_r(\underline{X})=0$, r=1,2,..., may be considered as an error yielding a different (conditional) failure probability (see figure 3). Such errors include typical design errors such as an incorrect idealization of the structural model (first-order linear elastic versus second-order linear elastic-plastic analysis), computational errors, ignorance of three-dimensional effects in structural behaviour, etc. In a certain sense, it also includes the omission of significant load scenarios.

ii. Inadequate uncertainty model: This primarily results in a wrong dimension of the uncertainty vector $\underline{X}$, i.e. certain structural parameters are mistakenly assumed deterministic or known but are uncertain and, therefore would need some precautions. Note that this type of error almost always results in a greater failure probability.

iii. Misclassification error: This error type comprises pure misclassification errors, for example, when classifying soils and, in misclassifying, using wrong (prior) information about one or several important properties. It also includes misspecification (misreading) of material grades and the like or simply delivery of a false grade (see figure 4).

Clearly, there are other types of errors, for example the omission of a regular protective device when designing the facility, the failure to inspect and maintain, or inadequate use of the structure. Although some of them may fall into the categories just mentioned with respect to their formal treatment, others might require further thoughts but will not considered herein.

In some cases it is possible to model the occurence of errors by a simple Bernoulli sequence, i.e. at each possibility it occurs with probability p but does not occur with probability 1-p. Hence, the number of errors in a total of tasks N is given by the Binomial (hypergeometric) distribution.

Certain theoretical considerations in control resp. search theory suggest that errors occur according to a homogeneous Poisson process with intensity λ. However, the intensity (occurence rate) depends on parameters which in part vary from decision maker to decision maker. For example, one could assume

$$\lambda_i = \lambda_{io} \times g\left(\frac{t}{t_o}\right) \qquad (15)$$

in which λ_{io} is the overall occurence rate of the error of type i, X a random variable with mean E[X]=1 and, possibly, varying between 0 and ∞ for the population of decision makers and g (t/t_o) a function expressing the variation of the occurence rate with the time pressure under which the given task has to be performed. If $g(t/t_o)=\Gamma(t/t_o)$, the function reflects the observation that for $t<t_o$, the time t_o being a reference time, the occurence rate can dramatically increase due to stress, for $t_o \leq t \leq 2t_o$ the occurence rate decreases below λ_{io} because the decision maker can afford much care but for $t>2t_o$ the absence of any pressure produces a larger occurence rate which is caused by increasing negligence and loss of motivation. Both the type of parameters and functions should, of course, only illustrate how the various factors influencing the occurence of errors could be modelled. It is here where much more research is needed. For simple intellectual tasks it is known that $\lambda_{io} \approx 10^{-3}$ but with greater differences between persons resulting, for example, in taking X_i as log-normally distributed with coefficient of variation V_i=0.3.

Now, let l_i be the number of tasks to be performed in a project, we have

$$P(N_i=1) \leq P(N_i \geq 1) = 1-\exp[-\lambda_i l_i] \approx \lambda_i l_i \tag{16}$$

for the occurence probability of errors of type i. For two errors of different type we may write

$$P((N_i=1) \cap (N_j=1)) \leq P((N_i \geq 1) \cap (N_j \geq 1)) \tag{17}$$

$$= \prod_{k=i,j} (1-\exp[-\lambda_k(X) l_k] \approx \prod_k (\lambda_k(X) l_k)$$

assuming conditional independence between the occurences. But occurences depend on the variable X which now can be interpreted as a numerical measure for the intelligence, experience and carefulness of the decision maker. If several tasks are performed by the same decision maker the occurences of errors in any of these tasks clearly are dependent events. It remains to formulate the above findings such that they are suitable for a numerical treatment according to section 3. Let $P(O_i)=P(N_i \geq 1)$. Then, it is

$$P(O_i) = P(U_i \leq -\beta_i) = P(U_i + \beta_i \leq 0) \tag{18}$$

with $\beta_i = -\phi^{-1}[P(O_i)]$ the generalized safety index. But the right-hand side of eq.(18) is precisely of the form required. For two errors occuring one obtains for the "failure = occurence" event with eq. (17):

$$F_{ij} = \{O_i \cap O_j\} = \{U_{ij} - \phi^{-1}[\lambda_i(X)\lambda_j(X)l_i l_j] \leq 0\} \qquad (19)$$

where $X = F_X^{-1}[\phi(U)]$. It is seen that the randomness in the error occurences is modelled by an additional, auxiliary standard normal variable U_i resp. U_{ij}. Generalisations to the simultaneous occurence of more errors or a more complex dependence structure appears straightforward.

A similar approach can be used to model the detection of errors [16,17]. The theory of (random or classified) search suggests that the probability of detections grows approximately exponentially with the search effort. Hence, if E is the random amount of effort (time) to successful search of an error, we have

$$F_E(e) = P(\text{detection of error } i) = 1 - \exp[-\kappa \frac{e}{e_o}] \qquad (20)$$

in which κ is the detection rate, e the effort and e_o some reference effort. Let M be a quantity measuring the size of the error. Then, as an example, one could assume

$$\kappa = \frac{1}{n}(\Sigma(M_i - M_{oi})^2 + \kappa_o Y \qquad (21)$$

n is the possible number of errors of different type, M_i the size of the error, M_o the magnitude of M in the absence of an error, κ_o a basic detection rate and Y a qualification parameter with a similar interpretation as the variable X for the occurence rate. The variables X and Y usually are dependent. For example, a low error occurence rate may imply a low detection rate and vice versa reflecting the fact that human beings tend to rely on experts. Again, the failure (= non-detection) event can be formulated according to section 3, i.e.:

$$F_j = \{E_j > e\} = \{e - E_j \leq 0\} = \{e - F_E^{-1}[\phi(U_j)] \leq 0\} \qquad (22)$$

in which U_j is another auxiliary standard normal variable modelling the uncertainty in detecting errors.

The foregoing occurence and detection models should be viewed only as first attempts. Even then, the lack of suitable data is obvious and serious efforts must be undertaken to obtain at least subjective assessments for the parameters. What is important is that these crude models can guide data collections and consequently the up-dating and up-grading of the models and that they indicate a way to formulate dependencies between "system components" in parallel which as emphasized earlier is essential when analysing quality assurance systems.

The situation is a little bit less subjective for misclassification errors if there are prescribed classification procedures. Assume a building material or type of soil is classified into several classes. The uncertain quantity of interest is X but it depends on an uncertain parameter Θ_i whose distribution is associated with class i. Further, a random sample is drawn yielding the statistic $z(\underline{x})$ where $\underline{x}=(x_1,\ldots,x_n)$ collects the observations. The classification (compliance) rule is such that if $z(\underline{x}) \in I_i$ the material is said to belong to class C_i. Any such procedure has two effects. On the one hand the distribution of X is modified through Bayes' rule, i.e. for the density of X:

$$f_X(x|C_i) = \int f_X(x|\Theta_j)\, f''(\Theta_j|C_i)d\Theta_j \tag{23}$$

with $$f''(\Theta_j|C_i) \propto P(\{z(\underline{x})\in I_i\}|\Theta_j)f'(\Theta_j) \tag{24}$$

On the other hand, the prior probabilities for the classes are changed according to

$$p''_j \propto p'_j \int P(\{z(\underline{x})\in I_i\}|\Theta_j)\, f'(\Theta_j)d\Theta_j \tag{25}$$

The normalizing constants have been omitted. As usual the terms with (') are denoted by prior, with (") by posterior quantities. The latter probabilities are the probabilities of the joint event of occurence and non-identification of the j-th class. Unless the prior probabilities (occurence probabilities) are rather high for a particular class and the decision rule $z(\underline{x})\in I_i \Leftrightarrow C_i$ confirms this (for example, by the use of efficient statistics for large samples), one probably cannot discard the other classes. Prior probabilities can, however, be made close to zero for incorrect classes if other variables indicative for a class membership are used in the classification process.

