AN UPDATE TO THE SURVEY OF FAILURES OF BRIDGE FALSEWORK SYSTEMS SINCE 1970

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Abstract: Bridge falsework systems are used to support the formwork during the construction of concrete bridges. Relevant stakeholders often do not consider them as important as permanent structures, and in recent years a high number of accidents involving bridge falsework systems have been reported. In this paper, a survey of the failures of bridge falsework systems since 1970 is presented, including an update to the information already published, covering the period between 1970 and 2012, with new data from the period between 2013 and 2015. The collected data provides useful statistics for risk assessments when considering the potential consequences associated with failures of bridge falsework systems.

1. Introduction

The present paper concerns bridge falsework, commonly used during the construction, and rehabilitation to the retrofit of bridge structures, in particular those using the Cuplok® systems, see Fig. 1.

Fig. 1: Example of bridge falsework Cuplok® systems

There are several stakeholders directly or indirectly concerned with bridge falsework systems: researchers, designers, producers, clients, consultants, insurers, contractors, sub-contractors and workers. In this context, the assemblage, use and dismantling of bridge falsework systems is usually done by a specialised sub-contractor, in accordance with a standard project or with a special developed project depending on the work complexity.

Through time the role of bridge falsework in the cost, construction rate, safety, quality, durability, efficiency, utility and aesthetics of any bridge project has increased in a consistent fashion [1]. Therefore, it is not surprising that a correct choice, good planning, design and operation of bridge falsework are keys for the success of every bridge project. In particular, it is vital that synchronised planning and continuous knowledge exchange exists between the bridge designer, the bridge contractor, the bridge falsework designer, the bridge falsework contractor and others.

Unfortunately this is not always a reality. As pointed out in [1] the framework of bridge construction consists of complex interactions between all the abovementioned stakeholders who have different backgrounds and can have different priorities, perceptions and goals, some of which can even be contradictory. Despite the construction phase being identified as the most critical stage of a structures' lifetime – most failures occur during construction rather than after projects have been completed, see [2,3] for examples – some stakeholders still do not recognise the importance of these systems: they are "temporary" and, therefore, their role is considered to be minor compared to that of the permanent structures. Consequently, the design and use of bridge falsework systems are not usually treated as carefully as in the case of permanent structures and do not receive the same level of research attention and research funding.

In practice the design of bridge falsework is usually an oversimplified process, based in a comparison of the design forces with reference resistance values given by falsework system producers, without knowing their fundamentals, which may lead to their misuse [4]. This is particularly common in the process of selecting the system bracing configuration.

The general framework outlined above contributes strongly to the high number of incidents and accidents involving the use of bridge falsework systems, which frequently cause human casualties and severe injuries, work inefficiency and partial (or total) structural damage of the infrastructure. Beyond human losses and injuries, these accidents may cause considerable economic, financial, environmental and political costs as well as damage to reputations and increased insurance premiums. Yet, despite their importance and extensive practical use, the existing research concerning bridge falsework systems is very limited, see [5].

In this paper, a survey of the failures of bridge falsework systems since 1970 is presented. The information was collected from failure databases, forensic engineering literature and from data available on the World Wide Web. From this data the most relevant procedural causes, enabling and triggering events of reported failures are identified. Estimates of the individual and of the structural risk involved with the use of bridge falsework systems are also given.

2. Individual and Structural Risk Estimates

In this section, estimates of risks to individuals, and of structural risks, are presented, specifically in terms of the Individual Risk Per Annum (IRPA), i.e. the annual probability of a fatal accident, and the annual probability of structural failure. These variables are calculated based on the results of a survey of the collapses involving bridge falsework structures since 1970 in 19 countries worldwide, which will be presented in section 3 of this paper. Note that the collapses found in the survey for the UAE occurred in the Emirate of Dubai.

The values presented below correspond to notional estimates since they are based on a necessarily limited sample, and therefore are subject to uncertainties. The methodology adopted can only provide an estimate of the average of individual and structural risk, since it is determined from a sample of heterogeneous data in terms of: i) design standards used (e.g. target reliability levels), ii) context and exposure characteristics, iii) modes of failure and procedural, enabling and triggering events and iv) types of bridge falsework systems. Therefore, they should only be interpreted in a comparative sense and not taken as the actual values.

