The High Cost of Low Maintenance and Design Mistakes

By Narendra K. Gosain, Ph.D., P.E.

In the engineering and construction industry, failure is a term that is commonly used to describe a situation when a component of a structure or the structure as a whole cannot perform its intended functions. Failures can be due to deferred maintenance as well as design or construction errors. Forensic engineers explain how and why failures occur. With the right detective work and appropriate recommendations on their part, structures can be repaired giving them a longer life while providing owners a better return on their investment.

Modern Structures, Modern Problems

Current codes provide adequate requirements for structural design; however, in spite of this, collapses and distresses sometimes occur. Due to the cost of borrowing money and escalation of labor costs, owners demand that their projects be done quicker and cheaper, with accelerated schedules being very common. Additionally, modern structures are much lighter, bigger, taller, more intricately detailed with complex shapes compared to structures of past eras, and they are often a mix of several different construction materials. These details make them more susceptible to the ravages of time, temperature, wind, ice and snow. It has become all the more important to design structures keeping durability in mind.

Durability and Maintenance

A durable structure performs satisfactorily with minimal maintenance over its anticipated life. Regrettably, minimal maintenance is often forgotten by the design professionals, who consider this to be the responsibility of the building owner once the building is completed. To ensure that maintenance aspects are built in the design, close collaboration needs to occur between the owner, architect, structural engineer, mechanical/electrical/plumbing (M/E/P) engineers as well as the facility maintenance group, which ultimately will have the overall responsibility to operate and maintain the facility. Maintenance is important for open structures like parking garages and open air stadiums. However, all enclosed structures need close attention because roof and perimeter cladding that comprise the building thermal envelope are both constantly exposed to the extremes in temperature, wind and water.

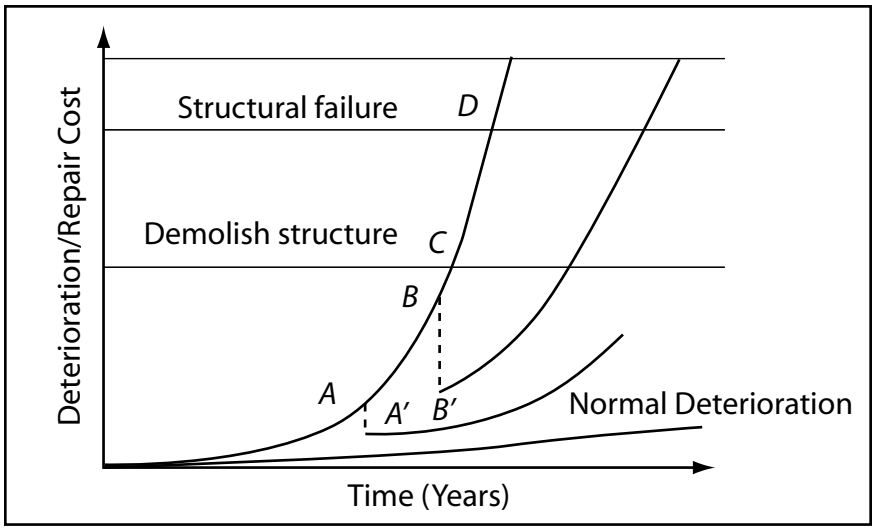

Figure 1: Structural Deterioration Model.

In the normal new building construction process, after the building is considered to be substantially complete and the contractor has taken care of the punch list items, the building owner receives the M/E/P operating and maintenance manuals. However, there is an important item that is mostly missed – the maintenance manual of the building itself. Unfortunately, this is not readily available. Structural engineers do not provide this maintenance manual since it is traditionally not included in the scope of services. Such a manual needs to be customized for the various buildings, and one can be put together for a nominal fee. Facility owners need to be educated to ask for this important manual and also be apprised of the fact there is a consultant's cost associated with it. This will save them money in the future if the items addressed in the manual are diligently executed.

Deferred Maintenance

The development and execution of a scheduled maintenance plan provides the greatest benefit. Plans for maintenance that are *not* executed are referred to as deferred maintenance. If exposed structures are not looked after adequately, concrete will crack and spall and unprotected, uncoated or poorly coated steel will corrode. These problems in various structural elements become very costly to fix if not maintained on a regular basis.

Deferred maintenance of America's infrastructure and structural facilities is part of the reason they were poorly rated in the ASCE's *2005 Report Card for American Infrastructure*. For instance, the ASCE Report Card gave bridges a Grade C, and, over the years, U.S. schools a Grade D to D minus.[1] Several independent school districts have recognized this and have started taking action, such as a plan adopted by Rockwall Independent School District in Texas called the Vision 2020 Plan[2] in which the school district formed a task group that visited every facility and did a complete audit from floor to ceiling. They projected a life cycle of all major items, assigned costs for maintenance and replacement for the next 15 years. The Plan is updated annually. This is a great example of being proactive rather than reactive.

