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Link between Durability Defects and Construction Failures

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Abstract. *Over thirty years ago enthusiastic and dedicated materials scientists and structural engineers initiated a series of research projects and draft International Standards which has now revolutionised the design approach to durability of concrete structures. Concrete mix design is dominated by the contractual requirement for the concrete supply not to exceed specified limiting values of the nationally favoured durability criteria. The specifying Authorities are striving to ensure that structures achieve their design service life (ideally 100 years+). Concrete research and development is their primary hope.*

During the 1990s, the concrete construction industry was also working hard to develop better specifications and contract management procedures to address the pressing problems of not only durability but also safety. Central to all the work of the construction industry was the principle that all concreting operations were 'special processes' (as universally acknowledged for welding processes), and therefore they had to be documented, trialled, verified and implemented in compliance with the process control requirements of ISO 9001:1987/1994.

Procedures had to be prepared, approved and implemented for all processes which were identified as being potentially 'adverse to quality' (which included most processes involved in concreting and prestressing operations (including grouting)). The critical question to answer in preparing a procedure is HOW the process will be carried out and verified. However, equally critical questions may be WHEN, WHERE and BY WHOM. The Project Specification must ask these questions in the tender documents and the Owner and/or his Designer must satisfy themselves that all the identified problems have been resolved – both technical and administrative – before relevant design/construction commences.

These questions must be answered by all subcontractors, including designers and checkers of falsework structures. Example are given, based on recent fatal bridge collapses largely caused by Owner and Designer failings to control subcontracting of temporary works design and checking.

Keywords: *Tender Requirements for Design-construct Contracts, Safety Culture, Controlling Concreting Processes, Subcontracting Falsework Design, Centres of Concreting Excellence.*

1 The Yantai Paper and Proposed International Joint Task Force

The author's intention and fervent hope is that this Paper (with its Companion Paper 201) will result in a resurrection of ideas discussed with Professors Fang and Han at Tsinghua University in 2008 and 2009. The proposals for preventing falsework collapses (Curtis, 2008) were inspired by reports of the disaster at Can Tho Bridge in Vietnam (2007), where 52 men died and 80+ were injured. The proposals contained in the Yantai Paper remain fully relevant today: For this purpose, an International Joint Task Force (IJTF) for Preventing Construction Disasters was to be promoted according to the steps suggested in the Yantai Flowchart.

Fifteen years ago the author closed the Yantai Paper with a personal challenge, stating: **"***This paper calls for a response from the international engineering fraternity which will require a departure from long established – but inadequate – procedures of project management and reliance on standard specifications which don't effectively address the issues of quality and safety on engineering construction projects. It also requires building bridges of understanding and trust among owners, consultants, contractors and subcontractors and their employees.*

*I trust that there will be engineers in China and Australia and many other nations who will work together to establish a new culture of contract management. The initial costs will be substantial, but they will be far outweighed by the eventual financial benefits - not to mention the benefits to our communities and nations by preventing future disasters.***”**

The author believes the same challenge applies today. In fact, it has become more urgent, as evidenced by the overall failure of the industry to establish a true safety culture both on-site and also in the contract/subcontract relationships where disasters are so often birthed, but not identified and prevented. However, the author also trusts that, in view of the fatal and costly consequences of several failed contracts in recent years, many infrastructure owners (and/or their design consultants) will re-evaluate their tendering policies and ensure that adequate pre-construction investigations, tests and trials are carried out before contracts are awarded.

2 ISO Design Codes Not To Be Used for Concrete Construction Contracts

Code-related aspects of this Paper are considered in more detail in its Companion Paper 201, where the author presented a lengthy critique of the ISO Design Codes, hoping to convince owners and their designers that these codes are not suitable for the detailed design and execution of reinforced and prestressed concrete members. Not only are these codes specifically non-contractual but they are also based on assumptions which are generally valid for the assembly of structural members, (whether steel or precast concrete); but invalid with respect to the processes involved in concreting and prestressing operations. (Curtis, 2023 Paper 201, Sect.2)

The processes by which fresh concrete is supplied, placed and compacted in a formwork-reinforcement assembly are ‘*special processes*’, i.e. (like welding), the conformity (including durability performance) of the finished product cannot be fully verified by inspection and testing (even of supposedly representative samples). Meaningful product verification can only be achieved by controlling and continuously monitoring each process according to pre-planned and pre-approved documented procedures. Older readers will realise the author is using words drawn from the pre-2000 versions of ISO 9001 (ISO, 1987), to explain why the post-2000 versions of ISO 9001 cannot be used to produce concrete members or structures which can be reliably verified for (durability) conformity. Furthermore, by referring to ISO 9001:2000/2015 in tender and contract documents, owners are setting themselves up for disappointments and unwelcome outcomes ranging from defective concrete cover to falsework failures.