The risk measures were obtained considering the following assumptions (assumed conservative):

- 60% of the concrete bridges and viaducts were built using bridge falsework systems;
- 80% (in the case of developed countries) and 90% (in the case of developing countries) of the existing concrete bridges were built after 1970;
- The average number of persons exposed to the risk of collapse of the bridge falsework structure was determined based on the number of reported fatalities and injuries, considering a minimum number of 40 persons and a maximum number of 100 persons at risk in each falsework structure.

Using these assumptions and the data presented in Table 1 and [6], the value of IRPA is obtained by:

$$\text{Individual Risk Per Annum, IRPA} = \frac{\text{Number of fatalities}}{\text{Number of persons at risk}} \tag{1}$$

The data presented in Table 1 corresponds to the complete information collected in each country since 1970. Since data relative to the number of bridges built each year in each country analysed is not available, an average value of IRPA in the last 45 years was determined for each country considering the total number of reported fatalities and the total number of persons exposed to the risk of collapse of bridge falsework structure. The latter is given by the product of the total number of concrete bridges built using these systems with the average number of persons exposed to the risk of collapse of the bridge falsework structure.

Fig. 2 illustrates the 19 IRPA values. It can be observed that in five countries (Andorra, Brazil, India, Portugal and Vietnam) there is an estimated chance of at least 10 in 100 000 of a fatal accident per year for this bridge construction method.

The results obtained from the survey carried out can be considered conservative because it is very likely that there are a number of unreported accidents with bridge falsework systems. This fact makes the recorded number of collapses and, possibly, the number of fatalities, a lower boundary.

Comparing the value for the individual risk obtained for bridge falsework systems with the limits specified in specialised literature, for example [7], for the acceptable and unacceptable risk levels, it can be concluded that in all countries included in the analysis, except Australia and New Zealand where no fatal injury was reported, the individual risk is higher than the broadly acceptable risk level (taken as 1×10^{-6} per year) and that in all countries, except Vietnam, the individual risk is lower than the unacceptable risk level (taken as 1×10^{-3} per year). Therefore, the individual risk for bridge falsework systems is in general within the risk tolerability zone and must be reduced “as low as reasonable practicable”, or ALARP.

The data presented in Table 1 can also be used to estimate the annual probability of failure, $P_{f,1}$, of a bridge falsework system, which can be obtained by Eq. **Error! Reference source not found.**. The results are presented in Fig. 3. As for the IRPA, the annual probability of failure was determined considering the total number of failures and the total number of concrete bridges built using bridge falsework systems in each country since 1970.

Using the method presented in [8] a value for the acceptable annual probability of failure of the bridge falsework in the order of 1×10^{-6} is obtained. Observing Fig. 3 it can also be concluded that this criterion is not satisfied.

$$P_{f,1} = \frac{\text{Number of failures}}{\text{Number of concrete bridges}} \quad (2)$$

Table 1: Summary of data used to calculate risk estimates for bridge falsework systems in 19 countries since 1970.

Country	Accidents	Fatalities	Injuries	Number of bridges[a] [6]	Persons at risk[b]
Andorra	1	5	6	200 [c]	40
Australia	1	0	15	20398	50
Austria	2	2	0	12958	40
Brazil	2	32	40	2700	100
Canada	4	7	16	17280	40
Czech Republic	1	7	67	6643	60
China	9	102	118	43200	100
Denmark	3	1	5	6161	40
Germany	19	19	42	31809	40
India	10	68	68	10044	100
Indonesia	1	4	19	2000 [c]	80
Japan	1	4	14	27938	60
New Zealand	1	0	0	7387	40
Portugal	7	10	38	2355	40
South Africa	1	2	20	3840	80
UAE	2	7	29	1021	100
UK	1	3	10	21866	40
USA	22	25	89	113400	60
Vietnam	1	60	80	500 [c]	100
Total	89	358	676		

a Number of concrete bridges built after 1970 using the bridge falsework construction method
b Average number of persons exposed to the risk of collapse of the bridge falsework structure.
c Estimated