A special case of the foregoing scheme is the quality control of materials. An error now is to misinterprete or hide the sample results or not to carry out quality control at all. Clearly, system failure can occur if this event happens which might very well be a small probability event but for physical failure one also has to assume a relatively diffuse unfiltered distribution of material qualities prone to be built into the structure and, hence, making failure rather likely. This possibility might be one of the reasons why for certain types of material and production a second independent barrier, the so-called external control (Fremdüberwachung) is introduced whose primary purpose is to check the regularity of normal control procedures and decisions and thus, making the probability of physical failure and lack of primary control and non-detection of absence of primary control hopefully close to zero. It should be an interesting exercise to actually compute the risk of non-detection of inadequate quality control given certain external control and naturally, production regimes. The probability of contradictory control decisions given positive decisions in internal control is easily calculated. The probability of non-acceptance of regular control on the basis of a decision rule such as "the control is regular if at most k contradictions are accounted in a total of n cases, otherwise it is irregular" given the value of the contradiction probability may simply be taken as the probability that a regular quality control procedure is non-existing.
This fortunate case is only mentioned here to point out that the level of modelling and analysis is, in fact, as far developed in certain fields as to allow such computations. These may then be used to decide on the necessity and/or efficiency of quality assurance measures, e.g. the planning of one or more error detection devices. In other fields not even the first step of modelling has been done and it appears to be this uncomfortable situation which presently even distorts the efforts to collect the right data information. You never observe anything you do not expect beforehand with reference to a famous saying of Albert Einstein! Most of the foregoing models for error occurence and error detection and certain modifications proposed elsewhere should be viewed in this sense. They may guide the aquisition of relevant data and, if falsified as adequate, suitably modified. But a first step is necessary.

6. QUALITY ASSURANCE BY SUITABLE DESIGN OF THE OVERALL SYSTEM

"Normal" quality assurance measures, such as prior investigations, prooftesting, quality control, proper design and its checking, etc., given a particular structure can, at least in principle, be modelled and quantified as outlined before. It should also be possible to quantify the relative efficiency of the measures. Sometimes, however, a change of the overall system, the structural lay-out or the construction methods can be much more efficient than any of the other measures. For example, one might wish to introduce additional, redundant control activities in order to reduce error probabilities. It is also generally true that structural reliability increases with the degree of static indeterminacy, with the degree of ductility of the relevant structural components and, most important, with decreasing stochastic dependence of the resistance quantities of the components. Further, for redundant structures it is generally not true that costly low variance - low mean materials are optimal. Only high variance - high mean materials can efficiently activate redundancy, if one takes for granted that low-variance-high mean materials always are uneconomical. It is not possible to consider here more such circumstances. When planning for quality one, in fact, has to concentrate on the aspects of redundancy, i.e. on the number and dependence structure of events below an "and" gate in our fault tree (or the number and dependence structure of the events along the branches of an event-tree). Planning for quality is also to provide an adequate number of "barriers" and to make their efficiency via proper organisations of tasks, distribution of responsibilities diversification in the delivery of materials, avoidance of undue time or economic pressure, etc., as independent as possible.

7. OPTIMISATION

In order to make our formulation sufficiently complete we still have to go one step further. The individual quality of a structure usually is not a binary property. i.e. perfect performance as opposed to total collaps. Each component may reach different states to which different benefits and losses can be assigned. The normal classification into three states, the states of so called full performance bounded by the serviceability limit state, the states of reduced performance resp. states requiring some maintenance and repair bounded by the ultimate limit state and the failure (collaps) states may be appropriate for most of the structural facilities but might be insufficient for more complex structures. Moreover, the losses may depend on the state of the structural system as a whole. The losses may particularly depend on the number and the type of components which have failed although the system has not yet reached the final collaps state. Just for illustration we shall assume states of the components and make the losses dependent on the system states such that the loss L is an increasing function of the system state. In particular, if the redundant system i fails the loss is H_i and the increment when passing from state i-1 into i equals $H_i - H_{i-1}$.

An objective function suitable for quality assurance orientated cost-effectiveness studies then is:

$$Z = C_0 + C(\underline{e}) + \sum_k P(F_{n,k}(\underline{e})) \times (H_i - H_{i-1}) \tag{26}$$

in which C_0 are the cost independent of any quality assurance measures, $C(\underline{e}) \approx C(\underline{e}_0) + \Sigma c_t (e_t - e_{t,0})$ the cost for the selected quality assurance measures as an (approximately) linear function of the marginal cost C_t and the effort parameter e_t (e.g. safety factor, time spent in checking design calculations, sample size pf pre-investigation or compliance control of material procuction). The vector $\underline{e}_0$ may be taken as a base effort. Taking derivatives of Z with respect to $\underline{e}$ and setting it to zero yields the system of equations from which the optimal set of values e^+ can be determined. Application of eq. (26) to the various overall system arrangements leads to the globally optimal system with optimal effort parameters. Optimization of eq. (26) can be made with or without constraints, e.g. constraints on so-called design failure probabilities which are those corresponding to some significant loading scenarios but no error scenario occuring. Proceeding in this manner quality assurance is by no means a simple task. Drastic simplifications can and must be introduced in practice.

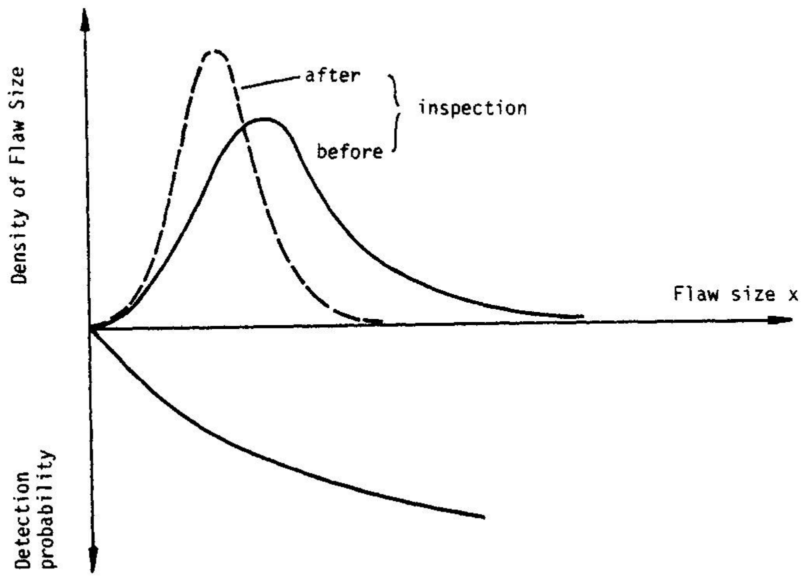

Figure 2: Flaw inspection and correction

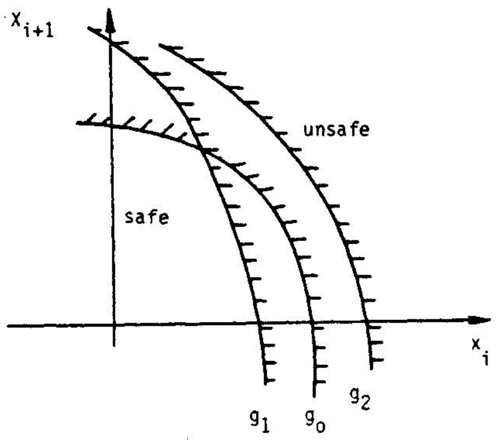

Figure 3: Failure domains for correct (g_0) and false (g_i, i=1,2,...) mechanical model

