120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013

Paper ID #5684

Ancient Structural Failures and Modern Incarnations:

Dr. Marilyn A. Dyrud, Oregon Institute of Technology

Dr. Marilyn Dyrud is a full professor in the Communication Department at Oregon Institute of Technology, where she regularly teaches courses in rhetoric, business/technical writing, and ethics. She is also a part of the faculty team for the Civil Engineering Department's integrated senior project. She has been active in ASEE for more than 25 years, serving as a regular conference presenter and moderator. She was OIT's campus representative for seventeen years and served in various section leadership positions, as well as Zone IV chair. Currently, she is the chair for the Engineering Ethics Division and also is a member of the Engineering Technology Division's Executive Committee. She is an ASEE Fellow and, in 2010, received ETD's McGraw Award.

Ancient Structural Failures and Modern Incarnations: Stadium Collapses & Engineering Ethics

Introduction

Sometimes, things fall apart. In examining stadium collapses over the years, we discover that they may be due to weather anomalies or natural occurrences, such as the record snowfall in 2010 that collapsed the roof of Minneapolis' Metrodome[1] or the 1994 earthquake that snapped the moorings of the 17.5 ton Jumbotron at Anaheim Stadium, sending it crashing into the upper tier of seats.[2] Often, though, failure is attributable to engineering error: a professional misjudgment, a miscalculation, or an inability to resist pressure, such as using lower quality materials to save money.

Engineering error is not an exclusively modern phenomenon but one that dates back at least two millennia. The Romans were known for their novel building techniques: stadia, for gladiatorial contests, and circuses, for chariot and horse racing, were standard fixtures in most Roman towns. Aqueducts ensured an ample supply of water, sophisticated sewer systems enhanced the quality of urban life, and the Roman transportation system was a marvel of the ancient world, as was the innovative use of the arch, the dome, and concrete. Some structures, such as the great Colosseum in Rome, have achieved iconic status, and Roman baths are still in use today in countries that were once part of the Roman Empire.

The past offers an enlightening prism for examining contemporary times. This paper focuses on ancient and contemporary stadia collapses, specifically, an examination of two ancient and two modern cases with an explanation of similarities; the role of engineering ethics, in particular, professional judgment, autonomy, responsibility; and suggestions for classroom usage. Cultural and historical information is included as appropriate to provide context.

Ancient Cases: The Fidenae Stadium and the Circus Maximus

Background

Our ancient engineering predecessors developed many landmark structures that have withstood the test of time. Building on Greek architectural principles, the Romans constructed a new genre of buildings: the stadium and the circus, elaborate and enormous arenas for public entertainment. Taking the Greek concepts of the amphitheater, for plays and other forms of public performance, and the hippodrome, for races, the Romans added unique engineering flourishes to produce structures that dramatically influenced the design of modern sports complexes.

Stadium, derived from the Greek *stadion*, originally referred to a measurement of length: one-eighth of a Roman mile[3] or about 210 yards, corresponding to the typical length of an ancient stadium.[4] The great Colosseum in Rome, completed in 80 CE, is considered to be the "mother of all stadia"[5] and is essentially two amphitheaters joined together[6] to form an oval 527 meters in diameter, with seating for about 45,000-50,000 spectators. Unique to this structure is an elaborate *hypogeum*, an underground complex of tunnels and rooms for gladiators, animals, and props, with a complex system of pulleys and ropes to elevate required elements to the stadium floor.[7] In addition, the arena could be flooded for reconstructions of famous sea battles.[8] Another unique feature was the *velarium*, an immense retractable fabric canopy that, when unfurled, provided shade for about 30% of the seating areas.[9]

While the great Colosseum represents the epitome of stadium engineering, most Roman towns and cities had scaled-down versions, either adding new buildings or converting existing structures. Gladiatorial and sporting events "played a significant role" in Roman social life,[10] promoting a sense of social cohesion among both upper and lower classes.[11] Indeed, by the first century CE, those citizens occupying specified municipal offices were required to provide the games, some of which continued for months, involving thousands of animals and men.[10]

It is necessary to note that engineering, as we know it, evolved in the late 17th/early 18th centuries. The builders/architects in ancient Rome were referred to by several terms: *machinatoris /mechanici* (machine maker), *munitororis* (fortifications builder), *faberbra* (craftsman), *architectus* (architect), or *cunicularius* (builder).[12, 13] So when we speak of "ancient engineering," we are adding our modern construct to what was, at the time, a relatively disorganized and unprofessional occupation but one which nonetheless made lasting contributions to world civilization.

