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## Common root causes in recent failures of cranes

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## ABSTRACT

Catastrophic failure of cranes is a potentially very dangerous event and has often fatal consequences. The failures of two cranes are discussed in this study. Both cranes have different designs, but common root causes have been identified, related to deficiencies in the design and construction of their bases. Striking similarities in failure circumstances are discussed in this study. These include errors in the identification and interpretation of previous symptoms, in the mitigation measures undertaken and in the risks assumed by personnel, due to lack of information and training. The cranes are slender structures subjected to large loads that generate alternate stresses in the bases. The effects and implications of variable loads are often not completely understood or valued by builders and operators, which are used to deal with intrinsically static loads. A normative gap in the identification of responsibilities deriving from the equipment rent or sale contracts has been identified and is discussed. Finally, these failures stress the importance of early indications. Often, what appears to be a minor hitch turns out to be a deadly disaster.

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## 1. Introduction

Catastrophic failures of cranes used in construction of buildings and for cargo movement in ports and ships are potentially very dangerous events, and have often fatal consequences. There are hundreds of annual falling events involving tower cranes only, with a fatality rate of one per accident. The available literature on construction safety is not very optimistic about the chances of evidence-based safety in the construction industry exerting a positive influence. Many articles indicate that the structures and processes that are designed to ensure safety in the industry are poor [1]. Cranes are a central component of many construction operations and are associated with a large fraction of construction deaths; in fact, estimates suggest that cranes are involved in up to one-third of all construction and maintenance fatalities [2]. For this reason, Investigation of root causes for these failures are important for the industry and public knowledge.

Tower crane safety issues are mostly attributed to human factors. Most crane failures are related to operational faults, indolent performance of requirements or responsibilities of practitioners in tower crane operations [3]. Inadequate training and fatigue of practitioners are one of the main reasons causing unsafe practices of tower crane operations [4]. When specific defects in the design of the crane are not identified, the accident is classified as a 'normal accident', one that is essentially integral to the design and could also thus occur in other tower cranes of the same make. Once the crane is on the market there appears to be no further effective safety net for the detection of structural weaknesses [5].

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The causes for structural collapse are varied, but most falls are due to harsh weather, structural deficiencies, foundation problems, overload and errors during dismantling of these structures [6]. Most frequent risks occurred in tower crane foundation, steel structure, connecting bolts, connecting pins, ropes, and safety limit devices. These are all key points for mechanical safety [7]. Mobile cranes, due to their always changing operating conditions, are more susceptible to suffer accidents or incidents, although perhaps with a lower incidence in casualties. Tower cranes are involved in 5% of all crane related incidents, these cranes are potentially more dangerous because they are mostly operating in highly crowded areas [8].

Many mechanical failures of crane structures are related to the configuration of the mast and the horizontal arm of the crane. Often, these collapse when subjected to loads greater than those calculated by the design engineer. This often happens when hoisting a heavy load in extreme crane geometries, or under conditions of unexpected winds, see for example Fig. 1 [9]. Less often, failures are not related to the steel structure of the crane but with problems in its foundation; see for example Fig. 2 [10].

Safety of metal structures of overhead cranes has been based on accident tree analyses, which have led to measures to prevent structural failures [10]. Lists of prevalent accident scenarios and central events are available and information is published on barrier failures. What is missing is a reliable exposure gauge of the relative importance of scenarios and the identification of pivotal events. The more clearly the cause-effect chains of accident processes can be recorded, the more specific the measures, solutions and interventions can be when it comes to avoiding or reducing the effects of accident scenarios.

When performing a root cause analysis (RCA), it is necessary to look at more than just the immediately visible causes, which are often the proximate causes. Root causes are multiple factors (events, conditions or exceeded barriers) that contributed to or created the proximate causes and subsequent undesired outcome. If eliminated or modified, the undesired outcome would have prevented. Typically multiple root causes contribute to an undesired outcome [11].

This paper deals with two crane failures. Both root cause analyses were carried out after requirement from insurance companies, which are increasing their interest in risk assessment, risk based inspection and quantitative risk analysis. The analyses involved:

- Field assessments and review of construction data.
- Fractographic, metallographic and mechanical tests.
- Stress analyses.
- Engineering critical analyses.

The cranes analyzed are used for different purposes, and their designs are conceptually different. However, common root causes have been identified, mostly related to design and construction of the foundation.