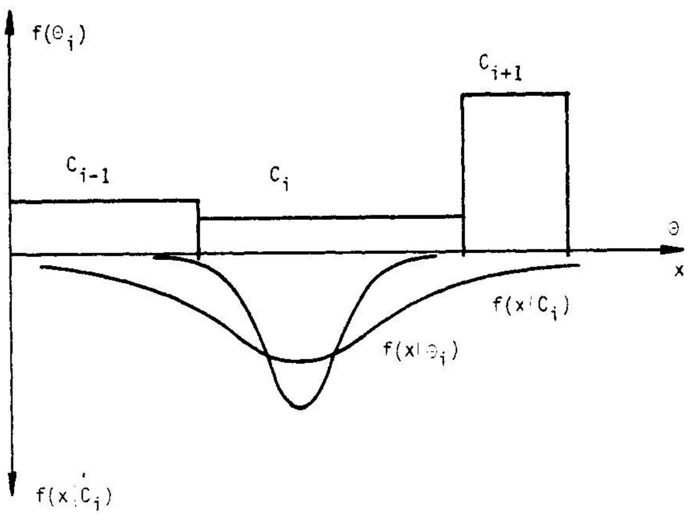

Figure 4: Prior information attached to classes

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Practical Aspects of Planning for Quality

Aspects pratiques de la planification de la qualité

Praktische Aspekte der Qualitätsplanung

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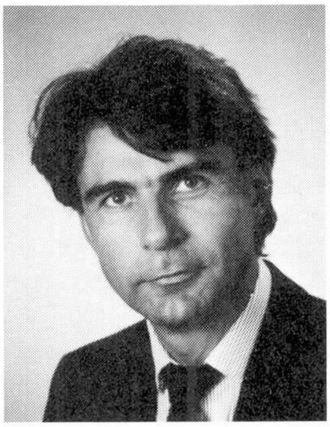

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SUMMARY

What are the main topics of quality planning, the complete and exact determination of the quality objectives or should it be the optimum project organization including the planning of effective controls? Ensuring the quality in civil engineering first requires an identification of critical areas in planning and execution, followed by the specification of priorities for their treatment. Exact observation, documentation and analysis of experience are essential activities. The crucial problem finally is the transfer of the results into practice. All departments in a company have to acknowledge these duties and cooperate with respect to this objective. It is of utmost importance that the board declares quality as an objective of the company.

RESUME

Sur quoi la planification de qualité doit-elle se concentrer en premier lieu? Sur une détermination complète et exacte des buts de qualité ou sur une organisation optimale du projet comprenant la planification de contrôles efficaces? Pour garantir ou améliorer la qualité des travaux de génie civil, les domaines critiques de la planification et de la méthode de construction doivent d'abord être identifiés, et des priorités fixées pour leur traitement. L'observation exacte, la documentation et l'analyse des expériences sont des activités essentielles. La difficulté consiste à mettre en pratique les résultats et les recommandations. Tous les départements d'une entreprise doivent accepter ces objectifs prioritaires. La condition essentielle pour la réussite est que le conseil d'administration déclare la qualité comme un but de l'entreprise.

ZUSAMMENFASSUNG

Worauf soll sich die Qualitätsplanung vorrangig konzentrieren, auf die vollständige und genaue Ermittlung der Qualitätsziele im Rahmen der technischen Anforderungen oder auf den richtigen Ablauf zur Leistungserbringung einschliesslich der Planung wirksamer Kontrollen? Um die Qualität bauingenieurgemässen Handelns zu gewährleisten oder zu verbessern, müssen zunächst kritische Bereiche in Planung und Ausführung erkannt und für ihre Bearbeitung Prioritäten gesetzt werden. Notwendig sind weiter genaue Beobachtung, Dokumentation und Datenaufbereitung. Entscheidend ist schliesslich die Umsetzung der Empfehlungen und Ergebnisse in die tägliche Praxis. An diesen grundsätzlichen Aufgabenzielen haben sich alle die Qualität der Bauausführung beeinflussenden Stellen zu orientieren. Voraussetzung für den Erfolg ist, dass die Geschäftsleitung Qualität zu einem erklärten Unternehmensziel macht.

1. The building process

The building process corresponds to the development of a prototype. Even only another location of the construction site involves a lot of new conditions which have to be considered: Other ratios of the foundation soil, building materials of another provenance, a new working team, other atmospheric conditions and modified quality requirements of the user.

The construction of a building is a complex process. The first steps involve the specification of the requirements by the user in terms of quality objectives. To fulfill the objectives the process of construction has to be kept under control during the following main phases

- planning
- structural analysis and design
- construction.

Demands to quality are always related to the requirements and cannot be requested absolutely. In the first place economic aspects ask for an individual differentiation of measures for the envisaged building project. Therefore the significance of the building determins the extent of the planning effort. Conventional building projects differ from those with special requirements.

Conventional (every day) projects refer to "standard" planning processes without special requirements for the contractor. Less sophisticated technologies (housing) and normal technologies (bridges) may be considered as conventional projects. Respective guidelines for the various project phases are generally codes, standards and particular prescriptions ergo in Germany the "German contract procedure in the building industry" (VOB).

For building projects with special demands (offshore-platform, nuclear power plant) the "standard" planning procedures are not sufficient because of the high technical risks. For instance specialised departments may be entrusted with specific planning for projects with a special safety demand.

In this contribution reference is only made to building projects with special safety demands.

Execution of projects with special demand, normally large scale projects, require interdepartemental activities, and usually even cooperation of different companies is necessary. Planning thus calls for a time - and placebound coordination.

In the following emphasis is placed on the coordination of quality planning of the building process with special reference to the handling of weak points.

2. The planning procedure

What are the main topics of quality planning?

- the complete and exact determination of the quality objectives, or should it be
- the optimum project organization including the planning of effective controls?

In order to determine quality objectives the expected influences on the structure are selected by utilisation scenarios and hazard scenarios. Utilisation scenarios are descriptions of operational, environmental and boundary conditions associated with the normal use of structures.

Hazard scenarios are similar descriptions of conditions dominated by a hazardous occurence during construction or the service phase, which alone or in combination with other normal conditions could cause the vital functions of a structure to be lost. Application of corresponding scenarios to the construction phase renders decision criteria for optimizing the project organization.

In common opinion quality planning refers to the process of determination of quality objectives. Quality governing and quality control are then employed to meet these objectives and to prove the efficiency of the measures.

However, the success of the realization of major projects depends more on the application of management rules than on exactly elaborated technical details. The following basic principles in this sense, have been recognized by Jolivet [1].