Of the five categories noted above, *architectus* is closest to our contemporary understanding of "engineer," although Vitruvius, perhaps the most famous Roman *architectus*, sees the position as involving much more than a knowledge of computation and physics: the *architectus* should be "a man of letters, an expert draftsman, a mathematician, familiar with scientific thought, a painstaking student of philosophy, acquainted with music, not ignorant of medicine, knowledgeable about the opinions of jurists, and familiar with astronomy and the theory of the heavens."[14] As a prototype of the Renaissance man, *architectus* was a prestigious position, held in high esteem.[15]

As inventive as Roman architects were, however, their structures were not immune from failure. Tacitus and other historians of the time detail a number of collapses, including the stadium at Fidenae, considered to be the worst structural failure in history with more than 20,000 fatalities and thousands injured.[16]

Fidenae Stadium

The wooden stadium at Fidenae, located 8 km north of Rome in a town now called Castel Guibileo,[17] was designed to host gladiatorial spectacles. Although most stadia were built of concrete and/or stone, wood was also used, especially in smaller venues. Wooden amphitheaters date to the second century BCE and were associated with Roman military might, as they usually included numerous monuments to the Roman military scattered around the venue.[18] They were, however, quite dangerous and more prone to collapse than the sturdier concrete and stone facilities.[6]

Emperor at the time of the Fidenae collapse was Tiberius, who "detested" the spectacles, even though Roman patricians were expected not only to enthusiastically attend but sponsor them as well. According to historian William Slater, a source of Tiberius' unpopularity was his censorship of the games. So in 27 CE, when a new venue opened north of Rome, thousands of people, "starved for gladiatorial presentations,"[11] poured into the small town of Fidenae and overloaded the wooden structure; some 50,000 were in attendance. Since the stadium had been built on either a poor foundation or no foundation (sources vary), it collapsed under the weight of the crowd, killing some 20,000 spectators and maiming thousands more. As is the case with other ancient failures, details are relatively sparse. Tacitus reports most vividly on the disaster:

> As destructive as a major war, it began and ended in a moment. An ex-slave called Atilius started building an amphitheater at Fidenae for a gladiatorial show. But he neither rested its foundations on solid ground nor fastened the wooden superstructure securely. He had undertaken the project not because of great wealth or municipal ambition but for sordid profits. Lovers of such displays, starved of amusements under Tiberius, flocked in—men and women of all ages. Their numbers, swollen by the town's proximity, intensified the tragedy. The packed structure collapsed, subsiding both inwards and outwards and precipitating or overwhelming a huge crowd of spectators and bystanders.
>
> Those killed at the outset of the catastrophe at least escaped torture, as far as their violent deaths permitted. More pitiable were those, mangled but not yet dead, who knew their wives and children lay there too. In daytime they could see them, and at night they heard their screams and moans. The news attracted crowds, lamenting kinsmen, brothers, and fathers. Even those whose friends and relations had gone away on other business were alarmed, for while the casualties remained unidentified uncertainty gave free range for anxieties. When the ruins began to be cleared, people reached to embrace and kiss the corpses—and even quarrelled over them, when features were unrecognizable but similarities of physique or age had caused wrong identifications.
>
> Fifty thousand people were mutilated or crushed to death in the disaster. . . . Immediately after the catastrophe, leading Romans threw open their homes, providing medical attention and supplies all around. In those days Rome, for all its miseries, recalled the practice of our ancestors, who after great battles had lavished gifts and attentions on the wounded.[6]

Some of the details of Tacitus' description are reminiscent of modern failures, such as the 1981 Hyatt Regency Kansas City walkways collapse, which crushed 114 people, or the 1995 Sampoong Superstore collapse in Seoul, Korea, which resulted in more than 500 killed and nearly 1,000 injured. And certainly the emphasis on "sordid profits" remains a continuing refrain in 20th century engineering failures.

Circus Maximus

While stadia were developed primarily to host gladiatorial spectacles, another popular Roman pastime, racing, required a different venue: the circus. Like the stadia, Roman circuses were based on an earlier Greek structure, the hippodrome, which was the chief venue for chariot races. Hippodromes were oval-shaped fields, about twice as long as a stadium, with a low barrier wall running down the center, to separate incoming and outgoing racers.[19]

In addition to hosting horse and chariot races, Roman circuses were venues for *venationes*, beast-hunts, which featured specially trained gladiators hunting animals in an arena replete with props to simulate hunting in the wild. *Venationes* were an extremely popular form of entertainment, so much so that some exotic species—lions, tigers, elephants, and giraffes—faced extinction, as the Romans imported them from all areas of the Empire expressly for the purpose of slaughter.[20] During a spectacle lasting 100 days, more than 9,000 animals were killed to celebrate a military victory.[21]

While these contests also were performed in stadia, the design of the circus was more amenable to the required staging. Most larger Roman towns had circuses, but the Circus Maximus in Rome was the largest and most impressive. It was an enormous arena, initially built in 530 BCE by an Etruscan ruler, and measured 621 meters long and 118 meters wide. The oblong staging area was bifurcated by the *spina*, a barrier running the length of the field. Tall columns, which also functioned as turning posts,[22] at each end of the *spina* were capped with statues of eggs and dolphins, symbolizing the patron saints of Rome, Castor and Pollux, and horses, in honor of Neptune. Other areas of the *spina* were adorned with decorative obelisks, bas-reliefs, and an elaborate lap counter.[23]