## 2. Failure of tower crane

The first case is the collapse of a tower crane used for constructing multi-storey buildings, Fig. 3. Its design relies in equilibrating the mechanical moments of the tower with ballasts. These are calculated to optimize the loads on structural members in all conditions from fully loaded to unloaded. As most tower cranes, this is a very slender, counterweighted structure. Slewing is on uppermost part of the tower. The tower is anchored in the foundation or basement, which includes concrete



Fig. 1. Example of failure in crane structure, when hoisting a heavy load [1].



Fig. 2. Example of crane failure from problems in foundation [10].



Fig. 3. Collapse of tower crane used for constructing a building.

ballasts. The failed crane has a horizontal arm or “boom” composed by three 10 m long sections followed by one 1 m long section, which supports a 2.5 ton maximum load. As indicated by the arrow in Fig. 3, the failure is localized in the foundation.

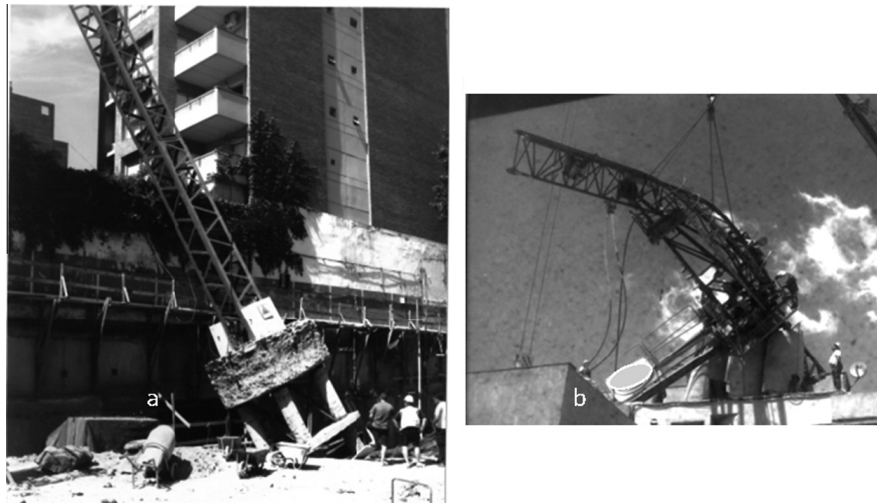
Earlier that day construction workers had noticed that the tower showed more inclination toward the counterweight than usual. The contractor asked for instructions. He was requested to perform leveling measurements in the concrete block while slewing the jib. He climbed the block and performed the measurements. He could detect how the platform tilted according to the position of the jib. He finished his inspection, left in free slew and while he was walking away from the crane, the structure collapsed.

The foundation failed and the tower fell over four buildings, destroying the roof of an apartment, Fig. 4a. Fortunately, three aluminum water tanks absorbed energy, Fig. 4b, so the counterweight did not make its way down all through the building, possibly up to street level. Fortunately no one resulted injured.

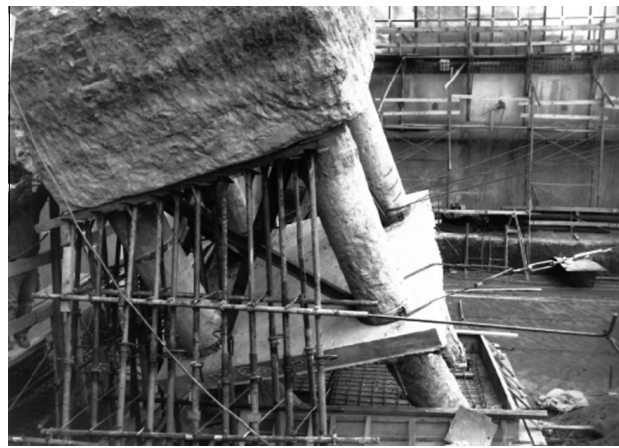
The foundation was composed by piles 12 m deep below the embedding block. Fig. 5(a and b), taken during cleaning and repair after the failure, show how the four columns were bent and displaced. The building was to have several underground levels, so as construction went on digging was done around the piles. During excavation, the crane was considered fully operative. Even in the absence of live loads, the counterweight exerts as much moment as fully loaded.

A close look at the construction history showed some previous indications of problems with the foundation. Excavations had been made around the pilots. At a certain stage, it was scheduled to place a second set of diagonal bars into the foundation. Calculations had been made considering the stability of the structure in each stage, but not in the meanwhile.