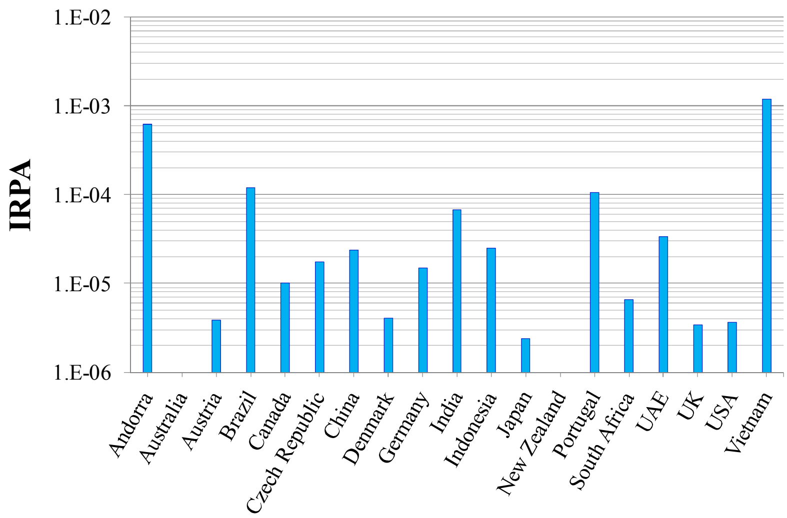

Fig. 2: IRPA values for the 19 countries considered in the survey.

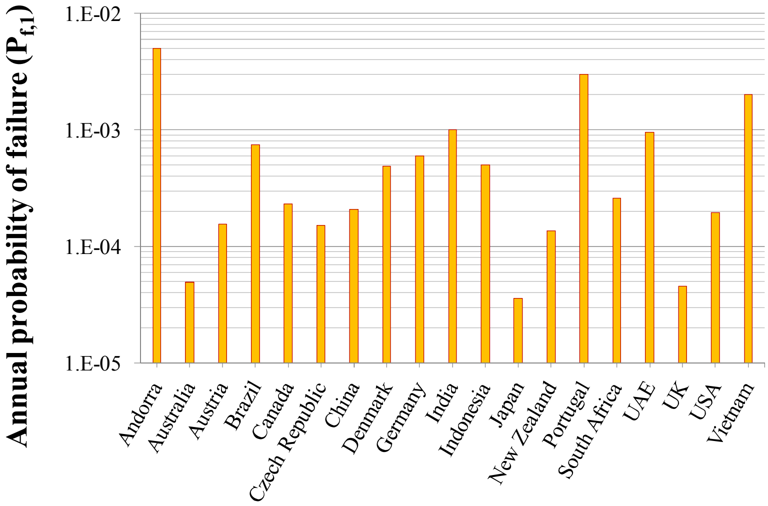

Fig. 3: Pf,1 values for the 19 countries considered in the survey.

In conclusion, the calculated estimated annual probabilities of a fatality and of a failure of a bridge falsework system are higher than the acceptable risk levels and, therefore, the development of a risk informed decision-making framework for bridge falsework systems is fully justified.

3. Survey of Bridge Falsework Systems Accidents since 1970

As part of the works carried out in the present investigation, an extensive survey over the available information reported in the literature, namely [3], in failures databases, www.bridgeforum.org for example, and in the various media channels has been performed concerning the numbers and causes of bridge falsework incidents and accidents.

It was found that since 1970, 89 major accidents have occurred in the 19 countries indicated on Table 1, involving the collapse of bridge falsework structures. It could be concluded that until the year 2000, the reported accidents occurred mainly in developed countries like Germany and USA; after the year 2000 there are an increasing number of reported bridge falsework failures in the developing world such as China, India and Dubai. The numbers also indicate a growing trend in the number of reported collapses, injuries and fatalities since 2000.