The Circus featured seating for 250,000—five times that of the Colosseum—and later additions increased seating to more than 270,000.[24] Lower tiers, for the upper classes, were made of stone or marble, and upper tiers, for the less affluent, were wooden.[23] Chariot races were very popular, especially with the masses, and also very dangerous, as up to 12 charioteers would madly race around the arena for 7 laps in very lightweight and unstable chariots. The mortality rate of the drivers, typically slaves or freed-men, was significant.[25]

Crowds were often unruly and betting was rampant, as was prostitution. The areas inside the interior corridor and around the Circus were labyrinths of shops, brothels, and arcades, teeming with pickpockets, gamblers, and drunks;[26] violence was not unusual in the Circus, as the masses argued over loyalties to their favored teams, often prompting soldiers to quell potential riots.[27] Writers of the day bemoaned the obsession with the races:

> . . . a people to whom one need only throw bread and give a spectacle of horses since they have no interest in anything else. When they enter a theatre or stadium they lose all consciousness of their former state and are not ashamed to say or do anything that occurs to them . . . constantly leaping and raving and beating one another and using abominable language and often reviling even the gods themselves and flinging their clothing at the charioteers and sometimes even departing naked from the show.[28]

As contemporary ethicist Sissela Bok notes, a culture of violence was necessary in ancient Rome, to foster public support for the constant warfare required to maintained the empire; Rome was "a warrior state," and the spectacles kept the populace "distracted, engaged, and entertained."[29]

In 140 AD, the wooden upper tier of seating collapsed, killing 1,112. The event is characterized as "the worst sporting disaster in history."[30] Curiously, there is no extant account of the event, although some contemporary writers cite overcrowding as the primary cause.[31]

Contemporary Cases: Husky Stadium and FC Twente Stadium

The design of modern stadia echoes their ancient origins: built in a style similar to the great Colosseum, they are essentially amphitheaters with tiered seating, developed for our contemporary gladiatorial contests: soccer, football, and other athletic competitions. And, just like their ancient counterparts, structural collapses punctuate modern history. In 1902, for example, 25 were killed and 517 injured when the west stands collapsed at Ibrox football (soccer) stadium in Glasgow.[32] More recently, the roof of the new "Pride of the State" stadium in Malaysia came crashing down in 2009, fortunately during a lull in activities.[33]

Our contemporary fascination with sports is reminiscent of the Roman obsession with gladiatorial contests and racing; one need only to look at the frenzy prompted by Super Bowl weekend or a World Cup competition to recognize the similarities, although we tend to replace the bloodlust aspect of the Roman spectacles with film or video games—games based on the Roman Colosseum, for example, invite the user to "develop your warrior skills" and practice "tactical thinking,"[34] and the popular 2000 movie, *Gladiator*, glorified the Romans' zeal for blood. Noticeably different is size: the largest football stadium in the world seats 150,000,[35] about half of the Circus Maximus' capacity; in the United States, the country's largest seats 109,000.[36]

Husky Stadium

Since 1920, the University of Washington's Husky Stadium has witnessed scores of college and professional football games; hosted the 1990 Goodwill Games, which included a speech by President Ronald Reagan;[37] and ushered in two innovations that have since become traditions: Astroturf in 1968 [38] and "The Wave" in 1981.[39] Located on the shores of Lake Washington, the stadium features panoramic views of the lake and Mt. Rainier. And, like the stadia of ancient Rome, it provides both a social outlet for spectators and a source of entertainment.

Over the years, the stadium has been renovated several times, primarily to increase seating: in 1936-8, 13,000 seats were added to the original 30,000; in1949-50, construction of a tiered south grandstand and a two-tiered press box, covered by a cantilevered roof, added another 15,000 seats; and in 1968, the stadium was enlarged by 3,000 more seats, in attempts to improve recruiting by offering a more contemporary venue.[40] By the 1980s, the stadium had more than doubled in seating capacity, from 30,000 to 61,000.

In 1987, construction began on a covered north grandstand to complement the 1950 addition and increase seating capacity to 72,500.[41] On the morning of February 25, a workman noticed a buckle in one of the 28-inch diameter supports for the cantilevered roof. Two hours later, the first two sections of a planned nine-section addition came tumbling down, with an ear-splitting roar.

