Analysis of Causes of Falsework Failures in Concrete Structures

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Abstract: A study of 85 major falsework collapses of bridges and buildings in the past 23 yrs has documented the types of collapsed falseworks and failed permanent structures, the construction stages at the time of collapse, and the causes of failures. Three causes of failure were identified: triggering; enabling; and procedural causes. Most failures occurred because of the interaction of the triggering and enabling events that were, in many cases, produced by inadequacies in the procedural methods. Impact forces resulting from concreting operations have repeatedly triggered falsework failures that were enabled by deficiencies in the falsework bracings, components, connections, foundations, and design. Inadequate review of falsework design and monitoring procedures were frequent problems that facilitated the occurrence of these events. The findings emphasize the importance of proper delineation of responsibility of each party in the building process in order to reduce falsework failures in the future.

Introduction

Several investigations of failures of structures have included falsework-related problems. Walker, e.g., surveyed 120 failure cases, most of which occurred in Great Britain (10). In 1977, ACI Committee 348 conducted an investigation of errors in concrete structures that occurred mostly in North America (1,5). In 1977, an extensive observation of European failures was performed by Matousek, who collected 800 cases from insurance files (7). Despite the valuable information that could be obtained from these sources, no detailed study of falsework problems has yet been prepared.

This study examined the causes that resulted in major falsework failures over the past 23 yrs. Data documented from published reports were classified, evaluated, and interpreted, leading to identification of the trends of events causing the accidents. The findings may alert members of the construction profession to the technical and procedural problems involved, and therefore may also serve as a guide to better practice in the design and construction of temporary structures in the future.

Definition and Scope of Study

Falsework is a temporary structure required to support the permanent main work until it can support itself, including any additional construction loads; formwork consists of temporary components used to maintain plastic concrete in its desired shape until it hardens (2). Failure is defined as the incapacity of a structure or its member(s) to perform as specified in the design and construction requirements; in general, failure

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refers to both collapse and distress. "Collapse" is the failure of all or a substantial part of a structure, where full or partial replacement is necessary; and "distress" is the unserviceability of a structure or its component(s) that may or may not result in a collapse (6).

For the purpose of this study, data on falsework failures during the past 23 yrs were surveyed. These data were derived from several published sources including *Engineering News Record* (3), *New Civil Engineers* (8), *New Civil Engineers International* (9), investigative reports from the Occupational Safety and Health Administration (OSHA), the National Bureau of Standards (NBS), earlier studies of falsework failures in Refs. 1, 5, 10, and the writers' own experiences (6,11). A total of 85 major falsework collapses of concrete structures including bridges and low-rise, multistory, and plant-industrial buildings occurring both inside and outside the United States, were found. While the number of cases in this study is limited, the authors believe that the cases analyzed include most of the major collapses during the observed period of study.

It is noted that many falsework distresses that have occurred have not been sufficiently documented in the above sources. The same is true for cases related to formwork distresses and collapses, but nearly every case examined during this survey was a falsework-related collapse. Therefore, this study was limited to major falsework failures, a distinction which, throughout this paper, refers to the total or partial collapse of falseworks. Also, due to the limited information on life and monetary losses, evaluation of these elements was excluded.

Survey Results

Type of Collapsed Falseworks.—Five categories of falseworks were identified in the survey.

1. Regular vertical shoring: This type is frequently made of 4 × 4 sq in. (10 × 10 cm^2) timber, overlapped by a clamping device to allow for length adjustment, and has a typical load capacity of about 3,000 lbs (1,360 kg) per leg. A second regular type is an all-metal adjustable braced shoring with safe load ratings ranging from 2,500–9,000 lbs (1,130–4,080 kg).
2. Steel tower shoring: This type is generally assembled from pairs of prefabricated steel frames or tubular steel pipes with diagonal cross bracings. Its carrying capacity is up to 50,000 lbs (22,700 kg) per leg, which is much greater than that of other types. It is used very often in bridge falsework.
3. Horizontal shoring: This applies to trusses, beams, and other components that support formwork over a clear span without intermediate vertical shoring. The allowable loads range up to 600 lbs (270 kg) per lineal foot.
4. Movable falsework system: This refers to the traveling-form, slip-form, gang-form, and jump-form systems. Since they carry fresh concrete loads, they may be considered falseworks.
5. Air pressure falsework: In some domed roofs, air pressure was applied to support the forms.