**Fig. 4.** Fall of crane. (a) Over building roof. (b) Water tanks absorbed crane's kinetic energy.



**Fig. 5.** Detail of bent and displaced foundation columns (piles) after crane failure.

Diagonal bars had been included in the previous digging stage, but not in latest. A lower reinforcement platform was under construction. Days before failure, the excavation was flooded from rainfall, it is known that the action of water lowers skin friction in structure-soil interaction [12].

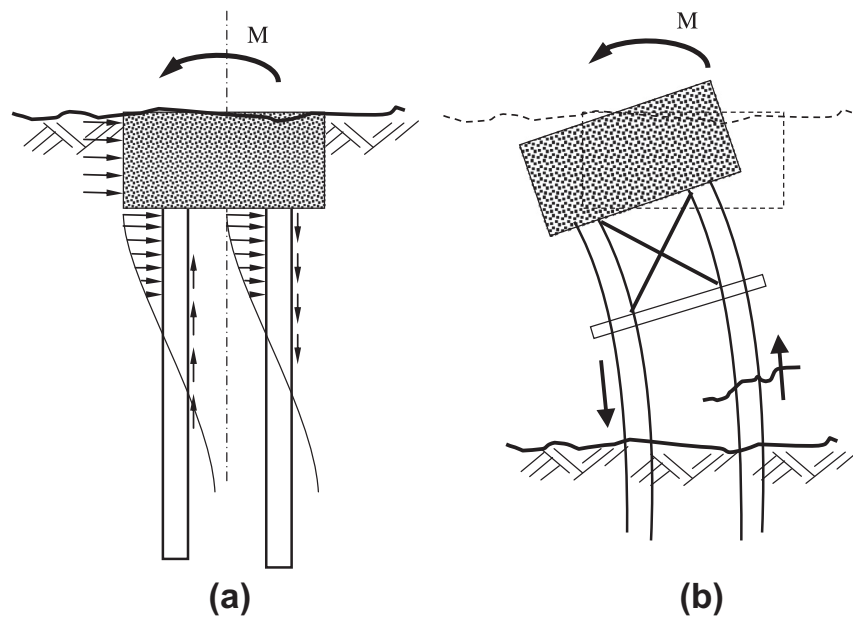
A simple mechanical analysis of the foundation allowed understanding the immediate physical cause for the failure, see sketch of Fig. 6(a and b). Fig. 6a shows how the foundation was designed to displace when subjected to the mechanical moment applied by the eccentric vertical load in the arm. After removing the ground around the pile cap, the cap was no longer laterally restricted. As piles lost skin friction, the four piles did not act as a cluster, this is depicted by Fig. 6b. Bending loads sustained by individual piles increased because of the modification of boundary conditions.

### 3. Failure of cylindrical luffing crane

The second case under study is a cylindrical luffing crane designed to handle containers and general cargoes at a river port, Fig. 7. This kind of crane has no counterweight; vertical loads and moments are withstood by a large slewing bearing anchored to the foundation. The crane was mounted on a concrete base built for the purpose. The insert of Fig. 7 was taken from an occasional witness video footage, taken at the time of the failure. It is seen how the failure occurred at the joint with the concrete structure.

Interviews with operators allowed reconstructing operating conditions just before the time of the failure. During recent operation the slewing mechanism had been producing sudden noises, so maintenance workers performed a sort of full load test with a heavily loaded container. In the middle of the test the fixed joint failed and the crane fell into the river.

All bolts of the joint broke and also fell into the river. These bolts fixed the non-rotating part of the crane to the concrete base (Fig. 8). The crane rotation system includes a 2.6 m diameter flange, containing 90  $1\frac{1}{2}$  diameter bolts. It was found that all bolts failed in a section just under a cylindrical nut (see inset in Fig. 8). This kind of nut is suitable to be used in combination with a hydraulic tightening device.



**Fig. 6.** simple mechanical model of foundation. (a) As designed. (b) Bending loads by individual piles after loss of ground support.