In a mere 12 seconds, the new grandstand resembled, as one reporter noted, “a fallen giant erector set.”[42]

University of Washington Athletic Director Mike Lude watched awe-struck from his office as the event unfolded during a regularly scheduled staff meeting: “it’s kind of like having a new offspring and having something happen to it . . . . It was unbelievable. I couldn’t believe what I was seeing, but I was seeing it and hearing it.” Others in the room simply uttered “one word expletives.”[43]

The collapse occurred in a stadium devoid of spectators and only occupied by some 40 steelworkers. Due to the workman’s keen observation of the buckle, all were safely evacuated; the only fatality was the structure itself. Even the workers’ mascot, a cat, emerged unscathed from the rubble.[43] Damages were estimated at $500,000 to $1 million.[40]

Structural failure analyst Ken Carper, from Washington State University, attributes the collapse not to the design but rather a poor decision to remove temporary stabilizing cables that prevented the roof from twisting. Because final stabilizing features were not finished when the guy lines were removed, the whole section simply “fold[ed] to the ground like an accordion.”[45] Despite this setback, the stadium addition was completed in time for fall football season.[44]

FC Twente Stadium

Passion in the United States for football pales in comparison to the messianic fervor in the rest of the world for soccer. Indeed, many structural collapses are the result of not uncommon crowd stampedes, such at the 1982 Moscow collapse of Luzhniki Stadium that resulted in up to 340 dead or the 1989 Hillsborough collapse in Sheffield, England, that claimed 96 lives. The sheer crush of people collapses portions of the stadia, typically the seating areas, and spectators caught in the chaos are overcome.[46] In fact, a CNN/*Sports Illustrated* review of major 20th century sports stadium incidents reveals that at least 7,000 people have been killed and nearly 10,000 injured by crowd stampedes.[47] This type of unruly conduct recalls the crude behavior of Romans in the Circus Maximus that so disturbed Juvenal and other Roman writers.

But engineering-based collapses also occur. In July 2011, a portion of the roof over the De Grolsch Veste Stadium collapsed in Enschede, The Netherlands, home to the country’s leading soccer club,[48] under circumstances similar to the failure at Husky Stadium. The Enschede stadium was under renovation to increase seating capacity from 13,000 to 30,000 when roof supports failed in the new section, trapping workers under the wreckage: 2 died and another 14 were injured.[49] One observer noted, “It collapsed with a huge noise like a house of cards.”[50]

In The Netherlands, a state agency is responsible for investigating incidents in a number of areas, including construction, and writing reports for public access.[51] After a year-long investigation, the Dutch Safety Board isolated several reasons for the Twente incident and offered a number of recommendations to prevent future occurrences. According to the board’s report, three major factors contributed to the collapse:

- the construction work was inadequately coordinated and checked
- duties, and therefore responsibilities, in the construction process had not been properly assigned or were not properly performed
- decisions were not made at the right level within the organization[52]

Apparently, the contractors were doing work simultaneously rather than sequentially to meet tight deadlines; they began finishing work on the roof structure before it was fully stabilized, and had, as in the Husky Stadium, prematurely removed guy lines. In addition, the main contractor abandoned the initial work schedule, moved tasks up by several weeks, and did not clearly inform the subcontractors of changes in procedures. The London-based Institution of Structural Engineers, in a position paper based on the Dutch failure, offered these words of wisdom: "Better to be alive and a few days late," and "hope should not be part of a safety regime."[53]

Contemporary engineers and ancient architects do not deliberately kill the public. However, in not paying appropriate attention to construction details or by miscommunicating to contractors, the result would appear to be a disregard for the value of human life.

Engineering Ethics

When does a physical failure become an ethical failure? According to Swiss researchers Matousek and Schneider, who analyzed 800 structural failures involving loss of life, major factors include the following:

Insufficient knowledge	36*
Underestimation of influence	16
Ignorance, carelessness, negligence	14
Forgetfulness, error	13
Relying upon others without sufficient control	9
Objectively unknown situation	7[54]

* = percentages

It is apparent from this list that breach of ethical conduct, as detailed in engineering codes, is a primary cause of physical disasters.

While the only extant code of ethics dating from ancient times is in the medical field,[13] Aristotle's *Nicomachean Ethics,* written c. 350 BCE, provides a blueprint for living the virtuous life, which, in turn, benefits the greater good of society.[55] Three centuries later, Roman builders and architects were accountable to both building codes and an assumed personal countenance, detailed by Vitruvius in his *Ten Books on Architecture*. Portions of this document compare favorably to contemporary engineering codes, especially in the areas of professional judgment, autonomy, and responsibility.

Modern engineering codes have as their first fundamental principle "using [the engineer's] knowledge and skill for the enhancement of human welfare and the environment,"[56] implying that engineers will use their talents to benefit the community. Similarly, Vitruvius speaks of the *architectus* as both a technical person and a scholar, as one function depends upon the other: "architects who have aimed at acquiring manual skill without scholarship have never been able to reach a position of authority to correspond to their pains, while those who relied only upon theories and scholarship were obviously hunting the shadow, not the substance."[57] The *architectus* pursues a harmony of design encompassing six principles: order, arrangement, eurythmy, symmetry, propriety, and economy. Order refers to proportion, and arrangement involves "the putting of things in their proper places," as expressed by the groundplan, elevation, and perspective. Eurythmy is the expression of artistry, while symmetry is "a proper agreement between the members of the work itself." Propriety involves following approved construction methods. Vitruvius' notion of economy is similar to our contemporary understanding of managing materials, equipment, and workforce, as well as the "thrifty balancing of cost and common sense."[57] If a designer adheres to these principles, the resultant building will perform its proper function, and the *architectus* will have fulfilled his mission and contributed to the public good, especially in the design and construction of public structures.