- suitable organisational set up of the construction firm
- formalisation of the procedures
- sufficient clarification of the responsibility of the single stages of execution
- permanent effort to improve efficiency and
- involving the contractor to planning at a very early stage

Experience shows, that the main causes for errors, defects and damages can be reduced to human insufficiency as

- ignorance
- carelessness
- negligence
- covetousness.

Concerning the complex projects in construction engineering performing new technical tasks is a minor problem. The larger problem is to solve simultaneously a lot of interdependent detailed tasks.

Weak points in the complicated organisational set up and operating sequence are not necessarily impediments on quality. But they definitely will influence costs in an extremely negative way, if only by causing delays in the project schedule.

3. Feed-back

3.1 Damage analyses

Analyses of building damages suggest that inadequate quality depends more on unsufficient planning and organisational errors than on poor detailing and erroneous construction. More errors are produced in offices than on site. Hence, table 1 comprises three analyses of building defects.

	PLANNING	CONSTRUCTION	Building materials environmental infl. service conditions
Germany (F.R.G.)	40,1 %	29,3 %	30,6 %
Belgium	49,0 %	22,0 %	29,0 %
Switzerland	>50,0 %	<50,0 %	10,0 %

Table 1 Individual sources of building defects [2], [3], [4].

3.2 Companies' experience and communication

To improve the quality of engineering conduct it is an upmost importance to identify critical phases in the course of planning and execution and to associate priorities.

Information on damage statistics may promote a better understanding of problems among the personnel involved. Basicly, transformation of this information is as difficult as the transfer of research results to practice. Exchange of informations, e.g. within training courses, of weak points and their causes may be considered as the most effective way to positively control the frequency of damages. Focusing on the major aspects is the prerequisite for the successful training towards an increased attention.

It should be noted that changing of recommendations and regulations influence quality. Too complicated and detailed prescriptions run the risk of not beeing considered, additional errors may occur dueto lack of clearness. Therefore the scope of decision should be enlarged for quality conscious engineers by appropriate code drafting.

Additional sources of information:

- Laboratory experiments to determine the behaviour of structural elements
- Observation, documentation and statistical treatment of data using stochastic models for assessing actions and hazards
- Practical experiences attained in similar projects
- Data from building insurance agencies for the frequency of damages

A well known complicating factor are the differing interests of the various parties involved. As an example take a building contractor and cement and conrete supplier, thus, a workshop of the German Concrete Association (DBV) for future problems in concrete technology suspects, that there is an increasing tendency for the liability of building contractors with respect to building defects, for which they are actually not responsible. This tendency arises because approved concrete mixing materials are substituted by other products. Basicly the contractor depends on the deliverer to provide him with material which must comply with his own expectations and those of the user. Moreover, his own requirements concerning quality objectives are based on the information offered by the supplying industry without, however, a clear acknowledgement of responsibilities.

4. Measures for quality planning

Ensuring an appropriate operating sequence for attaining operational efficiency is regarded as one of the most important interdepartmental quality assurance tasks. Up to now they are described only in very general terms in codes relating to quality assurance. A major issue for discussion is whether more details should be incorporated in codes or should this field remain competence of the company?

4.1 The interdepartemental organization

In the Federal Republic of Germany prescriptions with legal character require a framework description of the quality assurance activities for the construction of nuclear power plants. The aim of the framework is to improve the assessment of quality assurance measures including the organisational premises. A joint venture formed by a power supplying company, a plant supplier and two contractors drafted an outline for such a quality assurance frame, the requirements of which with respect to the internal organization of the contractor are as follows [5].

4.2 The masterplanning

The three parties with prime responsibility for the construction and safety in use of a nuclear power plant are

the power supplying company
the plant supplier
the contractor.

With the increasing number of groups concerned the necessary connections increase compared with conventional building projects. Thus explicit specifications of coordination rules are a useful instrument in the project organization and may be adopted according to the enclosed outline for nuclear power plants.

4.3 Quality assurance within the Technical Department

The activities and the quality assurance measures in the Technical Department are divided into internal and external activities. A detailed description would surmount the frame which is set here so that only the most important quality steps with external organizations are represented in the appendix.

5. Identification of weak points

Weak points may be identified within the phases of construction, design and organization.

Referring to weak points of the design, Design-Review-Checklists are a successful supplement in examining the design. They may assist in detecting weak points e.g. crucial quality characteristics which require increased data and information and a sophisticated analysis.

For very critical quality characteristics reliability assessments are necessary. Weak point analyses are therefore applied. A standardized method is the fault-tree-analyses (DIN 25424) which focuses at a unique adverse result and persecutes the causes back to the origin. The report of Dr. Rüdiger Rackwitz deals with that method which is mainly applied to detect causes with considerable risks for human safety and financial investment.

One of the main aspects associated with large scale projects is the fact that long lead times are involved.

To attain the quality objectives fixed by utilization and hazard scenarios the activities first focus on a schedule relevant for the following phases:

- planning
- structural analysis and design
- construction

It defines the operations which have to be required by whom and at what time respectively. Checking and approval of the shuttering drawings, interior work plans and reinforcement drawings are important activities.

A typical schedule for a nuclear power project is shown in the appendix as an example. However, the periods shown for different activities as well as the starting points are approximate and should be considered only indicative.

The main project-related and time-bound activities relating to the time schedule are (see appendix page A):

D - shipment of layout plans for the entire building and loading plans for regular and extraordinary loads.

W - detailed load data for main supporting systems and a schematic description of supports of components
  - basic plans for structural work (partial systems)

E - shipment of the basic plans, scale 1:50 (partial systems become obligatory)

F1 - approval of the shuttering drawings for design and reinforcement and of steel construction arrangement plans

F2 - approval of the shuttering drawings for the start of placement of formwork and reinforcement

A - start of the work at the construction site

As long as skilled personnel executes the work, as are engineers, chief operators, foremen and technical workers not all details must be extensively planned. We know, however, that certain unplanned works influence quality and economy in a most negative way. The following examples will focus the attention to some of those critical details.

5.1 Structural weak points

Basic decision of the type of structural systems are made at the stage of preliminary design. Hence, structural engineers should be involved in planning as early as possible. Experience shows that errors established at the initial phase hardly are corrected later. As an example take the preliminary design of a nuclear power plant which is planned on the basis of an existing but maybe out of date plant.

Groundwater sealings with expected dynamic loading should be considered at the earliest stage because they influence the design concept especially the details of joints separating the buildings. Usually the design of groundwater sealings is for a limited foundation depth. The suitability for deeper foundations may require experimental testing. Actions which are not standardized must be prescribed by the user. The selection of an Architect Engineer for a large scale project must mainly be taken on the basis of his competence in the field and on the key personnel that be can make available for the project.

5.2 Organizational weak points

Activities affecting quality shall be performed in an organizational structure with clearly defined responsibilities and authorities. Information obstacles have to be minimized. Engineers must have knowledge of the boundary conditions, missing it they cannot perform changes in a workmanlike and appropriate manner.

The planning of the work at the construction site must consider distinct market conditions, e.g. the building materials abroad very often do not satisfy domestic requirements.

Special attention has to be paid to the ventilating system of industrial structures, causing additional roof loads and wall penetrations, since it is often enlarged or not planned in advance because the construction period of the plant often lasts for several years.

Cracks are undesirable at housing construction. At industrial construction, apart from structures for which impermeability of water is required, cracks are of less significance. Exaggerated crack reducing requirements may thus be superfluous.