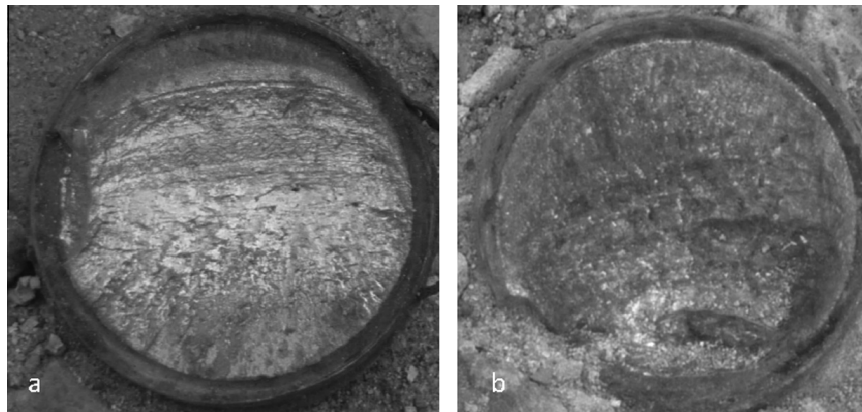
**Fig. 7.** Collapsed luffing crane at a river port. Inset: actual video footage of failure at joint with base.

Most of the other parts of the bolts were recovered from the water, and analyzed in the lab. Fig. 9(a and b) shows typical fracture surfaces in bolts. There are signs of fatigue in most of the bolt fracture surfaces. This means that fatigue damage occurred prior to catastrophic failure [13]. This reduced the number of bolts that transferred the load from the crane to the foundation. Fatigue crack growth accelerated in the remaining bolts, until remaining sections were not enough, causing collapse due to overloading of the remaining bolts. In all inspected bolts, fatigue occurred in a section below the lower nut.

Visual inspection showed that some nuts are different from the others, see inset in Fig. 8. These special nuts have a tapered end. Going back to fabrication data, it was found that these were used for positioning the upper and lower template, when aligning the bars at the erection site, see Fig. 10. There is a series of high nuts connecting some sort of extension studs. All this was confined within the grouting configuring a double nut joint (see inset in Fig. 10). There was not a leveling plate used during the erection of the tower on the foundation.



**Fig. 8.** Failure of bolted flange with base. Inset: some failed bolts, note two types of nuts, both part of the “lower nut” assembly.



**Fig. 9.** (a and b) Typical fatigue fracture surfaces of bolts recovered from river bottom.

A simple mechanical analysis of load transfer shows that these sections were not subject to the preload applied by the upper nuts, precisely due to the presence of lower nuts [14]. This is a determining factor in the joint failure, and is schematized in Fig. 11(a and b). To the left the present case, in which the lower nut closes the clamping forces generated by torquing of the upper nuts. On the right, the case without lower nuts is shown. It can be seen that bolt tightening generates compressive loads in the base and tensile preload in the bolt, which prevents it from being subjected to the cyclic loads that generate fatigue.

#### 4. Discussion of results

This article discusses two crane failures, both cranes were quite different in conception, and failure modes were also different. However, root causes in both cases are related to flawed design and construction of the foundations. These were designed and built with poor evaluation of operative conditions, reverse loading and variable stresses.

The failed foundation described in the first case has a particular condition: is a temporary structure (Fig. 4). These foundations are purpose built every time a new building is started, and a standard crane is attached to it. Once the building is finished, the crane is brought down and sent to a new job. Loads for temporary structures are different in type and magnitude from loads on permanent structures. Designer should include not only final anticipated loads on the temporary structure, but also loads during different phases of construction (such as trench shoring), and even accidental loads to a certain extent [6].

As temporary structures are not fully integrated like permanent structures are, they should be designed to stand alone as much as possible, with ties to existing permanent structures or guys to ground anchors. Triangulation of support frames, or anchors must be designed to prevent sidesway and lateral movement of the temporary structure.