It can be observed that in most of the 19 countries considered in the survey, the total number of registered collapses is smaller than or equal to two, which could mean that the risk of using bridge falsework systems is low (although not acceptable), or that there are a number of unreported collapses as suggested by [9–11].

No reported collapse happened because of accepted risks related to deficiencies in structural codes, or related to extraordinary severe external hazards like earthquakes, floods, landslides and hurricanes or tornados. All the collapses resulted from human errors, and the main cause of failure was design error (22%), see Fig. 4. However, in 54% of the accidents the causes could not be determined (unknown or unpublished). It should be mentioned that in a high percentage of reported accidents no detailed information was found, especially until the year 2000 (in 60% of the cases).

Looking in detail into the available information, the reported deficiencies were categorised in the following three categories:

- Procedural causes
- Enabling events and
- Triggering events.

The insight achieved by this deeper investigation is considered to be extremely valuable information for the identification of the major hazards and of the critical paths of events which could lead to the collapse of a bridge falsework structure. Also, it makes it easier to setup effective and efficient barriers to reduce and control the existing risk levels.

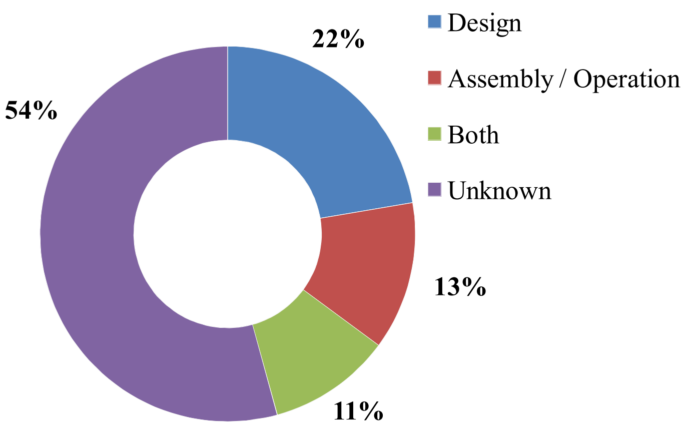

Fig. 5: Origins of errors leading to bridge falsework collapses since 1970.

3.1 Procedural Causes

Procedural causes are related to the context, and to organisational and management deficiencies. In the present investigation, eight possible procedural causes were considered, see Fig. 5.

It was found that the main contributors to procedural causes are inadequate and/or insufficient i) review of falsework design/assembly/operation methods, including falsework dismantling, (49%), ii) Quality Control and Quality Assurance (QC/QA) practices, including design and site procedures, (26%), iii) and four more specific procedural causes which occurred in almost 20% of the collapses. However, in 52% of the accidents the procedural causes could not be determined (unknown or unpublished). It can be concluded that in general several procedural causes coincide in a given accident, meaning that failures are rarely caused by one reason only, but rather by the accumulation of the detrimental effects caused by a series of small events, each of which might be not critical, but the total effect exceeds the falsework safety margin.

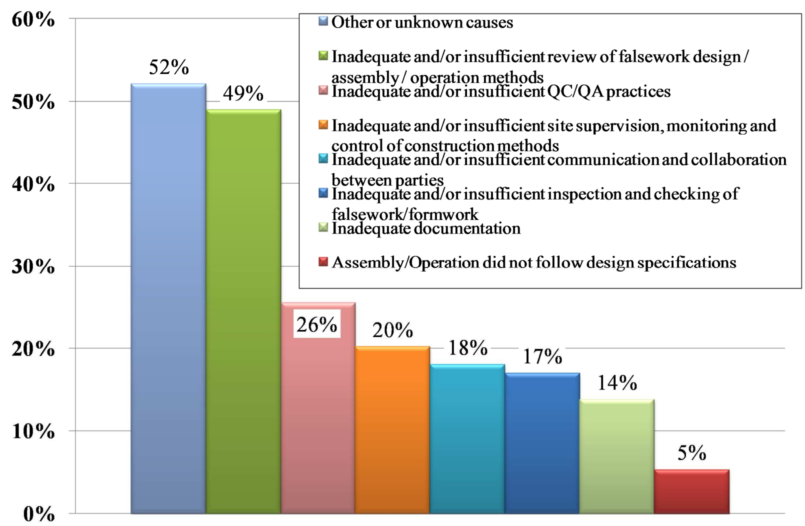

Fig. 5: Procedural causes of bridge falsework collapses since 1970.