In examining the ancient cases detailed above, it is clear that the builders of the Fidenae Stadium and the upper-tier seating in the Circus Maximus did not practice what we would consider "good" engineering judgment in their choice of building materials: using wood, which is cheaper but more prone to collapse and susceptible to fire, rather than the more durable stone. Although mores at the time accepted that the masses were expendable and hence their lives were less valuable than those of the patrician class, loss of seating areas would also prove expensive to replace. In addition, Atilius, the ambitious former slave, was ignorant of the characteristics of the site, which Vitruvius notes is a major responsibility of an *architectus*; the land was unsuitable for building such a grand structure. And Atilius himself was apparently ignorant of certain construction techniques, such as the proper method of fastening the seating to the structure. He was, as ancient records note, "banished" for his part in the disaster, although what that actually meant is unclear.[6]

The outcomes, however, were favorable to the general public: the Roman Senate passed a law with two major provisions: that a firm foundation be established prior to construction and that no one with a fortune valued at less than 400,000 sesterces (about $600,000 in contemporary dollars, assuming gold coinage and standard usage)[58] be allowed to construct public buildings.[6]

Practicing good engineering judgment is a contemporary virtue as well as an ancient one. In the modern cases, engineers were also remiss. Allowing the contractors to prematurely remove guy lines resulted in the collapse of the two stadium roof structures and, in the FC Twente incident, loss of life. While the presiding engineer did not actually order removal of the cables, he was certainly legally responsible for the action, which indicates a lack of communication and an apparent inability to effectively manage contractors and subcontractors.

While we consider autonomy to be a more modern aspect of professionalism, ancient designers were also given a certain freedom in design; just like contemporary engineers, they were expected to comply with regulations as well as the patrons' wishes, for private buildings. Failure to follow building codes could result in enormous loss of life, as ancient structures were built to house a significant portion of a city's population; the Circus Maximus, for example, held about one-fourth of the population of ancient Rome [59] and probably more, due to the popularity of the racing events and the beast-hunts.

Autonomy confers responsibility. In ancient Rome, the *architectus* had considerable obligations, more, in fact, than contemporary engineers: as a masterbuilder, he was responsible not only for design and construction but had "complete and total authority on the building site." Starting with the Renaissance, masterbuilder functions began to separate,[60] until today, when several people are responsible for design, construction management, contracting, project management, etc. When structures failed in the ancient world, only one individual was responsible: the masterbuilder. Now, legal and moral responsibility is much more diffuse, making it more difficult to assess blame.

Another point of intersection between ancient Rome and our contemporary world is the engineering codes' exhortation to "perform services only in areas of their competence."[56] A transportation engineer would not design an HVAC system nor would a mechanical engineer design a building. Tasks are completed as per the professional's area of expertise. While the ancient masterbuilder was responsible for all facets of a construction project, he was to be, as Vitruvius explains, both a scholar and a practitioner, knowledgeable in theory and artistry as well as appropriate construction techniques.[57] Atilius, a least according to the few extant descriptions, was neither: a member of the lower classes, he erected the flimsy stadium at Fidenae to make money, capitalizing on Rome's temporary abeyance of the games during Tiberius's reign. Focusing on the bottom line, of course, resonates in modern times, as many a failure is due to cutting costs, as with the 1911 Triangle Shirtwaist Fire in New York City, or delaying maintenance to economize, as in the 1988 Aloha Airlines incident, where the top part of the fuselage peeled back.

One notable difference between contemporary engineers and the ancient *architectus* is in the general area of public safety. All current engineering codes include the "hold paramount" phrase, which states that safeguarding the public safety, health, and welfare is the most essential aspect of an engineering venture. Vitruvius speaks of "public benefit," referring to aesthetics, but general safety is not a concern, with the exception of a passage expressing concern about using lead pipes.[57] The difference is undoubtedly due to cultural variations; the Roman view of "the masses" was "the antithesis of contemporary value-systems," and slaves, in particular, were subject to what we would view as abhorrent treatment.[61]

Classroom Usage

Mechanical and structural failures are surely inevitable: systems stop working, unmaintained structures collapse, and parts simply wear out. But those caused by human error—a lapse in judgment, a calculation error, cutting corners to reduce cost—are avoidable. Perhaps by focusing more on the engineer's ethical responsibility in all classes, we can help avert some of those failures or at least lessen their impact on an innocent public who spends much of their lives using and living in the technological artifacts designed by engineers.