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The survey results show that, in the category of the regular concrete bridges and box girder bridges, steel tower shorings constituted the most frequent type of falsework failures, as can be seen in Figs. 1(*a* and *b*). This finding is related to the fact that most of these bridges were constructed conventionally. Fig. 1(*c*) shows that almost half of the building falsework failures were due to deficiencies in regular vertical shores, and one-third of these buildings (those that had considerable heights, such as hangars and churches) failed while using steel tower shorings.

Type of Failed Permanent Structures.—Fig. 2 illustrates that more than one-third of the 85 cases studied were falsework collapses of concrete box girder and plate girder bridges. The span length varied from 40–220 ft (13–73 m), but the average was approximately 150 ft (50 m). Most of

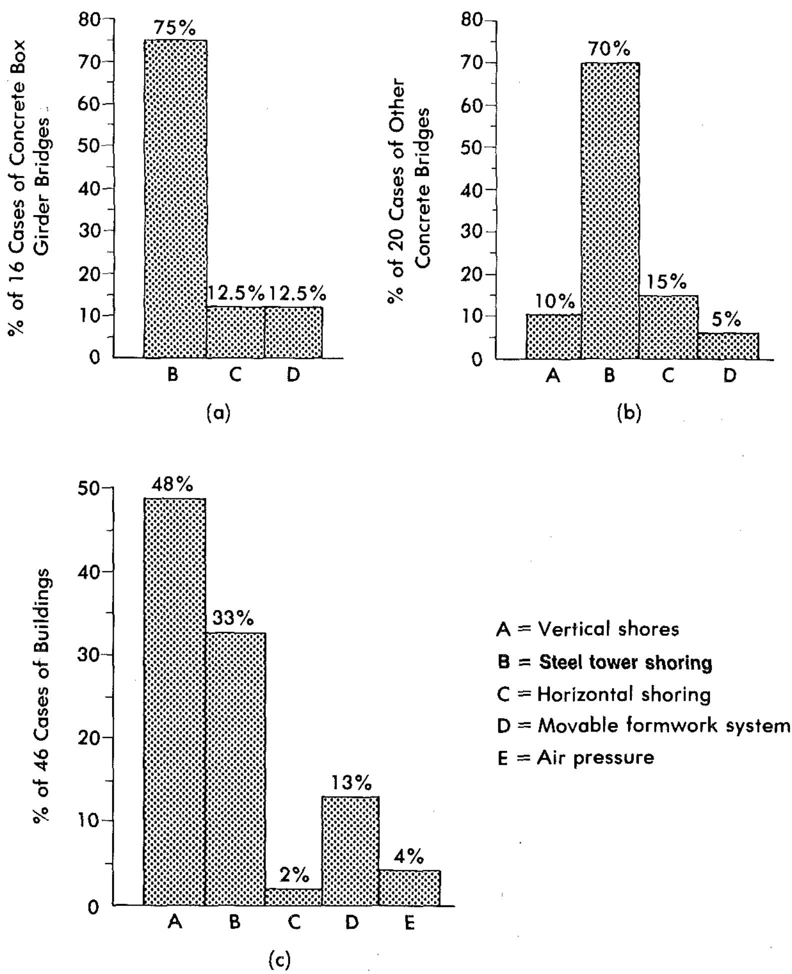

FIG. 1.—Falsework Collapse by Type of Falsework

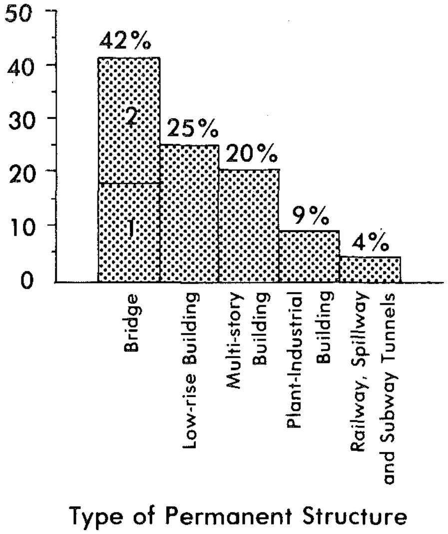

FIG. 2.—Falsework Collapse by Type of Failed Permanent Structure. Note: 1 = Concrete Box Girder Bridge; 2 = Other Concrete Bridges

