Engineering Dreams Into Disaster: History of the Tay Bridge

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The collapse of the Tay Bridge, a single-track railroad connection between Edinburgh and Dundee, on 28 December 1879 is a museum of management mistakes. The causes – railroad building mania, competitive companies and cities, design compromised by costs and politics, all tragically compounded by careless quality controls – are as contemporary as historic.

The collapse not only ended 76 lives, but linked anew "untamed euphoria" with the long submerged "paralyzing horror" of disaster. In the high-tide of Victorian over-confidence and unquestioned techno-hubris, the Tay Bridge, longest, largest and most celebrated, shone then as brilliantly as a symbol of human scientific achievement as a century later would man's first steps on the moon. Even today, the Bridge "radiates a special fascination," which only early examples of European technology evoke [Koerte, 1991, p. 6]. Failure of the high girders "ended an almost messianic self-confidence among engineering circles as well as the free experimentation" early pioneers enjoyed in bridge construction [Koerte, 1991, p.6]. Equally, the *Titanic* sinking three decades later sliced through illusions of technology's power to conquer all.

Human questions arise as well. Who boarded the train and met their deaths, or who missed it and lived raise age-old questions of accident or design. The bridge of San Luis Rey also was the finest of all in early eighteenth century Peru. How unthinkable it would ever break, plunging five travelers to their deaths [Wilder, 1982, p. 3]. Great disasters not only evoke great questions, but linger in mythology and minds. They alter forever design and management. Without the Tay, the magnificent edifice of the century, the Forth Bridge, over-engineered and over-cautious, would not have existed. Nor would the transition from cast-iron to steel age have been made.

After analyzing the milieux – Victorian, Scottish, railroad building, and technology – attention will focus on the bridge itself and its designer, Sir Thomas Bouch. Each step in the chain of causality presaged trouble unless someone saw, cared, and blew the whistle. But no one did, allowing weaknesses too large to control to well up.

What happened that awesome night when fierce gales ripped up the Firth of Tay? Who saw? Who believed a tragedy had occurred? Who was blamed and why? What profitable principles can engineers, crisis managers, and

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historians glean more than a century later? This museum of management mistakes is alive and still instructs.

Manias Escalating Risks

Four manias–mid-Victorian hubris, bridges, railroads and commercial competition – clustered to ensure trouble at the Tay. Although the Great Exhibition of 1851 was basically a trade show, its famed Crystal Palace became a religious festival, a shrine to technology, a glimpse of Eden on earth. *The Edinburgh Review* commented on "a living scroll of human progress," a display of growing scientific wonders [Wade, 1986, p. 4].

There were reasons to celebrate and worry. In the 1840s the steam engine transformed England. No part of culture was "free from the dizzying influence of leaping technology." Growth and progress seemed limitless. The reigning optimism was childlike in its innocence. The risks and downside dislocations were mere specks on the horizon. Determination for more, larger, faster, and increasingly daring projects, sheer optimism consumed any thought of complications [Wade, 1986, p. 3]. Without historical example or guidance, modern conventions appeared to shape material conditions. The acid of modernity was eating away not only the old, but the cautious.

Voices to the contrary cried unheeded into a wilderness. Thomas Carlyle reviled the "Gospel of Mammon," a hell in which terror of the infinite was swept aside by progress and money to be made. Matthew Arnold warned that inner growth must accompany endless material progress; that faith in machinery was *the* besetting danger. But there was no tempering Victorian optimism and momentum [Wade, 1986, p. 4-5].

Duke University professor of civil and environmental engineering Henry Petroski asks in *Engineers of Dreams, Great Bridge Builders and the Spanning of America*: Imagine the world without bridges? Without engineers? Modern bridge-building began, according to Petroski, in the late eighteenth century with daringly shallow stone arches built over the Seine. The first iron bridge, built in 1779 across the River Severn at Coalbrookdale, England, mimicked the stone arch. The race to bridge ever greater spans less expensively produced both increasingly innovative and daring designs as well as colossal failures. Even as the Victorian era was waning, advances in engineering, mathematics, and science gave bridge builders a perspective and the tools to tackle, with confidence (perhaps too much) and success, bridging problems once thought impossible [Petroski, 1995, p. 17].