The ISO Design Codes, and even ISO 22966:2009 (*Execution of concrete structures*) are inextricably linked to, and dependent on ‘*verification by product testing*’ and the concepts of ‘*quality management systems*’ and ‘*continual improvement*’ (which are contractually irrelevant). Consequently, the author has concluded that all direct references to ISO 22966 and its supporting ISO Design Codes need to be removed from the requirements in tender and contract documents for concrete construction works (Curtis, 2023, Paper 201,Sect 2, NOTE 2).

2.1 Documented Procedures Are Essential for Quality, Safety and Economy

The fundamental criticisms of ISO 9001:2000 for construction tender and contract documents were that **(a)** (unlike ISO 9001:1987), it could not be used for tender and contract purposes and **(b)** it had no mandatory requirements for process control procedures (thereby abdicating its role in dealing with potential nonconformities). (In the author’s opinion, the reason for (b) was that the recognition of concreting processes as ‘special processes’, (while widely accepted by the construction industry), was not properly recognised by the structural design community. The author further believes this was because of their full commitment to the Eurocodes and the reliability principles of ISO 2394. Thus, **(c)** the need to verify 'special processes' by process control procedures was virtually ignored for concreting operations, due to the assumption that product sampling and testing could be accepted as the primary means of product verification.

In the years between 1987 and 2000, a great deal of work was done in the UK, Canada and Australia, to try to convert ISO 9001 into a quality system specification which could be incorporated in tender and contract documents for concrete construction contracts. Some major European contractors also combined to produce a guide for Quality Management (CEB, 1998).

The early history of Quality Assurance in the civil construction industry (Marshall, 1993), indicates strongly that much of the controversy in the various code committees centred around the issue of 'procedures' and relevant definitions. (What is the difference between a procedure, a work method and a description – and who decides what information is required – and how are those requirements to be specified etc., etc.?)

For the purpose of this Paper, a Procedure is defined as a document which specifies

- The purpose and scope of an activity (or process),
- What shall be done and by whom,
- How, When and Where it shall be done, and
- How it will be verified (that it will produce conformity product)

Obviously prospective contractors will be concerned that the costs of complying with specified procedures may not be properly assessed during the tender evaluation process. Furthermore, when we look at the how, when, where and by whom questions, in relation to design subcontracts such as falsework , we realise that procedures are critical not only to quality but also to avoid death and injury to workers and the public - particularly during construction.

2.2 Detrimental Impact of Invalid ISO 9001 Assumptions on Concreting Practice

The assumptions of the ISO Design Codes, and their ineffectiveness in specifying concreting process requirements, are discussed at length in the Companion Paper 201, (mainly in Sections 3 and 4, which were developed to explain the observed defects in the Storebaelt Bridge and other major structures). However, in that Paper, the author has not been able to thoroughly explore the set of assumptions which materials scientists seem to have made in relation to the flow of concrete through the outer reinforcement and into the cover zone, (sometimes referred to as "covercrete' versus 'corecrete' or' realcrete' versus 'labcrete'). The author has proposed elsewhere (Curtis 2017) that these questions be addressed in a wide-ranging, industry-driven concrete research program; and it is now hoped that this program will be re-activated.

The author argues that the breakthrough developments in concrete durability technology and service life design in recent years have, to some extent, been misdirected and sometimes misapplied, (at least for potentially high performance concrete mixes), because of a lack of site concreting experience among materials scientists and engineers. One reason for this may be that the probabilistic philosophy promoted by ISO 2394 and the Eurocodes has so conditioned them to thinking in terms of '*variability within uniformity*' (the author's phrase), that they find it hard to specify for the gross defects and regions of poorly compacted cover concrete which occur randomly in the vicinity of congested reinforcement and sloping sides. (EU, 2005)

The author believes that a better understanding of the processes by which concrete is made to flow around obstacles under the influence of vibration would be of great value to materials experts as well as non-experts. Such practical experience will open up ground-breaking, field-verifiable opportunities for establishing specified limits for durability index limits. This would in turn, enable all parties to achieve conformity without the need to resort to undesirably low water-binder ratios. The author believes very strongly, that teaching on practical concreting technology has been badly neglected, and this has been a major contributor to many major concrete durability failures. These include the Storebaelt Bridge (1990--), SR-520 Floating Bridge near Seattle (2010--) and Panama Canal Extension (2012--) (Curtis, 2018)

In each of these durability failures, the specifications reveal a serious lack of understanding of the realities of current concreting practice. When this is combined with tender and contract documents which appear to include all the right product conformity requirements, but which are contractually ineffective and unenforceable, we have a recipe for disaster. The aim of this Paper is to stir up action to change documents and change the culture to prevent such disasters.