Looking at the past can reveal much about the present; as Henry Petroski notes in his examination of bridge failures over a 150-year period, "Failures always reveal weaknesses and provide incontrovertible evidence of our incomplete understanding of how things work."[62] Failures show us that we do not know what we think we know.

Examining ancient failures has a number of pedagogical advantages: acquainting students with the history of engineering and ancient cultures, helping students recognize the place of failure in studying design, and clarifying the evolution of engineering as a profession. Incidents such as ancient stadium collapses provide fodder for invigorating class discussions and research projects, allowing students to view their academic studies of engineering in an historical context. They may discover that our "contemporary" topics are not so contemporary after all; rather, issues of autonomy, responsibility, and engineering judgment date back millennia.

More importantly, however, studying engineering failures of the past can impress upon students the need for a certain humility in approaching any engineering project. Petroski cautions against hubris and complacency in engineering design, especially by experienced practitioners. Building new structures based on past experience can result in unexpected failures, as the 1928 collapse of the St. Francis Dam so aptly illustrates. "In fact," he states, "designing in a climate of success can be dangerous for an engineer," resulting in a loss of sensitivity to the demands of a new project. Failures cause engineers to view new projects with a "renewed respect for the laws and forces of nature" and with less arrogance.[62]

While the use of cases for teaching engineering ethics is, by now, fairly standard, using historical cases to shed light on the present adds a different element to ethical analysis, the moral being that instead of learning from our mistakes, as we naively assume, we do not. Lessons learned by one generation tend to be forgotten by the next, especially in regards to tragedies. "The greatest temptation when assessing a tragedy," writes Stephanie Schorow of the 1942 Cocoanut Grove fire, which took 500 lives, "is to infuse it with meaning, to promote the belief that something so bad must be a step to a greater good."[63] Humans are an optimistic species: we like to think that we learn from the mistakes of the past, that good comes from evil, that we can make our world a better place. The reality, though, is that we tend not to learn from prior errors; we just recast them in a different mold. Rather than a progressive march upwards, engineering history is more like a Möbius strip, a chiral band where beginning and end merge.

Conclusions

While knowledge of past failures cannot necessarily guarantee a brighter present or future, students can learn how and why engineering errors occurred, thus raising awareness of their professional duties. Incorporating historical cases into technical classes helps students perceive their place in history and see that engineering—indeed, society overall—is a process, not a distinct moment in time.

A report written for the American Historical Association comments on the importance of studying history and the greater values of ruminating on the past: students should "be led to see that society is in movement, that what one sees about him is not the eternal but the transient, and that in the processes of change virtue must be militant if it is to be triumphant."[64] By looking at the past, students can understand that present-day engineering does not occur in a vacuum but is based on thousands of years of achievements and disasters.

Finally, historical cases can emphasize the reciprocal relationship between engineering and society. Engineering can affect societal needs—the invention of the car, for example, led to our current system of roads—and societal needs can spur engineering developments—the pollution from gas engines has led to alternate and more fuel-efficient modes of transportation. In short, incorporating historical materials show how "society driving engineering developments and engineering developments changing society are interrelated and connected," as Oosthuizen and Paul explain.[65]

References

1. CNN. (2010, December 12). Snowstorm wreaks havoc, barrels east; Metrodome roof collapses. *CNN News*. Retrieved from http://www.cnn.com/2010/US/12/12/winter.weather/index.html

2. Spencer, T. (1994, January 18). Earthquake: Disaster before dawn: Scoreboard crashes onto seats in Anaheim stadium: Collapse: The 17.5-ton Sony 'Jumbotron' also destroyed a section of roof as it broke loose and fell to the left-field upper deck. *Los Angeles Times*. Retrieved from http://articles.latimes.com/1994-01-18/local/me-13025_1_anaheim-stadium

3. *Online etymology dictionary*. (2001-2012). Retrieved from http://www.etymonline.com/index.php

4, Calvert, J. B. (2010, May 13). *Old units of length*. Retrieved from http://mysite.du.edu/~jcalvert/tech/oldleng.htm

5. Mehzer, J. F. (2003, June). *Evolution in the design and construction of stadiums*. Retrieved from http://dspace.mit.edu/bitstream/handle/1721.1/29561/52724916.pdf?sequence=1

6. Grant, M. (1995). *Gladiators*. New York: Barnes and Noble.

7. *Roman Colosseum architecture*. (2012, January 3). Retrieved from http://romancolosseum.org/ roman-colosseum-architecture/

8. *Purpose of the Colosseum*. (2008). Retrieved from http://www.roman-colosseum.info/colosseum/purpose-of-the-colosseum.htm

9. *Awning at the Colosseum*. (2008). Retrieved from http://www.roman-colosseum.info/colosseum/awning-at-the-colosseum.htm

10. Brown, S. (2007, August 15). The Roman arena. *Archaeology*. Retrieved from http://archive.archaeology.org/gladiators/arena.html

11. Slater, W. J. (1996). *Roman theater and society: E. Togo Salmon papers*. Ann Arbor, MI: University of Michigan Press.