Cost of Deferred Maintenance

Cost of deferred maintenance is best described by *Figure 1*.[3] It is certain that all structures deteriorate over time, as indicated by the plot marked "Normal Deterioration." The curve marked ABCD is the plot that, shows that if the facility is not proactively taken care of, repair cost will escalate exponentially. If there is intervention at an early stage of its life at point A', then the deterioration cost will be much lower. If intervention is at a later stage at point B', the cost will be lower than that indicated by curve ABCD but higher than the curve for point A'.

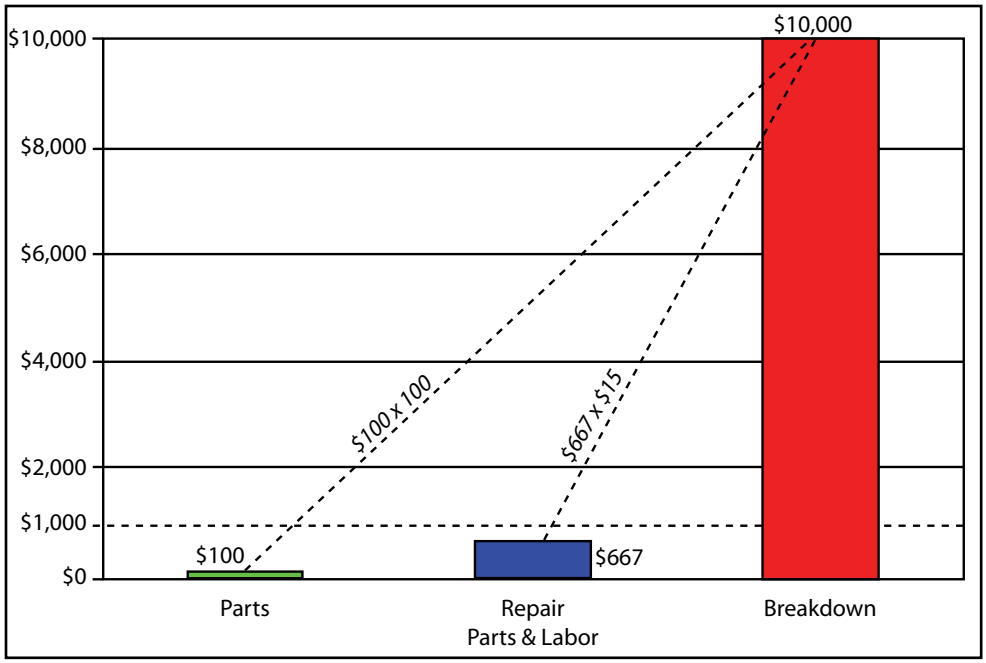

Figure 2: Geaslin's "Inverse Square Rule for Deferred Maintenance".

The primary reason owners defer maintenance of their facilities appears to be that some facility managers mistakenly consider maintenance to be a "black hole" in which resources are expended but nothing tangible comes out it. Other reasons are insufficient budget, inadequate staff to manage the process of maintenance, inability to tolerate disruption of services, lack of planning, and poor understanding of consequences.

Budgeting for maintenance has generally been done on the basis of what "feels right" and on past experience and expenditure. Very seldom do facility owners seek professional help from engineers or other professionals who understand what the critical items are and what needs to be done to proactively take care of their facility. Garage operators in the U.S. typically budget only half of what is needed to maintain their garages. The amount budgeted per year per parking space for structural work is approximately $38.00 versus $75.00 that is actually needed.

Keeping up maintenance over time does not seem to be a priority of business management. David Geaslin of the Geaslin Group[4] has taken on the challenge. He has found that time and cost to recover is huge compared to time and cost to avoid. He has developed a rule called I*nverse Square Rule for Deferred Maintenance*, which states that "If a part is known to be failing and the repair is deferred and allowed to remain in service until the next level of failure, the resultant expense will be the square of the failed part." (*Figure 2*) For example, if a missing bolt is found in a beam connection supporting a floor, and the cost to replace this is $100 but not done in a timely manner, then the cost of fixing the entire connection due to consequent failure of other bolts due to overstress and other related cost may be as much as $100 x 100 = $10,000.

Geaslin also observes that "deferred cost of repair is 15 times the cost of parts and labor when problem is first detected."

Design and Construction-Related Failures

An abundance of information is available about failures that have been attributed to both design and construction. It has often been stated that the most vulnerable stage in the life of a structure is during its construction, and sometimes critical items are inadvertently overlooked that can lead to failures. These can be related to inadequate bracing or design of formwork, premature removal of formwork, improper sequencing of erection work, improper placement of reinforcing bars, wrong profiles of post-tensioning tendons, welding flaws in structural steel connections or bracing of steel elements and masonry walls to name the most significant items.

Other construction related issues may not become apparent by manifestation of distress during construction, but will become apparent within a few months after the construction is completed. Many of these involve serviceability issues leading to water intrusion in the building. Lessons can be learned from each failure in spite of the fact that many basic causes of failure seem to get repeated.

