Learning from incidents during bridge erection

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Abstract
Bridge building is a highly uncertain endeavour that entails considerable risk, as attested to by the succession of construction-related incidents and accidents recently reported in Spain and elsewhere. While efforts are being made to improve on-site safety, many issues are still outstanding, such as the establishment of reliability requirements for the ancillary systems used. The problems that must be dealt with in everyday practice, however, are more elementary and often attributable to human error. The overall organisation of the use of bridge construction equipment is in need of improvement. Close cooperation between the bridge engineers responsible for construction planning and ancillary element suppliers is imperative, for flawed interaction between building equipment and the bridge under construction may generate structural vulnerability. External quality assurance should likewise be mandatory.

Keywords: temporary structures, bridge construction, accident, risk, human error, construction equipment, auxiliary elements, structure-equipment interaction, quality assurance.

1. Introduction

One of the most prominent trends in modern bridge construction is the deployment of automated solutions to shorten construction times and lower the associated costs. The wide variety of ancillary elements used for this purpose is being continually upgraded, in parallel with construction techniques. Standardised elements, designed to be re-used after adaptation to the specific characteristics of each new structure, are often the facilities of choice. The use of increasingly sophisticated facilities and in particular their interaction with the bridge structure under construction entails considerable risk. Several task groups working under the aegis of international organisations are presently discussing ways to improve structural safety in connection with temporary structures and activities such as bridge construction. That notwithstanding, many issues, including the establishment of reliability requirements for the ancillary systems used in construction, are outstanding.

Many of the problems that must be dealt with in everyday practice are more elementary, however [1]. An analysis of a number of incidents and accidents occurring over a fairly short period of time in recent Spanish bridge construction history, for instance [2], shows that they are often related to human error, which, on closer analysis, can be traced back to flawed organisation. On many an occasion, the origin of such flaws lies in the singularities inherent in the auxiliary elements used in construction. The design and application of these elements are governed by certain conditioning factors that differ from the factors normally applicable to permanent structures. Consequently, they cannot be analysed or dimensioned to the rules in place for normal structures. Such rules need to be supplemented with information on the behaviour of the ancillary elements, which is usually available only to the supplier, since these systems are often patented.

This situation has significant adverse implications for daily practice. One is that a detailed analysis of bridge structure - ancillary equipment interaction is often neglected. Moreover, such
circumstances affect the allocation of quality assurance and other tasks and responsibilities among
the parties involved in bridge construction. This is an extremely important issue since effective
quality assurance is a crucial tool for the early detection of possible human error and hence for
improving the strategies presently in place to reduce construction-related risks.

2. Definition of acceptable temporary structure-related risk

Structural design codes must deal with the safety issue, either implicitly or explicitly. Under the
implicit approach used in everyday practice, the risks involved in a specific project are not
quantified [3]. Accepted risk levels are implicitly laid down in structural safety requirements, which
are largely the result of self-regulation based on past experience. By definition, compliance with
those requirements should yield sufficiently safe structures whose inherent risks are regarded as
acceptable in current practice.

Such an implicit approach to structural safety further to the codes presently in force entails a
number of drawbacks, however [3]. For instance, the lack of fully rational criteria for decision-
making may induce over-reaction and hence the adoption of unreasonable and uneconomical safety
measures. Further research is certainly required until knowledgeable answers to questions such as
“How safe is safe enough?” or “How much is society willing to pay to reduce the current level of
structural risk?” may be given. Such questions should be addressed globally, accounting for all
possible situations to which structures may be exposed, from the beginning of construction planning
to final dismantlement.

The definition of acceptable risk levels associated with temporary structures and activities such as
bridge construction constitutes a particular challenge. This question is presently being addressed by
working groups specifically created by international organizations [4]. One of the mayor subjects of
controversy is the impact of the short service life of temporary structures on the definition of
acceptable risks. The 6th International Forum on Engineering Decision-Making (IFED) deliberated,
among others, on whether target reliability should be lower for temporary than permanent structures,
given the lower likelihood of exposure of the former to extreme hazards, or on the contrary, it
should be higher in light of the more severe and visible consequences in the event [5]. While no
solution has been forthcoming, the consensus opinion seems to be that design working life would
not appear to be the sole determinant to be taken into consideration when defining risk-acceptance
criteria for temporary systems and structures. For instance, it seems reasonable that their design
should not deviate from the requirements in place for “permanent structures” where structural
failure may be expected to have severe consequences. In this context, the Danish National Annex to
Eurocode 1, Part 1-6, is referred to as an example in [5]. It provides that where due to the presence
of extraordinary wind action during construction, structural “...collapse...involves the risk of loss of
human life, or considerable economic, social or environmental consequences, the design situation
should be assumed to be for persistent and transient design situations.”