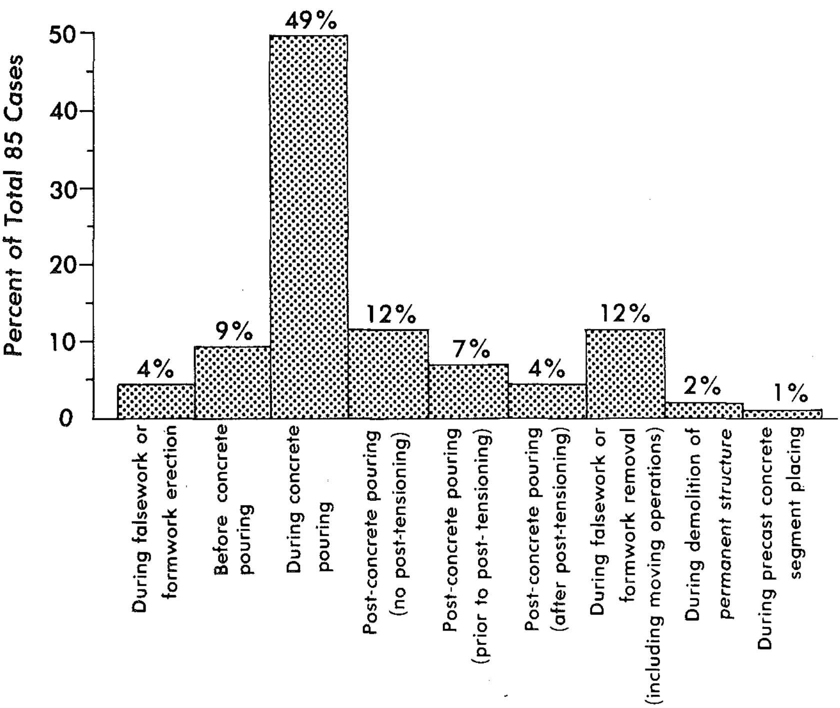

FIG. 3.—Falsework Collapse by Construction Stage

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the cases were related to partial collapses, i.e., failures of a single span or only some sections but not the entire structure. Other significant failures were those occurring in low-rise and multi-story buildings of various sizes. In many instances, local damage caused a chain reaction, which led to a progressive collapse.

Construction Stage at Falsework Collapse.—As can be seen in Fig. 3, one out of two falsework collapses occurred during concrete casting. In many cases, an excessive rate of pouring was performed during concreting, resulting in considerable lateral pressure on the formwork. Bursting of formworks led to impact loads of concrete debris on the falsework and initiated the collapse. In some cases, vibrators were used in direct contact with form ties, causing these ties to loosen or snap. The use of powered equipment, such as motor buggies, also imposed lateral forces on the falseworks; several of the falseworks that were not adequately braced have come down.

Falsework and formwork removal is another critical construction stage at which a number of failure cases were observed. A common cost-saving practice on a repetitive forming job is to remove the formwork and falsework when the concrete reaches the specified strength and to reuse them. In several cases, the concrete had not met the required strength when removal took place. In other cases, structures failed when removal took place before post-tensioning.

CAUSES OF FAILURES

Study of causes of failures resulted in the classification of these causes: the triggering, enabling, and procedural causes. The enabling causes are defined as events that contribute to the deficiencies in the design and construction of the falsework. The triggering causes are usually external events that could initiate falsework collapse. Procedural causes are frequently hidden events that produce the enabling and, many times, the triggering events. These procedural events arise from the interrelationships among various parties involved in the project.

Triggering Causes.—Table 1, section *a* shows the types and occurrences of events that fall under this category of causes of failures. Among them, the effects from concrete-pouring operations and the impact loads exerted by concrete debris when the formwork failed (cause j), are dominant. Several of these events are related to the excessive hydrostatic pressure of plastic concrete, which leads to the failures of the ties and formworks, and subsequently to the dropping of fresh concrete debris onto the falseworks. Untimely removal of falsework (cause m), is the second most significant event, and is related to weak concrete during removal and improper sequence in formwork stripping. Vibration from nearby equipment, vehicles, or excavation works (cause l) were responsible for a number of collapses. Failure of equipment for moving falsework (cause e) and impact of formwork component failures (cause f) generally result from lack of adequate maintenance. In this survey, cause *e* was found to be related to electric malfunction and loss or failure of component parts. On several occasions, excessive rain, river currents, and strong winds (causes a, b, and c, respectively) have caused bridge

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TABLE 1.—Causes of Falsework Failure