The adequate choice of the structural system and of the corresponding details should be based on decision criteria related to material, type of construction and manufacturing.

Aspects to consider include: [6]

- knowledge on the structural behaviour of different systems
- careful consideration of the advantages of hyperstatic systems with regard to redistribution capacities versus the disadvantages in the case of constraints caused by temperature, drying shrinkage, settlement and the like
- detectability of poor workmanship in manufacturing
- possibility of local failure due to accidental actions, improper execution, insufficient durability, etc.

6. Summary and conclusions

Ensuring the quality in civil engineering first requires an identification of critical areas in planning and execution, followed by the specification of priorities for their treatment. Exact observation, documentation and analysis of experience are essential activities. The crucial problem finally is the transfer of the results into practice. All departments in a company have to acknowledge these duties and cooperate with respect to this objective. It is of utmost importance that the board declares quality as an objective of the company.

Engineers, foremen and workers must be motivated to produce quality. They must be assisted because they suffer under narrow deadlines and often do not know whom to cantact in the company for support in case of urgent problems. Generally there is not enough time available to study technical literature. Check lists are missing for many important operations. With respect to information for special tasks planning data are often unsufficient.

There is an optimistic expectation that quality can be improved by motivation provided that the individual personality in the process of civil works is sufficiently regarded. This presumes well experienced engineers, foremen and skilled workers who fortunately are still available at the time beeing. But a tendency for a diminishing qualification is apparent. Hence, we must pursue possibilities in order to maintain the high quality standard of today with less experienced personnel in the future. Our activities will be successful if we make use of the principles of modern quality assurance systems as an essential part of industrial management by transferring them to civil works.

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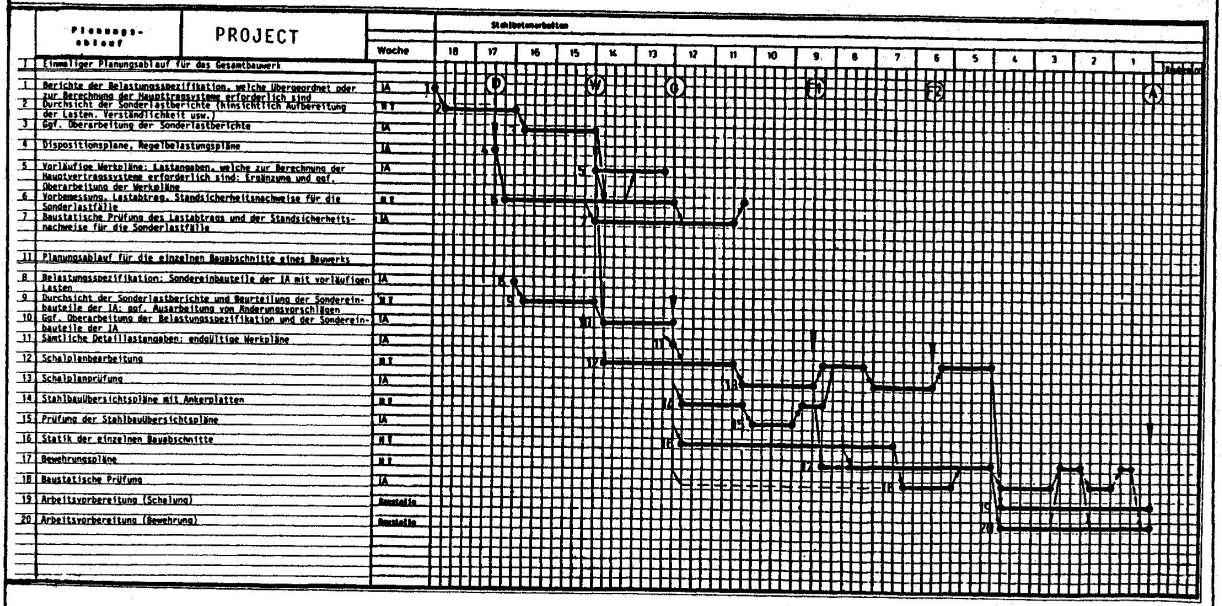
Abbreviations for the time-bound activities see chapter 5.



SCHEDULE FOR A NUCLEAR POWER PLANT
DURING THE PHASE OF PROJECT PLANNING

QUALITY ASSURANCE

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	COORDINATION RULES	QUALITY ASSURANCE		
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3.1 Plant Supplier (Software Management)
3.2 Companies For Planning Reinforced Concrete
3.3 Companies For Planning Structural Steel
3.4 Authorized Experts For Reinforced Concrete And Structural Steel
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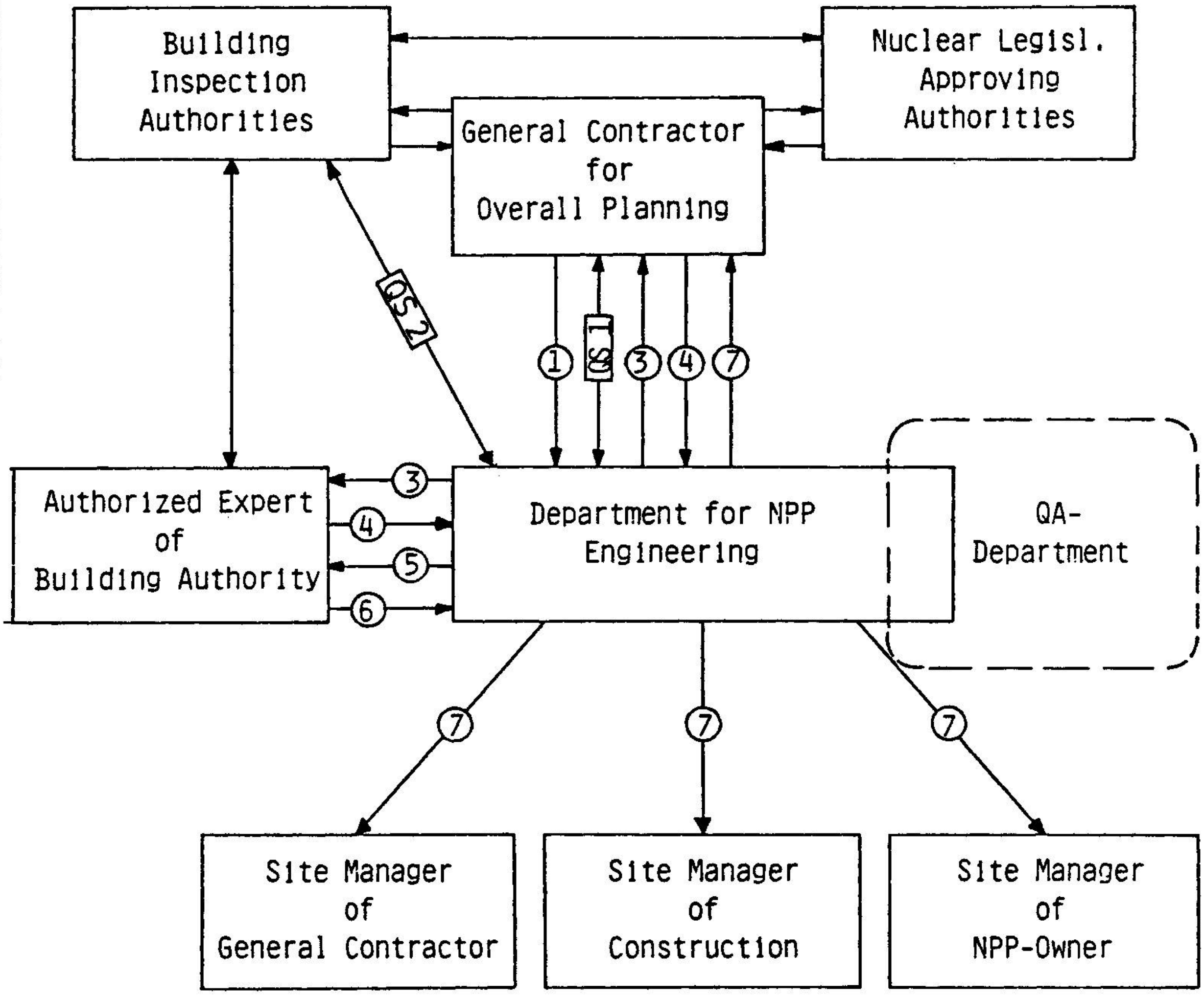