12. Davis, M. (2012, August 1). Personal communication, email.

13. Davis, M. (1998). *Thinking like an engineer: Studies in the ethics of a profession*. New York: Oxford University Press.

14. Mckay, A. G. (1978). *Vitruvius, architect and engineer: Builders and building techniques in Augustan Rome*. London: Bristol Classical Press.

15. Taylor, R. (2003). *Roman builders: A study in architectural process*. New York: Cambridge University Press.

16. Simon, L., ed. (2012). *A look at twenty-four of the deadliest structural failure disasters in history including the Fidenae amphitheater collapse and the World Trade Center collapse.* Secaucus, NJ: Paperbackshop.

17. Lendering, J. (2005). *Fidenae*. Retrieved from http://www.livius.org/fa-fn/fidenae/fidenae.html

18. Welch, K. E. (2007). *The Roman amphitheater: From its origins to the Colosseum*. New York: Cambridge University Press.

19. Marquand, A. (1909). *Greek architecture*. New York: Macmillan.

20. Persecution and hunting: Roman slaughters. (1983). *Endangered species handbook*. Retrieved from http://www.endangeredspecieshandbook.org/persecution_roman.php

21. Johnson, W. M. (1990). *The rose-tinted menagerie: A history of animals in entertainment, from ancient Rome to the 20th century*. New York: Iridescent Publishing.

22. Humphrey, J. H. (1986). *Roman circuses: Arenas for chariot racing*. Berkeley: University of California Press.

23. *Circus Maximus*. (2008). Retrieved from http://www.roman-colosseum.info/colosseum/circus-maximus.htm

24. Roberts, P. (2009). *Ancient Romans; Their lives and their world*. Los Angeles: Getty Publications.

25. *The Roman Empire in the first century: Chariot races*. (2006). Retrieved from http://www.pbs.org/empires/romans/empire/chariot.html

26. Kebric, R. B. (2000). *Roman people*. 3rd ed. Palo Alto, CA: Mayfield.

27. Brand, P. J. (n.d.). *Spectacles: Popular entertainment in Imperial Rome*. Retrieved from https://umdrive.memphis.edu/pbrand/public/Ancient%20World%20Online/Spectacles-%20Entertainment%20in%20Roman%20Cities.pdf

28. *Circus Maximus*. (n.d.). Retrieved from http://penelope.uchicago.edu/~grout/encyclopaedia_romana/circusmaximus/circusmaximus.html

29. Bok, S. (1998). *Mayhem: Violence as public entertainment*. Reading, MA: Addison-Wesley.

30. Withington, J. (2010). *A disastrous history of the world: Chronicles of war, earthquakes, plague, and floods*. New York: Skyhorse Publishing.

31. Ritsema, N. M. (2010, June 23). From Circus Maximus to mall parking lots. *The Manitoban*. Retrieved from http://www.themanitoban.com/2010/06/from-circus-maximus-to-mall-parking-lots/1171/

32. Gillon, D. (2008, April 7). A national tragedy: Ibrox disaster, 1902. *The Herald Scotland*. Retrieved from http://www.heraldscotland.com/a-national-tragedy-ibrox-disaster-1902-1.878072

33. Wabash, R. (2013). *The 7 most epic stadium collapses of all time*. Retrieved from http://www.ranker.com/list/the-7-most-epic-stadium-collapses-of-all-time/robert-wabash

34. *Colosseum road to freedom, product details*. (n.d.). Retrieved from http://www.amazon.com/Colosseum-Road-Freedom-Playstation-2/dp/B00092A71G

35. UEFA Championship League. (2003-2013). *The world's largest football stadiums*. Retrieved from http://champions-league-betting.com/worlds-biggest-football-stadiums.html

36. *Largest college football stadiums in the United States*. (2013). Retrieved from http://www.ranker.com/list/

largest-college-football-stadiums-in-the-united-states/world-stadiums

37. Bell, G. (2011, April 28). Storied, 90-year history of track at Husky Stadium nearing end. Retrieved from http://www.gohuskies.com/sports/c-track/spec-rel/042811aab.html

38. Husky Stadium. (n.d.). *Stadiums of pro football*. Retrieved from http://www.stadiumsofprofootball.com/past/HuskyStadium.htm

39. Rudman, S., and Thiel, A. (2011 ,November 4). *Husky Stadium closure: A look at the 1980s*. Retrieved from http://www.king5.com/sports/college/huskies/Husky-Stadium-Closure-A-look-at-the-1980s-133257173.html

40. Structures: University of Washington, Seattle (UW). (2010). *Pacific Coast Architecture Database*. Retrieved from https://digital.lib.washington.edu/architect/structures/8749/

41. The evolution of Husky Stadium. (2004, September 5). *The Seattle Times*. Retrieved from http://seattletimes.com/html/sports/2002026580_huskystadiumtimeline05.html