2.3 Proposed Relaunch of Draft International Project Specification (DIPS)

The Model Project Specification, (first proposed in *fib* Bulletin 44, Appendix G and referred to in recent *fib* correspondence as '*Model Version of ISO 22966*', will now be revised, after which it will be referred to as '*Draft International Project Specification (DIPS)* '. The overall purpose and methodology will remain the same (including alignment as far as possible with ISO 22966), but its terms and requirements will be simplified and streamlined so as to take advantage of QC/QA principles similar to those specified in Clause 9 of ISO 9001:1987.

Following Sections in this Paper support the apparently radical conclusions of this whole Section 2 with extracts from reports and comments on two of the worst design-related bridge construction disasters investigated in the last five years; Chirajara Bridge (2018 – 9 dead) and the Florida International University (FIU) Footbridge (also 2018 – 9 dead).

3 Insights from IABSE's Investigation of Chirajara Bridge Collapse

Obviously, as this was primarily a design failure, (IABSE, 2018), so the expert report relates initially to design failings. However, it became glaringly obvious to the reporters that the underlying causes were far deeper. In its closing remarks, the report states: "*The underlying condition of the collapse of the Chirajara Bridge has been the lack of exercising the duty of care as required in the design and construction of an unconventional cable stay bridge, as well as a lack of quality assurance and quality control over the different stages of the project.*"

Not surprisingly, and necessarily, the recommendations of the report focused on procurement and contractual issues. Among the major recommendations:

A quality management system like the ISO 9000 system is implemented and followed.
(The complete chain of involved parties needs to comply with such requirements from Owner/Operator of the facility to designer, contractor, subcontractors, ... Checkers etc. ...)

However, a quick look at the References for their report, shows that the experts' concepts of quality management and quality assurance etc. are solidly grounded in the Eurocodes and ISO 9000 series including ISO 9001:2015. These codes may be adequate to deal with the structural and design issues from the designer's point of view, but, as explained in the Companion Paper, (especially Section 2.2, Clause 7), they fail to address the contractual and quality management issues, which appear to have been largely ignored by the parties to the Chirajara Bridge Project.

The recommendations of the expert report are fully in line with FIDIC's own '*Guide to Quality in Construction'*, (FIDIC, 2004), which recommends ISO 9001:2000 type quality management systems. It appears that American and Chinese Structural Engineers also come under the same umbrella. However, the author suspects that few structural engineers, who still hope for a reliable assurance of quality in their structures, are aware that the traditional concept of quality assurance has been almost completely removed from the 2015 version of ISO 9001.

While structural engineers may be convinced of the need for traditional quality assurance provisions (QC/QA) for concreting operations in structural members and joints; they may be less likely to see the contractual ramifications for major structures such as cable-stayed bridges. The collapse at Chirajara was a wake-up call for the whole construction industry. The author questions whether the structural engineering profession, even now, has identified the failure of ISO Design Codes to address contractual failures which are still plaguing projects. In the next Section another recent disaster is discussed which has remarkably similar causes.

4 Disaster at Miami – FIU Footbridge Collapses During Erection

On March 15, 2018, the partially constructed FIU pedestrian bridge crossing an eight-lane roadway in the city of Miami, Florida, experienced a catastrophic structural failure in the nodal connection between truss members 11 and 12 and the bridge deck. (See Figure 1 below)

The National Transportation Safety Board (NTSB, 2019), determined that the probable cause of collapse was the load and capacity calculation errors made by [the designer] in its design of the main span truss member 11/12 nodal region and connection to the bridge deck. Contributing to the collapse was the inadequate peer review performed by [the design reviewer], which failed to detect the calculation errors in the bridge design.