But Petroski also warns of dreams spiraling into disasters, that engineers ignored the past at their peril. They are not alone. Tay promoters, managers, and suppliers did, too. Petroski documents a roughly 30-year cycle: bridge types proceed from inception to maturity to overconfidence. Designers are pushed to dangerous limits of simplicity, to ever greater feats of daring to create longer and larger spans. Times of unalloyed progress are the most dangerous [Siegel, 1995]. Confidence in materials and men looms so great that supervision by shoeleather, constant quality tests, and controls are treated cavalierly or just ignored. The Tay Bridge suffered from both. The only naysayer was dismissed as an agent of doom. One need only study NASA's dismissal of O-Ring warnings – cause of the Challenger 10 explosion – to see the problem lives today.

Petroski documents his cycle of bridge collapses, of design failures with the River Dee in 1847, the Tay in 1879, the St. Lawrence near Quebec City in 1907, the Tacoma disaster in 1940, and two box girder bridges in Wales and Austria in 1970. However, Robert Scanlan of Johns Hopkins University dismisses this 30-year theory. "We [engineers] look at things over and over and over again. That's how we avoid major catastrophes" [Pierson, 1996].

Into this already hubristic mix rushed the railroad building mania. In the 1840s all of England's major cities were linked by "thin ribbons of iron." Visions of quick fortunes, not careful strategic planning, drove development. This bred unnecessary lines and cut-throat competition, seldom more fierce than in Scotland. Entrepreneurs, so extravagant and successful in promoting and building lines, the big picture, proved "penurious" and lax in the mundane matters of operating them. Even today, the sheer accomplishment, the rugged streams, and the terrain crossed, impresses the passenger. They did this author in 1990 on the Queen of Scots train, a nostalgia trip akin to the Orient Express.

Although railroad mania peaked in Great Britain between 1845 and the 1850s, some large and lucrative connections remained to be made. One was the difficult, potentially expensive yet profitable crossing of the Firths of Tay, Scotland's longest river (120 miles, 193 km), and Forth. Both Firths sliced into the landscape on Scotland's eastern coast between Edinburgh, the capital, and the then parvenu Dundee, which had grown wealthy on jute and textiles. Town fathers wanted a connection, but worried about aesthetics – a bridge shadowing harbor views, the danger of it being too close, and footpaths. Perth, aristocratic, long-established and a great exporter, stood at the head of the Tay River. Perth's opening to the sea was a critical factor in the Tay Bridge design. The fatal high girders were the accommodating compromise.

Ambition fueled by survival quickened competition between the Caledonian Railroad (CR), which controlled the longer Western Scottish route, and North British Railroad (NBR). To avoid extinction, North British needed a quick, convenient link to open the Northeast to profitable transport of goods and passengers. In the 1850s, no one who made the arduous 46-mile (74-km) journey between Edinburgh and Dundee wanted to repeat it. It took 3 hours and 12 minutes normally, but substantially longer during stormy weather. The fastest train then left Edinburgh's Waverly Station by 6:25 am. In Granton at the Forth passengers transferred to a paddle-wheel steam ferry to reach Burntisland. There a second train took them through Fife to Tayport, to another ferry which took them across the Tay to Broughty Ferry, east of Dundee. A third train, owned by CR, completed the journey to Dundee. Even without storms, little wonder most travelers favored CR's route via Perth, even though 28 miles longer [Koerte, 1991, p. 21].

The obvious, but far from easy or inexpensive solution, was bridging the Tay and Forth. When Sir Thomas Bouch, who eventually designed both bridges, initially suggested the idea, NBR directors dismissed it as "the most insane idea that could ever be propounded." The Tay Bridge would be almost two miles long, estimated to cost 200,000 pounds (the over-runs made that laughable), and NBR was losing money [Koerte, 1991, p. 21]. Huge natural obstacles posed problems – too-soft shorelines and uncertain, uncharted riverbeds. The shorter route would remain a dream until Bouch's design was built. Famed equally for his design of light, inexpensive bridges, and his lax supervision, Bouch further insured disaster by adjusting his Tay design to accommodate cost pressures and local concerns. When Perth protested a low bridge would impede its access to the sea, the eight fatal high girders were added. Dundee's jute merchants wanted economic development, but not at the expense of aesthetics. Doomsayers were swept away as merely old-fashioned minds, obsolete amid progressive technological wonders.