	QA-PROGRAM FOR THE CIVIL PART OF NUCLEAR POWER PLANTS	QUALITY ASSURANCE		
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(Sign) Arranging office	Activity
(1) General	Planning and computation data for the civil part of NPP (Nuclear Power Plant) Technical description Overall-Plans scale 1:100 Detailed plans scale 1:50 Load plans continuous and discontinuous general loads additional loads resulting from special load reports
(QS 1) Department for NPP-Engineering	Examination of design data concerning correctness, completeness, in case correction
(2) Building Authorities	Requirements for approval documents unusual external loads (earthquakes, external explosions, aeroplane crash) supplementary safety requirements for interior unexpected loads
(QS 2) QS Department for NPP-Engineering	Examination of approval documents concerning completeness, clearness, in case completeness Application of licences for new building materials, structures or construction methods
(3) Department for NPP-Engineering	Shipment of shuttering and subcontractor drawings for the approval
(4) General Manager of Authorized Expert	Shipment of the plans approved for construction
(5) Department of NPP-Engineering	Shipment of the construction documents, required by the approval documents, for examination and approval
(6) Authorities Authorities Expert	Approval for construction of the construction documents (drawings and specifications) Agreement for the application of licences for new building material, structures or construction method
(7) Department of NPP-Engineering	Shipment of approved documents for construction

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Organization of the Design-Construction Process

Organisation du processus du projet et de l'exécution

Organisation des Entwurfs- und Ausführungs-Prozesses

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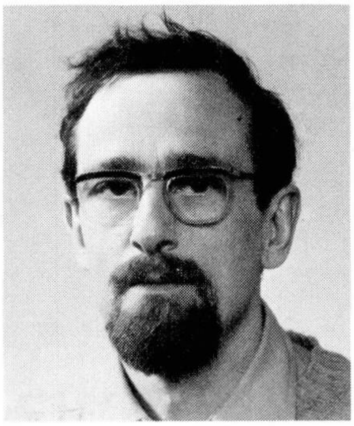

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SUMMARY
These introductory notes deal with organization and management of the design-construction process on a very general level. After a brief review of the evolution of safety analysis in structural engineering some elements of the present situation, alternative systems and motivation analysis are discussed. A number of interrelated questions are posed as a basis for discussion on a fundamental level.

RESUME
L'article présente d'une façon générale l'organisation et la gestion du processus de projet et de l'exécution. Après une revue de l'évolution de l'analyse de la sécurité des structures, il discute quelques éléments de la situation actuelle, de systèmes différents et traite de l'analyse de la motivation. Des questions sont proposées pour une discussion générale.

ZUSAMMENFASSUNG
Der vorliegende Bericht befasst sich mit Organisation und Management des Entwurfs- und Ausführungs-Prozesses in sehr allgemeiner Weise. Nach einem kurzen Blick auf die Entwicklung der Sicherheits-Analyse im konstruktiven Bauwesen werden einige Elemente der gegenwärtigen Situation, alternative Möglichkeiten und Fragen der Motivation erörtert. Eine Reihe miteinander verknüpfter Fragen wird gestellt als Basis für eine Diskussion auf grundsätzlicher Ebene.

1. INTRODUCTION

Earlier sessions in this workshop have dealt with several aspects of quality assurance in the design-construction process. Past and current experience with structural failures has been reviewed and primary causes of failure, including human error, have been described. The objectives of building have been formulated from several viewpoints and utility functions have been suggested in an effort to develop a logical framework for an optimal approach to design and construction control.

In this introductory note we will examine such aspects of the building process from an overall or macro point of view. To provide a background to discussion of construction organization, the evolution of concepts of structural safety within the profession will be reviewed. An understanding of this evolution and the present state-of-the-art is essential if the construction process is to be approached at an appropriate level of generality.

A major objective of this note is to develop a number of basic questions which the workshop may use as a basis for discussion. Attention will be focussed on private rather than government construction although most elements seem to be very similar in both situations.

2. EVOLUTION OF SAFETY CONCEPTS

2.1 The Traditional Concept

In spite of many painful experiences to the contrary, engineers have traditionally rejected the role of uncertainty in design. Using loads that could "never" be exceeded and strengths that were "guaranteed", buildings were made "absolutely safe". For generations, engineers relied on such an "it's true because I say it's true" philosophy.

This apparently absurd philosophy is actually quite sensible. It simply means that the engineer assumed personal responsibility for his decisions.

Absolute Safety

2.2 Rational Man - The Optimizer

To establish a rational basis for decision, the basic design components of load, analysis and resistance has been studied in great detail. Inevitably, a great deal of uncertainty in the various elements must be accepted and measured. Similarly, the relative importance of safety, time, and money must be established. Finally, we must define the context of safety decisions. Who is to make them? What are the boundary conditions?

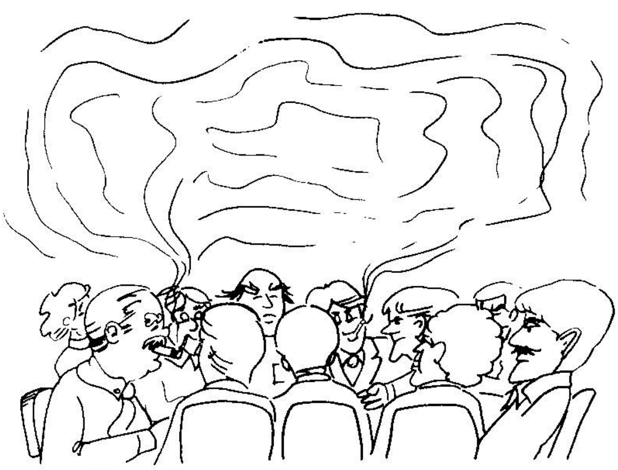
Beginning with the work of Forsell in 1924, (2), numerous attempts have been made to formulate a "rational" approach to decision (3, 5). In these formulations, a "rational man" first lists all his alternatives and all possible future events. To each design alternative- future event combination he assigns a probability of occurence and a measure of desirability. Decision follows automatically through maximization of expected benefits or utilities.

Because of the magnitude and variability of civil engineering works, subjective probabilities and values must be introduced to account for missing data and the nonmonetary costs of human life. By simple extension, one can consider an hierarchy of decisions involving testing and evolving probabilities through Bayes' theorem.