Number of occurrence (1)	Symbol (2)	Causes of failure (3)
		(*a*) Triggering Cause of Failure
3	a	Heavy rain causing falsework foundation slippage
1	b	Strong river current causing falsework foundation slippage
1	c	Strong winds
4	d	Fire
5	e	Failure of equipment for moving formwork
4	f	Effects of formwork component failure
1	g	Concentrated load due to improper prestressing operation
2	h	Concentrated load due to construction material
2	i	Other imposed loads
27	j	Impact loads from concrete debris and other effects during concreting
3	k	Impact load from construction equipment/vehicles
5	l	Vibration from nearby equipment/vehicles or excavation work
6	m	Effect of improper/premature falsework or formwork removal
20	n	Other causes or not available
		(*b*) Enabling Causes of Failure
17	A	Inadequate falsework cross-bracing/lacing
14	B	Inadequate falsework component
9	C	Inadequate falsework connection
7	D	Inadequate falsework foundation
8	E	Inadequate falsework design
4	F	Insufficient number of shoring
1	G	Inadequate reshoring
4	H	Failure of movable falsework/formwork components
2	I	Improper installation/maintenance of construction equipment
1	J	Failure of permanent structure component
4	K	Inadequate soil foundation
2	L	Inadequate design/construction of permanent structure
30	S	Other causes or not available
		(*c*) Procedural Causes of Failure
23	M	Inadequate review of falsework design/construction
22	N	Lack of inspection of falsework/formwork during concreting
2	O	Improper concrete test prior to removing falsework/formwork
4	P	Employment of inexperienced/inadequately trained workmen
1	Q	Inadequate communication between parties involved
5	R	Change of falsework design concept during construction
38	T	Other causes or not available

falsework to come down. These latter events were not considered in the design of falseworks since such events were regarded as "Acts of God."

Enabling Causes.—Inadequate falsework cross bracings or lacings, defective components, improper connections, insufficiently strong foundations, and design flaws (causes A, B, C, D, and E, respectively) were the primary sources of several falsework accidents (see Table 1, section *b*). Several major incidents, such as the collapses of the Koblenz Bridge in West Germany, the Arroyo Seco Bridge in CA, the Heron Road Bridge in Ottawa, the Skyline Center Complex in VA, and the highway ramp in East Chicago, to name but a few, have been partially or totally attributed to inadequate falsework cross bracings or lacings (cause A). Cross bracing (diagonal bracing) functions primarily to resist lateral forces, which are usually generated by wind, vibration from nearby vehicles, equipment or excavation work, concrete pouring operations, and post-tensioning activities. The function of horizontal lacing is to prevent the shores from buckling by reducing the unsupported shore length. The study shows that many of these bracings and lacings have been omitted or casually installed.

In many cases, falseworks had been used and reused several times without adequate maintenance. Many became defective due to corrosion and impact damages (cause B). This problem led to the reduction of their capacity, which was seldom considered during erection. Also, in an attempt to make dismantling easier, several falsework components were improperly connected (cause C). Many lacked bolts, nails or splicing; occasionally, unconnected components rested on top of each other and relied on friction for structural stability. Other connections suffered from poor weld quality and faulty wedges. Several connection problems gave rise to progressive collapses.

In this study, it was found that falsework foundations were constructed mostly from mudsills, concrete pads, and piles. Many of these foundations failed to transfer the loads to the ground, and many more were placed on weak subsoil (cause D). Several mudsills that were casually installed on weak ground, e.g., caused differential settlements of the falsework, resulting in the overloading of some shores, which led to collapse. In other cases, falsework foundation piles were driven to insufficient depths, which reduced the carrying capacity of the falsework.

The most frequent deficiencies in falsework design (cause E) are the inadequate consideration of the lateral forces and the stability of the temporary structures. Many unbraced shore members had excessive heights. In some instances, such members were braced intermittently, but the integrity of the total system of the structure was neglected. On other occasions, falsework design was based on the carrying capacity of original components while, in fact, many components were used and reused several times. The safety facor allocated was then consumed by the deteriorated condition of these recycled components and the subsequent decrease in their compressive and flexural strength.

Procedural Causes.—Further investigation of the cases revealed that most of the triggering and enabling causes stemmed from inadequate procedural methods. Evaluation of these factors, however, is generally available only in more detailed reports; hence, some assessments of the events shown in Table 1, section *c*, were based on personal communications with people involved in the incidents and on the writers' judgment and experience.

The most noticeable cause in this category is lack of review of falsework design/construction (case M). A common practice is for the contractor to plan, design, and erect the falseworks. Upon completion of the design, the engineer will review and approve the start of the erection process. In several cases, however, this procedure was not followed properly; the contractor did not submit his/her plan or design and the engineer felt that site work was not part of his/her responsibility. Many of the falseworks surveyed were complex, and the design could have been performed or at least verified by the engineer.