3.2 Enabling Events

Enabling events of bridge falsework failures are related to design and operation issues, most often, both of them. Six different enabling events were considered, see Fig. 6.

It was found that the most important ones are i) inadequate falsework bracing (18%), ii) inadequate falsework main element (13%) and iii) inadequate falsework foundation (11%). The survey in Fig. 5 showed that the primary enabling event associated with bridge falsework collapses is insufficient or missing bracing elements. This can be justified by the lack of awareness in the design and in the construction stage of the stability requirements of each bridge falsework solution. Finally, in a great number of accidents (49%) the enabling events could not be determined (unknown or unpublished). Additionally, 24% of the accidents were caused by unknown design related errors.

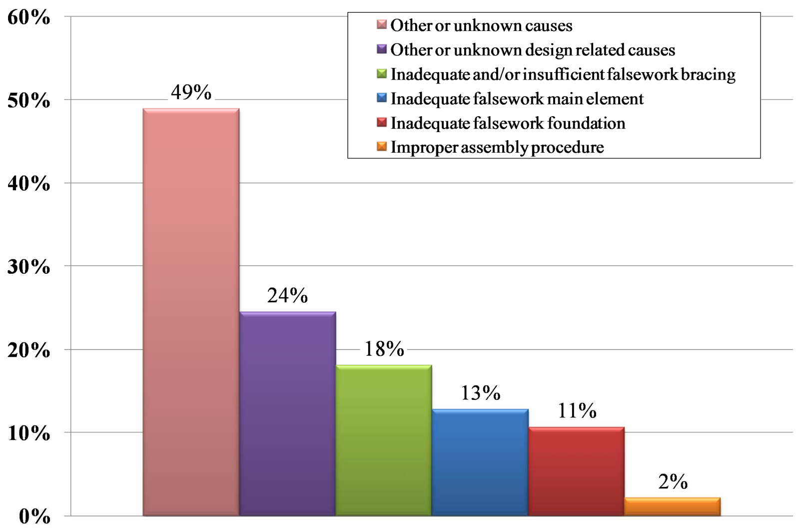

Fig. 6: Enabling events of bridge falsework collapses since 1970.

3.3 Triggering Events

In the present investigation, six triggering events were analysed, see Fig. 7. Three events emerged as the most critical ones: i) construction material loads (55%), ii) unknown events (21%) and iii) effects of improper/premature falsework or formwork assembly/removal (12%). It can be seen that expected loads during design of the falsework are responsible for 55% of collapses by triggering a local failure which then generally develops as a progressive collapse of part of the bridge falsework structure. These loads are mainly due to concreting operations.

4. Evolution from 2012 survey

In 2012 a similar survey was performed, and the results published in [6]. In that survey, the same 19 countries were analysed and 72 collapses of bridge falsework structures were found. Therefore, since the last survey 17 additional collapses have been found, 16 of them having occurred after 2012. An upward trend in the annual rate of bridge falsework structures collapses is observed since 2012, see Fig. 8.

The majority of the collapses since 2012 have occurred in India and in the USA. In the latter, it was found that the collapses are mainly due to vehicle impact into the falsework structure.

Concerning the causes, the results do not show a significant difference from the ones determined in 2012.