The question "Who is to make the decisions with whose values?" once seemed relatively straightforward. Since most design is based on standard procedures, code committees were elected to decide, based on the values of "society".

It now seems that code committees can not normally be expected to be rational. Their primary function is to assemble experience and resolve conflicts between interested parties. When they do provide leadership, it is usually because of a dominant individual or group.

In spite of these problems, a rational man analysis does provide a reasonable model of ideal problems. In practice, decisions involve many personal and organizational constraints that are not considered.



The Code Commmittee

2.3 Bounded Rationality - The Satisficer

To construct a more useful model of decision, the practical design process must be considered. The starting point must once again be an individual or small group, making decisions guided by codes and historical practices and, except for totally routine cases, assuming a certain responsibility for their actions.

The practical decision maker differs from the classical rational man in several essential ways.

(1) He does not list all feasible solutions but scans adjacent possibilities around an initial trial and stops when he has found a "satisfactory" solution.

(2) His decision may change with time as a result of consultation with superiors, clients, contractors, material suppliers, and government officials.

(3) He is under powerful organizational constraints in respect to his efficiency and practices. Substantial innovation implying significant risk may be contrary to his organization's or his own goals.

(4) He has limited control of the total construction process and has limited responsibility.

This decision maker will not normally seek to optimize with the values of some abstract entity called "society". Instead, he will tend to act as what Simon has called a "Satisficer" (4).

The satisficer does not seek to optimize but rather looks for solutions which satisfy possibly conflicting constraints. To a large extent, decisions are imposed by the practices and objectives of organizations. The training of individuals plays a major role.

The satisficing concept helps to bridge the gap between a utopian rational solution and practical behavior. The global design experiment can thus be viewed as an incremental satisficing evolution. Unfortunately, a satisficing model is not normative in the sense that it suggests ideal behavior. It simply describes what we actually do in the face of complex uncertain situations.

The satisficing concept does, however, lead to one obvious fundamental qualitative conclusion. If a decision process and its results are to be changed, the attitudes and constraints of the decision makers must be altered.

The Satisficer

2.4 Strategic Man

An interesting alternative "organic" approach to decision analysis has been suggested recently by Crozier and Friedberg (1) , and others. In this view, individuals are considered as players in a set of complex games within organizations and between organizations. Both organizations and individuals are in constant flux, attempting to grow and increase their power and influence, constantly sensing the environment for opportunities and responding to hostile behavior.

This rather colorful image seems well suited to the construction industry. Material suppliers, unions, fabricators, contractors, governments, consultants and owners are in a constant state of evolution as competitive forces between materials, methods, and organizations are resolved. All elements of this system interact with society as a whole both as individuals and as a industry. For example, inadequate construction practices can lead to changes in government regulations, the decline of one component of the system, and growth in another.

The Construction Game

A strategic view of construction may provide the theoretical basis for a major redefinition of the design process. Instead of viewing design as a game against natural hazards, an engineer can see himself as a player within a complex game where other players have other, conflicting, but equally rational objectives. With the best will in world, the construction game can be so badly structured that major problems are almost inevitable.

3. FIVE BASIC QUESTIONS

3.1 The Present Situation

From the perspective of this brief theoretical background, we can begin to evaluate the present situation. How, for example, should the profession react to press accounts featuring spectacular failures such as the Kansas City skywalks or bridge sections in New York? What are the implications of relatively frequent minor disasters involving collapsing formwork or veneers.

In related areas we must confront rather shocking statistics such as: "Jobsite accidents now cost the American construction industry $8.9 billion a year". Injuries, fatalities and illnesses in construction occur at a rate said to be 54% higher than all other industries" ("Civil Engineering", ASCE, Sept. 1982). Recently, the costs of human error were estimated as 5% of the total cost of construction and no one challenged the estimate as unreasonable.

As a counterpoint, the results of a recent survey of senior executives in major property development corporations is of interest. Although the official objective of the interviews was to assess building owners' value systems with respect to serviceability failures, a great deal of unexpected information was obtained.

Although the opinions of each executive tended to depend on his background, general attitudes were evident in all cases. In particular, all agreed that structural design and construction were not major sources of concern. Problems could be avoided by careful selection of materials and the use of experienced consultants.

Most owners were very insensitive to structural costs. Compared to other sources of uncertainty such as heating and air conditioning, interest rates, tax considerations and the real estate market, structures themselves were a minor consideration. These opinions suggest that present quality assurance procedures for buildings are generally adequate, at least for the structure.

In spite of this note of optimism, nagging doubts as to the quality and trends in current construction continue within the profession. Somehow one feels that the repeated incidence of sway problems in tall buildings (The New York Times, October 24, 1982) is an important phenomena which we must move to prevent. The continued use of totally discredited details in masonry curtain walls, for example, does not seem acceptable.

As professionals we are legitimately concerned about such problems, but to ensure a realistic perspective we should perhaps ask ourselves the following question.

Question No. 1 *By attempting to improve the construction process, are we not, in fact, trying to cure a healthy patient?*

It may well be that the errors and mistakes we observe are simply the inevitable consequences of an evolutionary process and, like all such processes, essential for progress.

3.2 Systems of Design and Construction

Until fairly recently, the organizational structure of the civilian building process was quite simple. A person or organization wishing to have a structure would commission an individual builder for both design and construction. Because building techniques were largely traditional and relevant crafts were well established, a single authoritative person could assume responsibility for the complete operation including supervision. Such a simple organization was prevalent as late as the nineteenth century, even for large projects such as Roebling's Brooklyn Bridge.

At some point the separation of design and construction began with architects and engineers emerging as separate professional groups between owners and builders. At about the same time, the state began to assume an explicit role in the building process through design codes, building codes and construction codes. Labor unions developed powerful positions which imposed serious constraints on the actions of others. As new techniques emerged, construction activities became more highly specialized. At least in North America, insurance, legal and financial agencies have assumed an ever expanding role in both pre and post construction.

In North America the present situation is extremely variable and in rapid evolution. Although design engineers and architects, contractors, and tradesmen are relatively tightly controlled by licensing authorities and labor agreements, economic pressures and competition generally are dominant. The relationship between time and money is uppermost in the minds of many people.

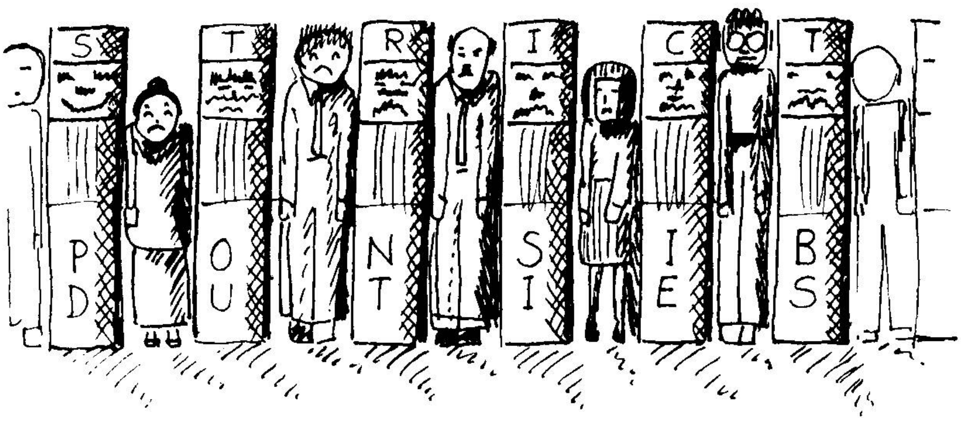
Responsibility for design usually lies with licensed engineers who are constrained by design codes. In the United States, these codes are developed by industry groups and adopted with or without amendment by local governments who generally have very limited technical competence. In most cases there is a number of alternative codes which have been developed by other groups and are consulted even though they may not be legally binding. It is unlikely that an engineer would be forgiven a serious blunder simply because a local code permitted it. Some cities require an independent design check for certain buildings but this is by no means a uniform practice.