Basing the definition of acceptance criteria for structural safety on the consequences of failure is not,
of course, new, as a review of the provisions of several common codes and guidelines shows [6], [7].
ISO 2394 [6], for instance, states that “structural reliability is important first and foremost if people
may be killed or injured as a result of a collapse”. Taking an overall individual lethal accident rate
of 10⁻⁴ per year as a reference, the mentioned guideline [6] defines admissible average individual
risk associated with structures as \( r_{\text{ADM,ISO}} = 10^{-6} \, [y^{-1}] \). A former study [3] has shown that this value
compares very well to the average deduced for the implicitly accepted individual risk to persons
associated with collapse of structures in persistent situations. Although [3] refers to building
structures only (consequence class CC2 [7]), the comparison seems to suggest that accepting higher
levels of risk to human life for temporary structures may not be justified.

3. Vulnerability in bridge construction procedures

The preceding section provides some insight into the many significant aspects that inform the
definition of suitable design philosophy for temporary structures and activities. Further research is
required to establish guidelines for more consistent treatment of structure-related risks. For the time
being, a consensus seems to have been reached to the effect that such guidelines would be generally
useful to ensure that problems are carefully studied. Concern has also been expressed that overly
prescriptive guidelines may prevent flaws from being detected [5]. Indeed, as noted earlier, many of the temporary activity-related problems that must be dealt with in everyday bridge construction are more elementary [1] and often associated with the sort of human error not usually envisaged in design codes and standards. André et al. [8] summarise the findings of a survey conducted by Matousek and Schneider [9] on the causes of damage in different types of structures. Most of the types of damage identified in the 800 cases reviewed occurred during the construction phase and were primarily attributable to carelessness, ignorance or insufficient expertise. Hadipriono and Wang [10] identified the most recurrent causes of severe falsework collapse during construction to be inadequate review of falsework design and construction and the lack of falsework and formwork inspection during concrete casting. Those causes were found to stem from the lack of coordination among the parties involved in falsework erection, in particular the interaction between engineers and contractors.

Broadly speaking, the analysis of recent incidents and accidents occurring over a fairly short number of years in Spain and involving a variety of bridge erection techniques, special equipment and temporary structures confirmed the aforementioned reports. It showed that the cause of damage can normally be classified into one or several of the following categories, all associated with some manner of human error: flawed communication among the parties concerned, insufficient expertise, lack of insight, oversights, misguided judgements. In the presence of such errors, the potential hazards in a system are not fully recognised and consequently not all the measures required to prevent accidents are adopted [2].

This analysis of incidents and accidents also showed that there is sufficient scope for improvement. Indeed, the causes of failure discussed above may be traced back to organisational flaws in and around the tasks, skills and responsibilities of the participants in bridge construction. The origin of such flaws often lies in the singular nature of the ancillary equipment used in construction and the concomitant need for specific knowledge and experience to ensure their suitable design, analysis, assembly and quality control. Such control is a particularly important issue since it constitutes an efficient tool for the early detection of possible human error and hence for preventing accidents during bridge construction.

The following section contains a descriptive analysis of the arrangements presently in place for the use of ancillary equipment in bridge construction, while the lessons and recommendations drawn from this analysis are summarised in section 5.

4. Ancillary equipment - current practice

4.1 General

A wide variety of ancillary equipment is available for bridge construction, from static support scaffolding to mobile systems such as moving scaffolding and launching girders or gantries. Analysing the particular features of such systems lies beyond the scope of the present paper. The considerations discussed here refer to conventional scaffolding, in light of both their frequent use in everyday practice and their apparent structural simplicity. The conclusions drawn from these considerations (section 5) are readily adaptable to other ancillary systems.

4.2 Scaffolding as an example

Support scaffolding is used in bridge construction to provide temporary support for the loads generated by concrete and rebar, formwork, construction equipment and workers [11]. It normally consists of standards (vertical members), ledgers (horizontal members), and braces (diagonal members). These members are inter-connected by different types of specially designed joints to ensure efficient on-site assembly and dismantling operations. The base of a scaffold comprises screw jacks to accommodate ground irregularities. On the top, such jacks are normally fitted with U-heads that support timber bearers and enable the levelling of the formwork (Figure 1, left) [11].
As noted above, like other bridge construction equipment, support scaffolding is generally designed to be re-used after adaptation to the specific characteristics of each new structure. Its behaviour is consequently governed by a number of factors that may differ significantly from the actions prevailing in permanent structures. For instance, the structural behaviour of joints and therefore the structural behaviour and safety of the system as a whole are complex and may vary significantly depending on the type of joint used. This can be drawn from Figure 1 (right) [11] which compares the empirical moment-rotation curves for the wedge-type and Cuplok joints frequently used to connect ledgers to standards in support scaffolding [11]. An example given in [12] illustrates the importance of such considerations, showing that the number of diagonal braces required to assure the stability of support scaffolding may not be accurately determined unless knowledge is available on the behaviour of the connecting joints between braces and standards.