The Detective Work of Forensic Engineers

The examples that follow describe case histories of three interesting projects on which Walter P Moore provided structural diagnostics services:

Case History 1: Deferred Maintenance

The deferred maintenance case of a **high-rise building built in the 1960s** is a lesson in the value of addressing problems soon after they occur. The columns – which are made of steel encased in lightweight concrete and function mainly as fireproofing – are partially exposed to the weather (*Figure 3*). Marble panels were adhered to the concrete to provide the architectural finish to the columns. A couple of years after the building

Figure 3: Segment of high rise building with marble clad columns exposed to weather.

Figure 4: Failed and fallen steel angle bracket connection bolted to concrete.

was built, some of the marble panels showed signs of distress and were replaced. Then, in the 1990s, some additional panels were found to be cracked; these cracks were routed and sealed. Walter P Moore's engineers conducted a thorough hazard survey in 2001 to identify potentially loose façade panels or sections of panels that could pose an overhead hazard, to rate the relative degree of damage and to determine a future course of action.

The cracking of the marble panels was caused by water intrusion into the interior of the columns through improperly sealed panel joints. The water caused corrosion of the reinforcing bars placed within the lightweight concrete encasement, which resulted in high volumetric expansion of the cross section of the bar. The expansion process then exerted very high pressures on the marble panels that were adhered to the concrete, causing the panels to crack.

The owner was presented with a color coded system for rating the observed stress shown on the building's full facades. The owner carefully evaluated the threat this posed to the public on the streets below. After obtaining the cost to replace and/or repair some distressed panels, the owner decided to remove all the marble panels completely and replace them with aluminum panels that would be far more durable. This project was completed at the end of 2007. The cost of this recladding project was approximately $20 million, and would have been much less if a façade consultant had been engaged in the 1960s.

Case History 2: Design Related Failure

A construction and design related failure occurred after many years in a **hotel ballroom floor made of precast double tees**. In the 1970s, a ballroom of a major hotel was constructed using precast double tees. The ballroom functioned satisfactorily for about 30 years until one day, while the wait staff were preparing for a major banquet, they noted a visible sag in the ballroom floor. Responding to a request for an urgent investigation of the reported sag, several pieces of concrete were found on the ceiling (*Figure 4*) and severe distress in the inverted T beam supporting the precast double tees with dapped ends. The entire floor was shored up immediately and investigation conducted. In the absence of construction drawings for this area, it was surmised that the all the precast double tee members were cast about 6 inches too short in that area. In order to use these members, a steel angle bracket was bolted to the inverted T beam by post installed expansion anchors to support the double tees.

In doing the analysis of the capacity of the as-built post installed anchor connection, the capacity was found to be only 25% of the required design capacity. This was due to the tremendous reduction in capacity due to the close spacing of the post installed anchors in the connection. Working with the contractor, a steel saddle support system was designed and installed. Post installed anchors are one of the most neglected areas of retrofit design. Fortunately, the inclusion of design requirements of post installed anchors is now included in the current ACI code.

Case History 3: Construction Related Failure

Another construction-related failure occurred in an **elementary school building masonry facade infiltrated with water**. Exterior wall construction of a two-story school building was comprised of a nominal 4-inch brick veneer with 2-inch of cavity and 8-inch thick concrete masonry wall backup in the interior. Within 12 months of the construction of the school, the paint on the concrete masonry wall failed. It was repainted, but failed again within a few months. Moisture was evident at several locations in the exterior brick veneer wall that also had lime runs as seen in (*Figure 5*). Three bricks at the mortar joints were removed to investigate the condition of the cavity and the back side of the concrete masonry units. As the mortar was being cut, water started running out of the wall, and once the bricks were removed, it was found that water had filled the brick cores. No insulation was found in the cavity. Apparently, the moisture and freeze-thaw action in the cavity had turned the insulation into a paste, and the freeze-thaw action of the collected water in the core of the brick had also split the bricks. The problem of water intrusion was caused by the poor quality of the mortar and joints. To solve the problem, the brick veneer wall would have to be removed so that new insulation could be installed. The cost of doing this work was considered to be prohibitively expense, and the school board decided not to do any repairs.

Conclusions

Failures in structures and structural elements can be due to maintenance issues, design errors and construction problems. Owners very seldom budget adequate funds to maintain their structures in a satisfactory condition. This deferred maintenance can lead to failures in performance of the structure, and subsequently involve fairly expensive repairs in the future. Design errors can occur due to lack of expertise on the part of the engineer, and the lack of commitment to perform an independent check of the design and drawings prepared by the engineer through an external or internal quality control program. Construction errors generally arise due to the desire to speed up the construction work, in which it becomes difficult to provide adequate supervision. Fortunately, the skills of the engineers and contractors have resulted in some marvelous modern structures that will undoubtedly stand the test of time. And when a minority of them have problems, we have the capacity to determine the cause and the solution so some lessons can be learned.▪

Figure 5: Lime runs in brick wall.

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