In cities such as New York, general contractors who assume overall responsibility for a building have become a vanishing species. Not long ago general contractors began to subcontract almost all their work and so avoided, or at least diffused, responsibility for quality. To exert greater control, the construction manager has evolved as an agent of the owner, thus passing a great deal of responsibility back to the owner.

Owners have responded to this situation in various ways. Some have developed in-house design and construction groups while others have developed a short list of reliable people whom they use exclusively. Some have opted for turn-key operations, in effect returning to the traditional concept of a single builder.

Insurance companies in North America normally do not become directly involved in the building process although they do provide an educational service based on losses that occur in practice. Insurance rates are generally not related to the competence and reputation of the people involved in a building's design and construction.

The practice of "fast-tracking", where parts of a building are completed before other, interdependent parts have been designed, has also been adopted. The frame for at least one of the taller buildings in the world was well underway before wind tunnel tests had been completed.



TIGHTENING THE ORGANISATION

There are many cases where the process has performed very badly indeed. In one locally celebrated series of cases in Canada, architects combined the roles of part owners, designers, and general contractors for a set of speculative high-rise condominium apartments. With little construction supervision from the architects or building officials and the use of least cost subcontractors, the buildings were very badly built. The costs of repairs, which were extensive, were borne by subsequent owners.

No law was broken and no one could be held responsible in a legal sense. Such a failure may be called an "organizational failure" because the building process itself was fatally flawed. Since government authorities were unable to fulfill a protective role for budgetary and political reasons, the construction process was not sufficiently constrained legally. Everyone followed the human but unprofessional principal of maximizing his personal gain within the constraints.

In other countries, organization of the building process is very different. In France, for example, there is no legal constraint on designers but insurance companies play a major role in building quality control. Since these insurance companies are dominated by the government, there is in fact an indirect but very strong control of practice.

In Germany, a review of design is mandated by the State through the institution of the "Prufingenieur". Design itself is also rather rigidly controlled by comprehensive government norms.

From these observations it is quite clear that there is no consensus on how best to organize the building process. With this conclusion we can formulate two very general questions closely related to the first.

Question No. 2 *Given the variety of forms and great complexity of the building process with many potentially conflicting participants, can we expect to improve quality without constraining or formalizing organization?*

Question No. 3 — *If we tighten organization through definitions of tasks, roles, and responsibilities, do we not inevitably inhibit the natural evolution of the building process, including its self-healing capabilities?*

In attempting to answer such questions we might be led to many subsidiary questions. For example, does the separation of the design and construction function in the hands of independent designers and contractors contribute more to quality of design than it contributes to error proneness through communication problems?

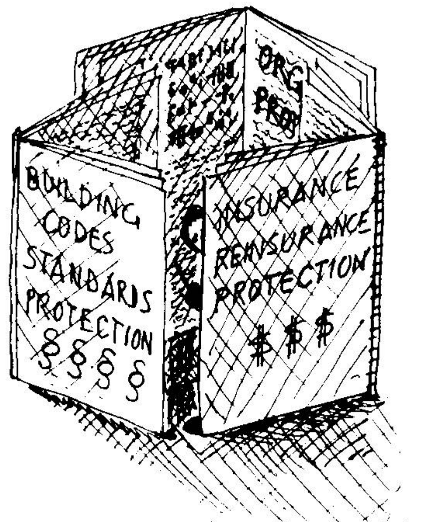
3.3 Motivation

Human beings are relatively complex organisms which respond to stimuli in many ways. According to one well known theory, they are motivated by an hierarchy of factors the first of which is the basic requirement for survival. Beyond this, people are motivated by a desire to be accepted by their peers and ultimately, if all other factors are satisfied, by the possibility of satisfying their own, usually high, image of themselves. This last factor is the dominant motivation of the artist who may accept a relatively low satisfaction level for more basic factors.

Attempts to improve the quality of construction tend to be founded in two basic types of assumptions concerning human behavior. The first assumes that man is essentially a risk and responsibility averter, seeking to maximize his personal gain while avoiding trouble and effort. Essentially, such a person assigns a high priority to the lower level of the motivation scale.

A second approach assumes that man is anxious to expand his capabilities, to assume ever greater responsibilities and to rise in the estimation of his peers. This assumption underlies appeals to professionalism, a sense of responsibility and "esprit de corps".

The first set of assumptions leads to strict regulation of the construction process and every actor in it. The second set leads to educational programs and relatively flexible control schemes. Some theoreticians assert that people will tend to behave as the system they inhabit expects them to.



BUILDER'S ARMOUR

Such questions of motivation enter into many discussions of construction organization. For example, our answers to the following questions will depend on our perception of the motivation of others:

Question No. 4 — *Given that the existence of insurance reduces an individual's exposure to risk from the consequences of his actions, is insurance not a disincentive to careful work?*

Question No. 5 *Since the use of established design codes generally protects a designer from many of the consequences of his actions while disregard of codes enhance designer liability, are codes not major obstacles to progress and improvement?*

It would indeed be bizarre if the introduction of measures to protect individuals and the public should lead structural engineering into a sterile state of equilibrium where innovation is restricted, competence is not rewarded and repeated errors are accepted as routine.

An indication of the critical role of individual and organizational motivations is provided by the current U.S. controversy over nuclear power ("New Yorker", November 1, 1982). In an environment where large, powerful, private and government organizations were vying for growth and profit, technical assessments of risk were simply overwhelmed. Naive assumptions concerning the efficiency of individuals and equipment were accepted with the result that risk assessments were seriously underestimated. In several cases, warnings of potentially dangerous possibilities were ignored with near disastrous results.

Problems such as nuclear reactor policy are beyond the control of professional groups since they involve the complete economic and political systems of a society. However, the fact that an exceptionally tightly regulated design and construction process can produce disastrous results does suggest a limit to the value of formal constraints.

4. CONCLUDING REMARKS

In these introductory notes, we have attempted to take a "devil's advocate" view of several very general aspects of the building process. Our perspective was that of the process as a whole rather than an individual within the process. While this view is rather different than that of other introductory notes, it is not in conflict with them. Rather, our objectives were to broaden and generalize the problem so as to open new lines of thought and suggest limitations to the value of some approaches.

Consideration of organizational options cannot in itself lead to improved performance. Improvement must also be made through quality control in the micro-structure of individual design offices, material supply operations, and the many stages of construction itself.

However, by examining the overall construction process we may be able to identify particular organizational arrangements which tend to function exceptionally well or exceptionally poorly. At the moment we have no clear concept of the possible variants, no scientific data on their performance, and no scale for measuring their relative value. Although it is well known that organizational environment influences performance very strongly, we lack the basic tools to assess the effects.

Hopefully, some effort to understand the overall construction process, its communication links and responsibility flows will be made. Without such an understanding, many well intentioned innovations may result in failure.

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