In everyday practice, given the general want of specific standards for bridge construction equipment [8] (with an occasional exception, such as [13]), ancillary equipment designers often resort to codes and standards intended for permanent structures, structural engineering principles and best practice. Nonetheless, the aforementioned considerations on the specific behaviour of ancillary equipment are a clear indication that standard rules for permanent structures may not suffice for the design and analysis of such equipment. Rather, these rules must be supplemented with specific information on equipment performance [1], which can normally be obtained by experimental testing only [14]. That specific knowledge is generally available only to the supplier, however, among others because ancillary systems designed in-house are often patented [2]. From this perspective, given current practice, it should be incumbent upon the supplier to furnish all necessary information on temporary structure design and verification.

4.3 Analysis and design

Bridge construction is characterised by the interaction between the evolving bridge structure and the ancillary elements used to build it. Depending on bridge geometry and the construction procedure, interaction may be fairly simple or extraordinarily complex. Consider, for instance, the casting operations on an ordinary overpass superstructure with relatively simple geometry resting on elementary scaffolding, such as shown in Figure 2 (left) [15]. The formwork panels constitute the interface between bridge and ancillary structure. Together with the support scaffolding, these panels are designed by the supplier based on the information on bridge characteristics such as geometry and material properties provided by the builder. The latter’s main concern in this regard is to assure structural resistance and stability of the proper bridge structure, during construction, particularly after deshoring and, of course, in the finished state.

More complex bridge geometries and therefore construction procedures induce greater complexity in the interaction between the ancillary equipment and the bridge structure. The support scaffolding used to build the superstructure for the nearly 800-m long curved viaduct depicted in Figure 2 (right) is a case in point. Its hollow box girders are characterised by variable dimensions and continuously changing inclinations in both the longitudinal and lateral directions [16]. Here the interaction between the bridge and the ancillary substructure is much more complex than in the preceding example, due, among others, to the effect of lateral forces on the scaffolding induced by the combined effect of bridge gravity loads and its curved geometry. In this case, analysing the bridge
structure and the bearing capacity of the ancillary elements separately, as in standard practice, may not suffice. Certain risk scenarios affecting the ancillary structure may not be detected in such an approach and as a result some of the measures required to ensure structural safety in those scenarios may not be adopted. Therefore, what is actually needed is a detailed interaction analysis based on a unique, especially developed structural model that factors in both the bridge and the ancillary system. All the parties involved, i.e., the construction procedure designer (often but not necessarily the bridge designer), the contractor and the ancillary element supplier must cooperate closely in this analysis. Since the behaviour of the (frequently patented) ancillary elements is normally available to the supplier only, such an analysis is often mistakenly neglected [2].

Fig. 2: Examples of support scaffolding for bridge construction [15], [16]

4.4 Assembly

As noted earlier, ancillary bridge construction elements are re-used to save costs. Erection inaccuracies and assembly errors are therefore likely to occur. In support scaffolding such errors may contribute to load eccentricities and hence to unforeseen second order effects in the constituent members.

These considerations denote the importance of correct on-site assembly, performed to the specifications of the temporary structure design. The inference is that the workers implementing these procedures must be familiar with the ancillary system at issue. Moreover, they identify a need for efficient quality control both during assembly and prior to loading. The persons responsible for on-site quality assurance must be acquainted with all the particularities governing the behaviour of the ancillary elements used. In keeping with current practice, these persons are necessarily persons in the employ of the supplier, since such details are generally not available to the other parties concerned.

4.5 Responsibility and liability under current Spanish legislation

As a result of the severity of the consequences (six fatalities and several injuries) and the intense press coverage that ensued, the collapse in 2005 of the movable scaffolding used to build the River Verde bridge [17] drove change in Spanish legislation on the use of ancillary equipment in bridge construction. Supplementary provisions [18] were developed and included as an Annex to the national design code for structural concrete [19]. One of the major innovations contained in these supplementary provisions is the explicit obligation to draw up a specific temporary structure design adapted to bridge circumstances, which must be approved and signed by a qualified expert with a full command of the elements used. The annex further provides that all on-site operations, from structural assembly to dismantling of the ancillary components, must be supervised and coordinated by the supplier’s qualified employees, who must also verify that operations are performed in accordance with the pre-established temporary structure design. The general contractor must also sign a statement of conformity. The site manager, on behalf of the general contractor, is also responsible for assuring that the ancillary equipment is used during construction to the specifications laid down in the temporary structure design.