42. Huge grandstand collapses: Nobody hurt in the mishap. (1987, February 26). *The Lodi Sentinel*. Retrieved from http://news.google.com/newspapers?nid=2245&dat=19870226&id=NZszAAAAIBAJ&sjid=rjIHAAAAIBAJ&pg=7067,7232036

43. Seattle history: The first time Husky Stadium came down. (1996-2011). *Seattle Post Intelligencer*. Retrieved from http://blog.seattlepi.com/thebigblog/2011/12/22/seattle-history-the-first-time-husky-stadium-came-down/

44. Lange, G. (2001, January 18). *Husky Stadium collapses on February 25, 1987*. Retrieved from http://www.historylink.org/index.cfm?DisplayPage=output.cfm&File_Id=2947

45. Feld, J., and Carper, K. L. (1996). *Construction failures*. 3rd ed. New York: Wiley & Sons.

46. Weidinger, P. (2010, November 26). *10 tragic human panics and stampedes*. Retrieved from http://listverse.com/2010/11/26/10-tragic-human-panics-and-stampedes/

47. CNN/*Sports Illustrated.* (2011, May 9). *Major stadium disasters.* Retrieved from http://sportsillustrated.cnn.com/ soccer/world/news/2000/07/09/stadium_disasters_ap/

48. Club history. 2010-2013). *FC Twente*. Retrieved from http://www.fctwente.nl/en/the-club/club-history/.

49. Callow, J. (2011, July 7). FC Twente stadium collapses, killing one and injuring 16. *The Guardian*. Retrieved from http://www.guardian.co.uk/football/2011/jul/07/fc-twente-stadium

50. Dutch FC Twente stadium roof collapse kills workers. (2011, July 8). *BBC News Europe*. Retrieved from http://www.bbc.co.uk/news/world-europe-14063640

51. Dutch Safety Board. (n.d.). *About the board*. Retrieved from http://www.onderzoeksraad.nl/en/index.php/over/

52. Dutch Safety Board. (2012). *Summary: Roof collapse during extension work at the stadium of CF Twente in Enschede, The Netherlands*. Retrieved from http://www.onderzoeksraad.nl/docs/rapporten/Samenvattig_Rapport_Grolsch_Veste_EN_DEF_web.pdf

53. Institution of Structural Engineers. (2012, October). SCOSS Topic Paper: FC Twente stadium roof collapse – learning from the fatal consequences. *Structural-Safety, incorporating CROSS and SCOSS*. Retrieved from http://cms.structural-safety.org/assets/uploaded//documents/280_FC%20twente%20stadium%20roof%20collapse%20-%20final%203%20Oct%2012.pdf

54. Department of Materials Science and Engineering, SUNY at Stony Brook. (2008). *Learning from failure: Engineering disasters*. Retrieved from http://www.matscieng.sunysb.edu/disaster/

55. Aristotle. (c. 350 BCE). *Nicomachean ethics*. Trans. W. D. Ross. Seattle: Pacific Publishing, 2011.

56. American Society of Civil Engineers. (2009). *Code of ethics*. Retrieved from http://www.asce.org/Leadership-and-Management/Ethics/Code-of-Ethics/

57. Vitruvius. (c. 15 BCE). *The ten books on architecture*. Trans. M. H. Morgan and A. A. Howard. Cambridge, MA: Harvard University Press, 1914.

58. *How much is that in real money?* (2000-2013). Retrieved from http://www.globalsecurity.org/military/world/spqr/money-1.htm

59. Russell, C., and Russell, W. M. S. (1996, September). *Population crises and population cycles: 5. The Northern Mediterranean: Rome and after*. Retrieved from http://www.galtoninstitute.org.uk/Newsletters/GINL9609/population%20crises.htm

60. Dinsmore, H. Robert. (2008). *The ancient masterbuilder*. Retrieved from http://www.masterbuilderfellowship.com/page5.html

61. Wallace-Hadrill, A. (2011, February 17). *Roman Empire: The paradox of power*. Retrieved from http://www.bbc.co.uk/history/ancient/romans/empire_01.shtml

62. Petroski, H. (2004, May 11). *Historical memory and engineering failures*. *Project Syndicate*. Retrieved from http://www.project-syndicate.org/commentary/historical-memory-and-engineering-failure

63. Schorow, S. (2005). *The Cocoanut Grove Fire*. Beverly, MA: Commonwealth Editions.

64. Committee of Seven. (2007, July 19). Value of historical study. In *The Study of History in Schools: A Report to the American Historical Association*. Retrieved from http://www.historians.org/pubs/archives/CommitteeofSeven/ReportValue.cfm

65. Oosthuizen, P H. and Paul, J. T. (2007). Teaching the history of engineering: Reasons and possible approaches. *Proceedings of the 3rd International CDI Conference,* MIT, Cambridge, Massachusetts, June 11-14, 2007.