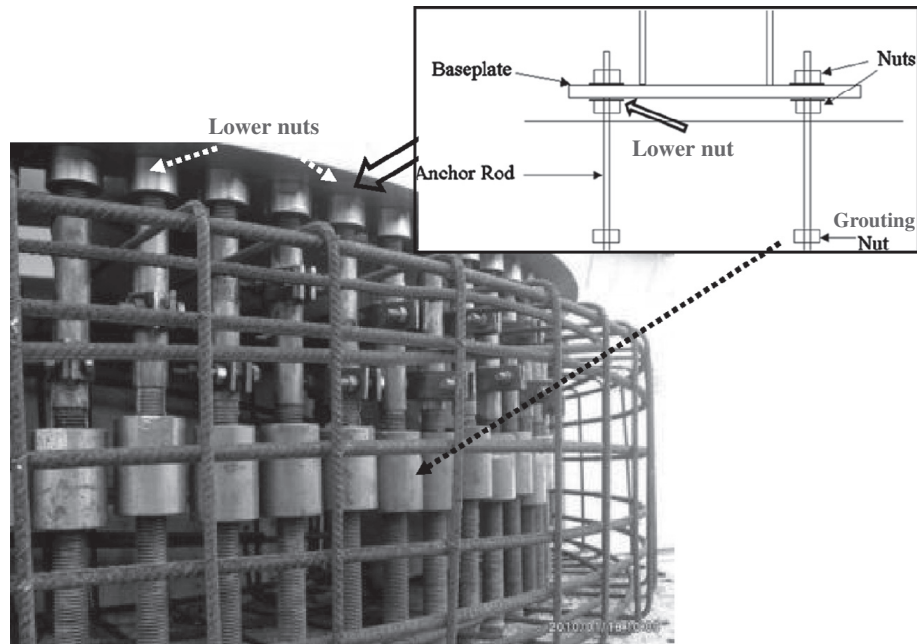


Fig. 10. “Lower nuts” that support crane, as placed during base construction, before grouting.

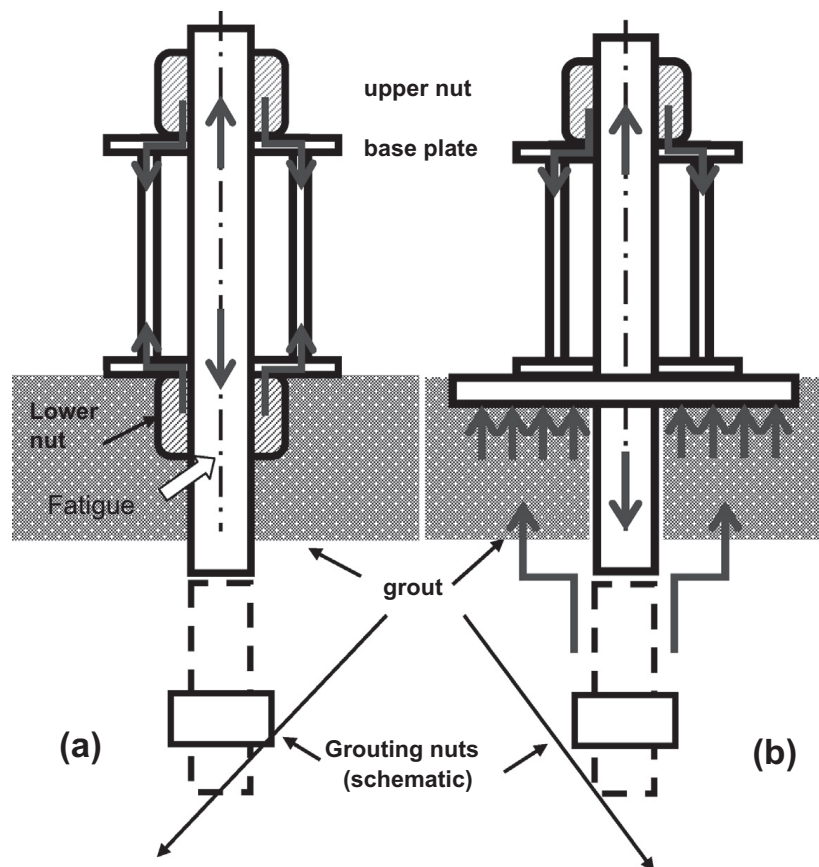


Fig. 11. Bolting scheme and “force circuit” between grout and base plate along one single bolt: (a) as in failed crane, (b) according to design, without “lower nut”.

As these temporary foundations was built with long and slender members, buckling can become a very common problem, and proper cross bracings for panels and intermediate bracings for tall columns must be designed to prevent buckling. Because of the uncertainty of foundation conditions and the impossibility of ensuring fixity at supports and continuity at



joints (except where welded), no assumption of fixed supports or rigid joints must be made in the design. The safest assumption and simplest to implement in practice, is to take columns as simply supported at bottom and top, and joints as pinned.