See [1] for a detailed discussion of the aforementioned provisions ([18], [19]), which lies beyond
the scope of the present paper. Nevertheless, the foregoing suffices as an indication of the clear allocation of bridge construction responsibilities in Spanish legislation: ancillary equipment is selected by the supplier who, along with the general contractor, is responsible for its correct on-site assembly and use. Neither the promoter nor the project manager may be held liable in this respect. For this reason, project managers do not participate in the temporary structure design, nor are they responsible for determining its technical suitability. Under such provisions, their control tasks are limited to mere documentary verification. Actual quality assurance during bridge construction is assumed by the ancillary equipment supplier. More specifically, control is to be performed by a qualified person in the supplier’s employ who had no direct part in the object to be controlled (the temporary structure design or its implementation, for instance). That employee must, moreover, verify proper system assembly and use, signing a statement of conformity as appropriate. Bearing in mind that such tasks require specific expertise available in most cases to the supplier only, such an internal quality control approach would appear to be justified.

5. Scope for improvement

After the succession of incidents and accidents over a fairly short period of time mentioned in section 3 and in light of the specific difficulties associated with the ancillary systems used in bridge construction, the competent authorities laid down the new regulatory framework (see [18] and [19]), described in section 4. That constituted a substantial move toward more consistent treatment of structural safety associated with bridge construction. Although it might yet be too early to judge the effectiveness of the legislative change, in practice the situation does not seem to have changed significantly. Accidents and incidents unfortunately continue to happen, at times with severe consequences. Their rate of occurrence must be reduced further, for there would appear to be scope for improvement. Indeed, an analysis of some of such accidents and incidents shows that they were caused primarily by human error, which, on closer inspection, may be traced back to organisational flaws. The conclusions drawn from the analysis are elementary and independent of the bridge erection technique, special equipment and temporary structures involved [1].

- The safe and efficient use of increasingly sophisticated facilities for bridge construction calls for technical expertise based on a comprehensive vision of all the issues involved in these complex processes, as well as specific technical culture.
- The tasks, activities and skills of the actors concerned in project planning and construction must be unequivocally defined.
- The above is equally applicable to the protocol for the exchange of information among the parties concerned. This is a crucial concern, for inappropriate interaction between a structure under construction and the ancillary resources used may generate structural vulnerability.
- Effective analysis of these interactions calls for close cooperation between the ancillary element supplier and the bridge builder. The corollary is that the information on ancillary element behaviour should be shared.
- Wider availability of information on ancillary element behaviour would favour a change in the quality control approach presently applied, which is based on rather inefficient internal control mechanisms.

The suggestion stemming from the above conclusions is that the competent authorities should overhaul the provisions on the use of temporary equipment for bridge construction entirely. Construction procedures should be defined by an engineering team with experience and specific expertise in bridge design. This team should cooperate closely with the ancillary construction element supplier, who, if necessary, should be legally required to provide full information on ancillary element behaviour. Where systems are patented, such disclosure should be subject to the conclusion of the respective confidentiality agreements. Based on that information, the interaction between the structure to be built and the ancillary resources used should be specifically analysed, particularly where complex bridge geometries and construction procedures are involved.

Where information on the ancillary element behaviour is available, the competent authorities should require quality assurance based on external controls. In current Spanish practice, quality control is internal and conducted primarily by the ancillary construction equipment supplier. The necessary reorganisation of these aspects should eschew an overly formal, bureaucratic approach to quality
assurance. Such arrangements may be counterproductive, for they risk being used to reinforce the belief that if the letter of the law is followed, “then everything will be alright” [20]. In the approach suggested, self-regulation and associated individual responsibility should play a major role, and clear boundaries of competence should be drawn for the actors involved.

6. Conclusions

Bridge construction is a highly uncertain undertaking that entails considerable risk, as attested to by the number of construction incidents and accidents recently recorded in Spain. Many issues are still outstanding, such as the establishment of reliability requirements for the ancillary systems used. The problems that must be dealt with in everyday practice, however, are often more elementary and attributable to human error. This unsatisfactory situation can be improved by reforming the use of ancillary equipment in bridge building. Construction should be planned under the leadership of an engineering team with specific bridge-building experience and expertise, in close cooperation with the ancillary element supplier. If necessary, such specialist suppliers should be legally required to furnish the authors of the detailed design with full information on ancillary element behaviour. Where their systems are patented, such disclosure should be subject to the conclusion of the respective confidentiality agreements. The detailed design should include a specific analysis, based on that information, of the interaction between the structure to be built and the ancillary resources used. The availability of this information would also contribute to improving the effectiveness of quality assurance in temporary structure design and implementation both, and hence to perfecting the strategies presently in place to reduce human error and with it construction-related risks.

7. References