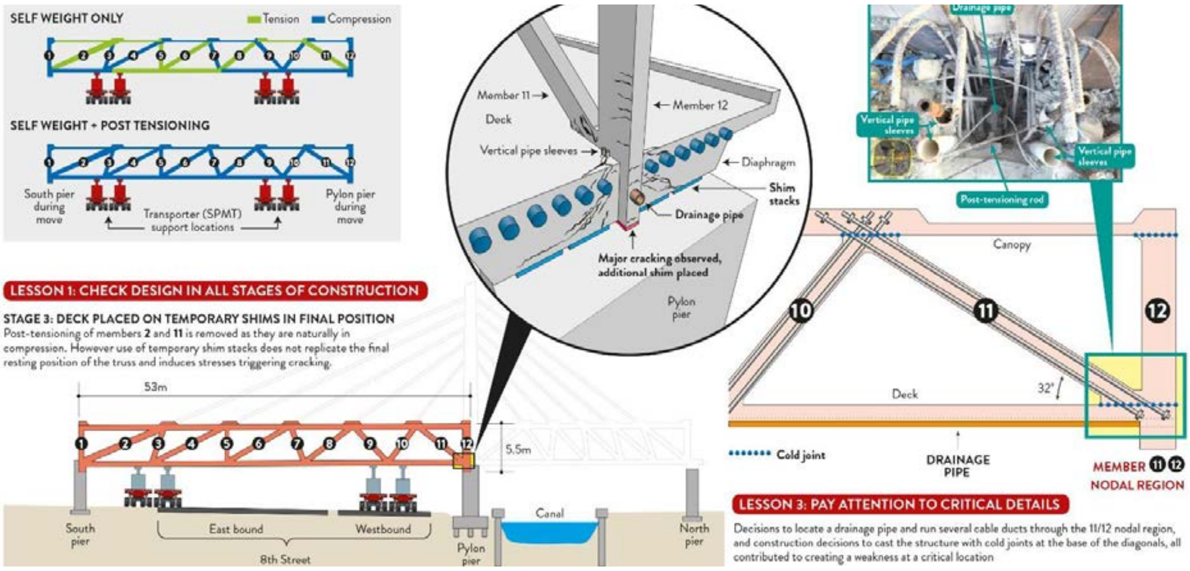

Figure 1. Part Reproduction of Diagram from Review by Akram Malik in New Civil Engineer

The following paragraphs are composed of extracts from and comments on several reports including a formal report by the NTSB. A more extensive summary was assembled by the author (Curtis, 2021) as further evidence in support of his campaign to ‘limit code harmonisation’ strictly to design planning.

The failure of this 11/12 nodal region was the triggering event for the bridge collapse. Factors in the collapse included bridge design errors, inadequate peer review of the bridge design, poor engineering judgment ....

A firm was hired to independently review the bridge design for errors. However, the review conducted by this firm did not evaluate the nodes of the bridge truss where they connected with the bridge deck and canopy, nor did it consider the multiple stages the bridge construction involved. Although the design reviewer recognized that he should have examined the nodes and stages, he indicated that there was not enough budget or time to evaluate those factors.

The designer confirmed to NTSB investigators that it analysed the design as one structure in its completed state. It only analysed the design for the completed structure and not for its various construction phases.

In an Appended Board Member Statement, the Vice-Chairman wrote:“…. *The investigation clearly highlighted basic design flaws and a complete lack of oversight by every single party that had responsibility to either identify the design errors or stop work and call for a safety stand-down, once it was clear that there was a massive internal failure.*

5 A Limitation of AASHTO LRFD Bridge Design Specification (2010)

Addressing ‘*Constructability Issues in Tender and Contract Documents*’, the BDS (Cl. 2.5.3) states that, “W*hen the designer has assumed a particular sequence of construction in order to induce certain stresses under dead load, that sequence shall be defined in the contract documents.* ”(The BDS Comment C2.5.3 applies this to an example of a cable-stayed bridge.)

Presumably, this requirement (for defining the sequence of construction) is still applicable even in a design and construct contract, where the Designer is likely to be a (sub)contractor to the Main Contractor and the design reviewer has a separate (sub)contract with the Main Contractor or (as for the FIU Footbridge) a direct contract with the Designer.

There is an obvious implicit requirement upon the client/owner (and his consultants) to draw from available resources of knowledge and experience to be able to identify that a particular process includes serious potential problems or risks. However, in the author’s opinion, this identification process needs to go deeper and to examine each sub-process so that the nature of each potential problem or risk is clearly understood, and so that practicable preventive actions can be envisaged even at the pre-tender stage. For safety’s sake, it becomes essential for the owner to develop a tentative or assumed (documented) procedure for each identified process, and to identify the potential problems and risks he has become aware of in preparing that assumed documented procedure.