Because of the variable nature of materials, labor, and technology available at the site for fabrication, the factor of safety must be at least 2, although for the permanent structure, lower factors of safety usually apply. In stress analysis and design, care must be taken to model support and joint conditions realistically. For instance, in the example presented, the effect of excavation and flooding was grossly underestimated. 10. Sufficient redundancy must be built in, to prevent any local failure from escalating to system collapse by domino effect (Fig. 6). Designer has the legal (and professional) responsibility to define the conditions and limits of his design in his documentation, and to provide sufficient instructions and guidelines for the contractor to implement his design in letter as well as in spirit.

The failed crane base shown in the second example (Fig. 7) was intended to be permanent. It works with a strong bending component as it has no counterweight. The bending plane rotates with the rotation of the arm, generating alternating loads at any position around the base. All bolted joint must be preloaded with a compressive load that exceeds the loads, to which the joint will be subjected under operational conditions. Otherwise, the bolts are susceptible to fatigue [15]. This is normally accomplished with an appropriate tightening of the bolts, resulting in tensile stress close to the maximum allowable material strength (Fig. 11(a)). Thus, bolts work tensioned, but at a constant stress, at any operating load. Fatigue cracking is initiated by cyclic loads at stress levels significantly lower than overload critical stress. In the crane under study, bolts did not have any preload below the lower nut, so they were subjected to tensile and compressive axial stress during every rotation of the arm (Fig. 10).

Due to the presence of the lower nuts, bolts could not be tensile preloaded, the upper nuts just clamped the crane base to the lower nuts. This creates a “floating” condition of the base under which the tensile loads cause the incipient separation of the surfaces and the appearance of cyclic loads on the bolts. In this case, upper nuts can be tightened but tensile stress ends in the lower nut. So, when tensile stress is applied to that part of the joint, it is fully transferred by the rod to the lower part or the lower nut, Fig. 11b. There, the load is transferred by shear to the grouting. Only few threads are fully loaded. Properly preloaded bolts do not sustain cyclic stress and are fatigue safe.

In this type of structures no lower should nut have been added, and the crane should have been supported on a metal bearing plate included in the grouting. The positioning and leveling of the platform should be done by other means than the bolts. Bolts should penetrate this platform and be anchored in the concrete far below the joint surface and, if possible, free from shear stress against the concrete by jacketing or other effective way [16]. The preload must be applied by hydraulic methods to reduce the uncertainty of the torquing.

To avoid shear stress between grout and bolt, and consequently future cracking in the bolts, a non-adherent jacket could be covering the bolt; see Fig. 12. This arrangement generates a compression zone in the grouting and a tensile stress along the full length of the rod. In the “two-nuts” arrangement (which in fact have three nuts per bolt, if the lower nut inside grouting is counted) the bolt has no preload below the second (“lower”) nut. This leads to the bolt taking alternative loads that could eventually produce fatigue

There are striking similarities in the circumstances in which both failures occurred. Most relevant in order to avoid future repentance of similar failures are poor decisions made immediately before the accidents, due to poor information and poor training:

1. Information was not properly transferred between the company's design and construction teams. Load conditions taken into account during the design stage were not fully valued by constructors.
2. Early symptoms were mistakenly identified or interpreted, when the catastrophic failure could still be prevented.

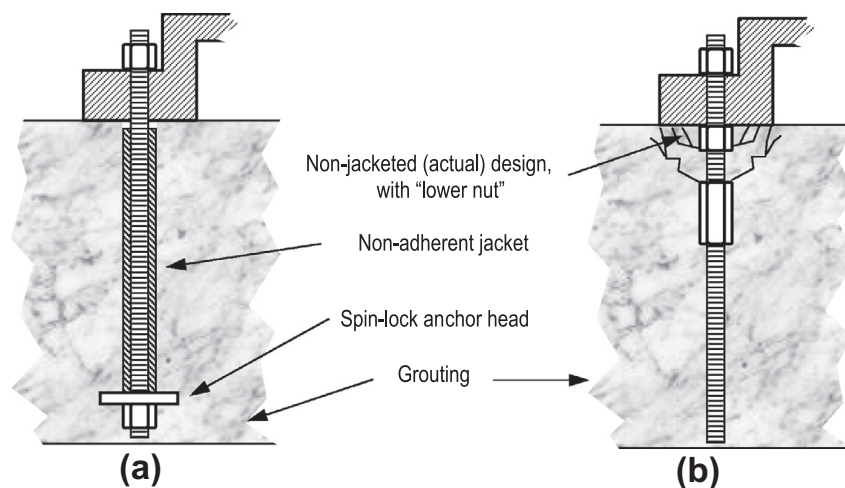


Fig. 12. (a) Non-adherent jacket to avoid shear stresses between bolt and grouting, (b) actual design.