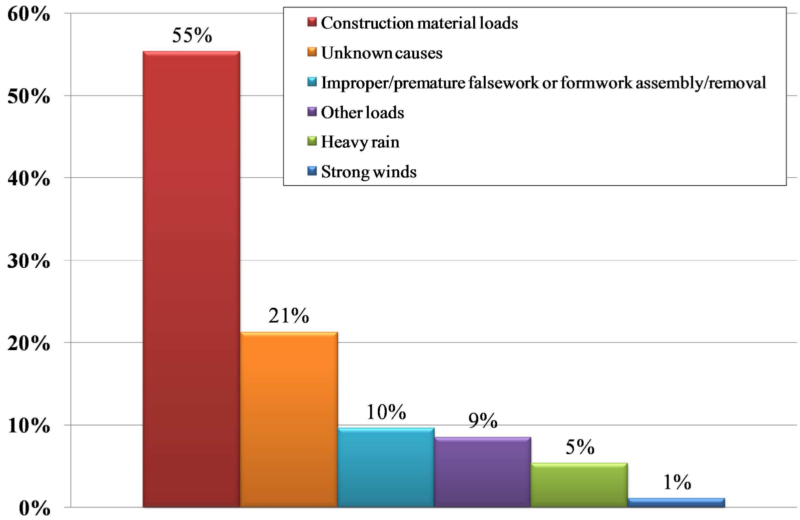

Fig. 7: Triggering events of bridge falsework collapses since 1970.

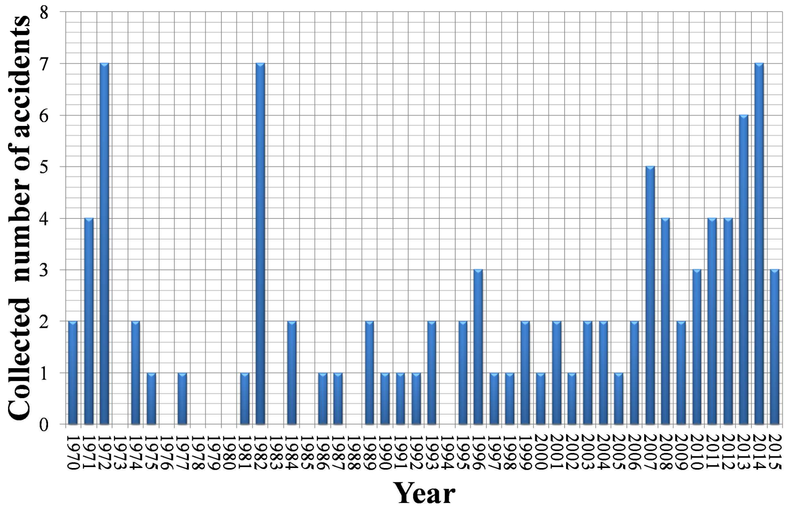

Fig. 8: Number of annual bridge falsework collapses since 1970.

The details of the more recent collapses are more difficult to find, because of the increasing confidentiality of the forensic reports due to legal matters or because these reports are still being developed. This observation justifies the larger number of cases from which there is no available information, when compared with the cases collected in the 2012 survey.

Nevertheless, the IRPA values in countries like India, the USA and China increase, in particular in the former (28%). Concerning the structural risk figures, additionally to the abovementioned countries, Austria and Denmark have also increased values. However, the increase of the structural risk obtained for India is dramatic: a 233% increase since 2012.

5. Conclusions

Bridge falsework systems are the structures most commonly used during the construction of concrete bridges. They play a significant role in the safety and profitability of a bridge project. However, based on a survey of the available literature and other information channels, 89 accidents associated with the use of bridge falsework systems have been identified since 1970 in 19 countries worldwide.

The most critical stage for temporary works safety occurs during concrete bridge deck casting. The most common design error is insufficient bracing.

Based on the information collected in the survey, the average risk to individuals, and structural risk have been estimated and evaluated against proper risk criteria. It can be concluded that, in the majority of the 19 countries discussed in this paper that the risks of using bridge falsework systems are higher than broadly acceptable levels and can even, in some countries, be higher than the intolerable risk levels. Therefore, the development of a risk informed decision-making framework for bridge falsework systems is fully justified.

The procedural, enabling and triggering events of bridge falsework collapses have been identified. It can be concluded that, in general, failures do not occur from a single error but rather from the accumulation of undetected or badly corrected errors in planning, design and operation phases. In particular the management of temporary works is essential in improving safety factors.

Comparing the results of this survey with the ones determined in 2012, it was possible to observe an overall trend in bridge falsework collapses occurring annually, and in particular in India.

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