The owner or his designer/specifier must ensure that the tender documents are so worded that each listed set of procedure requirements demands answers to all the necessary WHAT, HOW, WHEN, WHERE and BY WHOM questions, and that the subject work is not allowed to commence until these questions have been satisfactorily answered – at least for that stage. The requirements of the above paragraph present a massive challenge to owners but with it the opportunity to regain control of risks and costs, by appropriate pre-tender investigations.

This philosophy, (or culture), requiring significant pre-tender investigation and solving of design-construction problems by owners (or their design teams), was a central feature of *fib* Bulletin 44 Appendix G. This culture was therefore the basis for the draft international project specification (DIPS) re-introduced in the Companion Paper. Its application to tender and contract documents requires acceptance by structural engineers of relevant code limitations.

6 How Do We Establish a New Culture of Contract Management?

No one is likely to invest in developing a new culture if they believe the existing culture is still working. The author was very encouraged to read of the recent work done by Professor Fang and his team from Tsinghua University, on what he calls the LCB approach to construction safety, (where LCB stands for Leadership, Culture and Behaviour). What was especially encouraging was that this team from Tsinghua's Department of Construction Management has apparently begun to liaise with some contractors and owners on major infrastructure projects. It appears that the door has been opened, in China at least, to start addressing the issues which were raised 15 years ago in the Yantai Paper, but on which no further progress has been made.

Perhaps, with international involvement and support, there is now a more favourable climate for re-evaluating the goals and proposed methodology of the International Joint Task Force for Preventing Construction Disasters? A suggested starting point would be to define and develop skill sets for '*reinforcement detailer*', as introduced in requirements for a '*Reinforcement Plan*' in *fib* Bulletin 44, Appendix G, "*Project specifications – An owners tool*" (fib, 2008).

7 Building an Effective Safety Culture - Obstacles and Opportunities

The LCB Paper confirms the sad truth that while many nations, including China and the United States, have implemented many construction safety-related laws and regulations, there has been no significant decrease in the numbers of deaths and injuries in construction.

The LCB Paper indicates that there is often a leadership vacuum between workers and their supervisors. (Safety leadership is defined as "the ability, skill and art of a leader influencing subordinates' safety awareness and behavior"). It is the author's guess that in China, as in Europe, America and Australia, there are not many project engineers with sufficient practical knowledge and experience to be able to 'advise' the workers under their supervision. In fact, the experienced workers might better serve as instructors to inexperienced project engineers. (At least, that has been the author's experience when a junior bridge engineer. This reflects a common military tradition, where junior officers are 'mentored' by senior NCOs).

The author believes very strongly that a true construction safety culture will only be established when young structural engineers and materials scientists are willing to step out of their academic or consulting environment and spend a couple of years working on well-run construction sites. The message the author tried to share in his *fib* Osaka (2002) Presentation https://www.youtube.com/watch?v=yZqpdd_S1Ks is virtually what he would share today.

However, if you, the reader, are challenged by this video, the author would like to invite you to also view his *fib* Melbourne (Curtis, 2018) Presentation https://youtu.be/ONolO3Xm4p4 If you appreciate these videos, you are probably one of those young engineers who will want to build a new bridge between design and construction; and help strengthen and expand the new safety culture that the Tsinghua team are pioneering.

8 Concluding Remarks and Proposed Centres of Concreting Excellence

The author trusts that, in view of the fatal and costly consequences of several failed contracts in recent years, many infrastructure owners (and/or their design consultants) will re-evaluate their tendering policies and ensure that adequate pre-construction investigations, tests and trials are carried out before contracts are awarded. It is for Owners to initiate this new culture.

The author is also optimistic that, before this Paper is published, a new *fib* Task Group will be initiated under Commission 8 (Durability), which will focus on the contractual and QA/QC issues of concrete construction projects - those which are specifically not dealt with under the *fib* Model Code and relevant ISO design codes, including ISO 22966.

It is also proposed that 'Centres of Concreting Excellence' (CCEs), be established by several universities around the world which can collaborate effectively and efficiently with contractors to facilitate practical research projects on concreting and related processes. On construction sites and/or in purpose-built facilities for fabricating mock-up cages for trial placing operations, students will enjoy hands-on, expertly supervised experience in all aspects of concreting operations and over a wide range of reinforced and prestressed concrete member types

The proposed CCEs will enable materials engineers to observe and experiment with selected mixes in terms of w/b ratios, flow characteristics and durability index values. Their interaction with construction and design engineers during actual concreting operations will lead to major improvements in the specifying of holistic performance requirements for concrete mix designs.

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