3. No proper mitigation measures were adopted and risks were assumed: working personnel had detected abnormalities, but failed to take into account in their early stages.
4. Personnel performed tests, with no previously established procedures.

All these root causes are related to human errors, and can be defined as exceeded barriers. That is, measures that could have prevented a major failure but failed to be taken properly. Many accidents are blamed on human error, usually an error by someone at the bottom of the pile who cannot blame someone which below him [17]. Personnel had not received adequate instruction from the owner or the equipment manufacturer.

In addition, a regulatory grey region in the definition of responsibilities arising from the lease or sale of the equipment can also be identified in both cases.

Presently, the responsibility of the crane manufacturer does not go beyond the specification of the maximum load and moments that the foundations must sustain. In the presented cases human errors arose because building contractors did not fully understand the importance of variable loads and the effect of cyclic stresses on structures. The participation of crane manufactures in building crane bases, crane commissioning and also in maintenance and inspection should be very important. The early rectification of non-compliances and design defects, mainly through assuring the transference of state of the art knowledge in different kind of cranes foundations, would help avoid future errors by constructors [1,2].

To address and counteract all the potential failures discussed in the preceding sections, most developed nations establish standards and codes of practice, based on extensive analyses, experimentation, research, and experience [3,5]. Smaller and less developed countries either specify these other codes for their construction, or adopt and modify them to suit their special needs. Codes contain elaborate rules for analysis and design, tables and charts for selecting sizes, spans, etc. for various configurations and loadings, and drawings of typical arrangements and details [18].

The use of tower cranes, big mobile cranes and heavy port cranes is an increasing activity in many of South American countries. Some of these structures do not completely fulfill local regulations. Supplementary actions are needed from government and professional bodies, that include raising awareness, guidebooks, training of contractors and workers, and site inspections. Safety officers and workers should undergo formal training courses and get certified. A regulation project recently presented for study can be checked at Ref. [19].

As explanatory and supplementary material to the codes, government and professional bodies should also develop guidebooks, manuals, brochures, posters, slides, etc. They should send advisories to contractors, and conduct announced and unannounced site visits. Safety officers and workers should undergo training courses and get certified. Once a code becomes law, any violation carries legal prosecution and penalties. Formal procedures are available to identify and assess the hazards (dangers) that can lead to accidents, and to install measures ("controls") to eliminate or at least to minimize them [6]. The phases of general approach to hazard assessment and control are:

- Hazard identification.
- Risk assessment.
- Risk control.

In the final analysis, construction safety is a matter of commitment by the authorities: The management of the organization in setting out a budget and assigning safety responsibilities to trained personnel, and the government in establishing safety policies and enforcing regulations. One final caution that may be mentioned is this: If and when someone, anyone, mentions some misgiving or reports some untoward happening about anything, higher ups should take them seriously. All too often, what appears to be a minor hitch turns out to be a deadly disaster [6].

## 5. Conclusions

Catastrophic failure of cranes is a potentially very dangerous event and has often fatal consequences. The failures of two cranes are discussed in this study. Both cranes have different designs, but common root causes have been identified, related to deficiencies in the design and construction of their bases. Striking similarities in failure circumstances are discussed in this study. These include errors in the identification and interpretation of previous symptoms, in the mitigation measures undertaken and in the risks assumed by personnel, due to lack of information and training.

The cranes are slender structures subjected to large loads that generate alternate stresses in the bases. The effects and implications of variable loads were not completely understood or valued by builders and operators. A normative gap in the identification of responsibilities deriving from the equipment rent or sale contracts has been identified.

All countries specify codes for crane construction and operation, which contain rules for analysis and design for various configurations and loadings, and drawings of typical arrangements and details. Supplementary actions are needed, from government and professional bodies, that include raising awareness, guidebooks, advise to contractors and workers, and site inspections. Safety officers and workers should undergo training courses and get certified.

Finally, these failures stress the importance of early indications. Often, what appears to be a minor hitch turns out to be a deadly disaster. Accidents and failures may be prevented by promotion of training, control, and improved communications and organization in the construction industry.

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