A significant number of monitoring problems were found in association with concreting procedures (cause N). Many failures occurred when the concrete inspectors in charge were absent during concreting activities, or when they were present but overlooked the enabling causes described earlier. It was also found that employing unqualified persons to monitor the erection procedures was commonplace. Improvization in erecting the falsework was found to produce changes in several falsework design concepts (cause R), a fact frequently coupled with a lack of supervision in monitoring the changes.

Interactions between Causes of Failures

The interactions between the procedural and enabling causes can be shown graphically, as in Fig. 4(*a*). A collapse enabled by design flaws (circle E) and facilitated by inadequacy in design review (circle M), e.g., is indicated by an interaction line ME connecting both circles. The den-

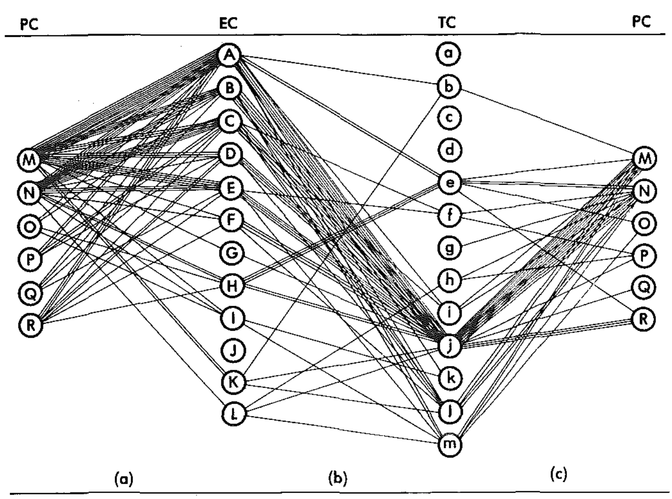

FIG. 4.—Interaction Diagram between Causes of Falsework Failure. Note: PC = **Procedural Cause;** EC = **Enabling Cause;** TC = **Triggering Cause. (See Table 1 for Symbol Description.)**

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sity of the line identifies the significance of the interaction. The diagram also shows that both inadequate review of fasework design/construction (cause M) and inadequate monitoring during concrete pouring (cause N), facilitated the failure of the temporary structures, which was enabled by bracing/lacing deficiencies (cause A), substandard components (cause B), incomplete connections (cause C), and casually installed falsework foundations (cause D).

The interactions between the triggering and enabling causes are illustrated in Fig. 4(*b*). It is evident that most failures were triggered by the impact of concrete pouring (cause j) and enabled by inadequate falsework bracing/lacing (cause A), defective falsework components (cause B), incomplete falsework connections (cause C), weak falsework foundations (cause D), falsework design errors (cause E), and insufficient number of shorings (cause F).

Fig. 4(*c*) shows the interaction diagram between the triggering and procedural causes. The most significant interaction is between the impact of concrete pouring (cause j) the inadequate review of falsework design/construction (cause M), and the lack of monitoring during concreting (cause N).

Conclusions

The study found that the most oft-repeated enabling and triggering causes were generated from inadequacies in the procedural methods employed in the project phases. These problems, such as confusion at interfaces between the contractors', engineers', and owners' staffs, were reflected in the interrelationships among the parties involved in the project. Consequently, they cause inadequacies in procedural practices, such as falsework design review and monitoring of falsework erection, leading to the previously mentioned technical problems.

The results of this study suggest the need for evaluating problems that have occurred in the past, a task that can be accomplished by using sources such as this report and others, including the Architecture Engineering Performance Information Center's (AEPIC) data bank currently at the Univ. of Maryland (4). Performance data of similar falsework structures can be retrieved from these sources; potential problems can be identified and thus, preventive measures can be anticipated and effective quality control processes may be implemented.

Despite the importance of understanding the technical problems involved, further evaluations of the institutional methods should also be performed. Much attention should be given to falsework design review and monitoring during concreting if falsework failures are to be minimized in the future. In the past, the engineer would be involved throughout the entire phase of the project, including the falsework design and field monitoring. In recent years, however, the engineer has become less involved in site supervision. One reason contributing to this problem is related to the extent of the engineer's responsibility. In this study, it was found that many contract documents did not specifically address the need for the engineer to monitor construction, even during such critical phases as concreting and falsework removal. Legal liability factors are also attributable to this problem. The engineer's approval of falsework design performed by the contractor and the engineer's interference during erection activities may result in the engineer being liable for legal claims if something goes wrong. Therefore, in order to avoid confusion among various parties involved in the project phase, proper delineation of the responsibilities of each party should be instituted.

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