Clustering of Backers and Doubters

North British was far from alone in its enthusiasm. A small but influential group of Dundee businessmen, particularly from the textile industry, quickly grasped the advantage of a direct, fast access to Fife coal fields. Steam engines drove the machinery in their mills. The *Dundee Advertiser* registered support. Public meetings, at which Sir Thomas proselytized for the bridge, and a local committee furthered the cause. Doubters, daunted by the project's sheer size, were reassured by him. The undertaking was "very ordinary." "Far more stupendous and greater bridges" had already been constructed, he said. Others assured that only an unthinkable westerly gale of 90 tons pressure per square foot on the top of the pier standing on bare rock could knock it over [Swinfen, 1994, p. 29-30].

Assurances from Bouch, the many benefits of a direct link, prospects of good return on investment, and public advantage, all hyped by the overly confident temper of the times led to formation by mid-November 1863 of a committee to push for an enabling Parliamentary Bill. It would incorporate a company to construct the bridge and connecting lines [Koerte, 1991, p. 21]. Several times Parliament slowed enthusiasm. (After the disaster, it effectively barred Bouch from any new projects.) Finally, in July 1870, the Parliamentary Bill for the Tay Bridge received Royal assent. Most systems were go.

Analysis of disaster after disaster, historic or current, corporate or governmental, reveals warning signals repeatedly rushed past or ignored. Naysayers, whistle-blowers, even loyal but critical questioners suffer, most of all if they prove right [Swinfen, 1994, p. 19]. Countering Tay fever was a farmer, Patrick Matthew, called the Seer of Gourdie. In a series of eight letters to the *Advertiser* between December 1869 and March 1870, Gourdie "foresaw all kinds of mishaps": rapid flow of the river scouring foundations, collapse of bridge supports if hit by a ship, loss of centrifugal force as the train took the sharp curve at bridge's northern end and destruction by earthquake tremors.

The *Advertiser*, booster of the bridge, quickly dismissed Matthew's fancies, calling him a crank. He was far from that, despite describing himself as a "crotchety old man, his head stuffed with old world notions, quite obsolete in the present age of progress" [Swinfen, 1994, p. 22]. His advice for strengthening the north end had already been addressed. His advice for building a cheaper bridge at Newburgh was ignored. The idea of not building a bridge at all and using the savings to clean up slums and build healthy, good quality housing for the working class was simply too far ahead of its times to be heard. Few heeded his concerns about earth tremors and a very high, top heavy bridge, either. With fearful accuracy, he issued one final, macabre warning before his death in September 1870: "In the case of an accident with a heavy passenger train...the whole of the passengers will be killed. The eels will come to gloat over in delight the horrible wreck and banquet" [Swinfen, 1994, p. 22].

The validity of warnings of structural and design problems, inspection and quality laxness would have been quickly apparent to anyone diligent enough to inspect carefully, to see danger in cracks, falling lugs, and sparks. All this, so evident during construction, was only recognized and made public during three investigations following the tragedy. To prevent that awesome chain of causality from being a twice-told tale, grim analysis will stay in the shadows of the glorious opening June 1, 1878.

It had taken 600 men six years to complete the Tay ahead of the Brooklyn Bridge, its only rival in size and splendor. The Tay's single track looked like a gossamer web strung across the Firth. Some marveled such a spidery outline could be strong enough to withstand heavy loads and winds. Judgements on bridge and designer were all glowing [Swinfen, 1994, p. 22]. Its widely sweeping curve before Dundee was a pleasing sight. In profile it made several subtle leaps. It descended from the southern shore over the first three piers, ran level for another three, "then climbed like a tired wave" to meet the central girders. Here it ran very high, but level until descending steadily to the northern end. There the bridge swung in a gentle curve "past the beautiful new esplanade" to terminate in even more beautiful Tay Bridge Station [Koerte, 1991, p. 48]. After a year in operation, "this powerful structure tracing a dark straight line through the Scottish landscape" was considered "the pride and triumph of its age." One critic dubbed it "early American," highlighting a pragmatic sophistication [Koerte, 1991, p. 48].

Plain folks and celebrities gathered to marvel at this bridge which was proving both profitable and practical. At night from darkened windows many watched the moving necklace of white lights ending in ruby red tail lights. By day, they watched "a train rolling along with a long smokey trail." General and President Ulysses S. Grant, who arrived on a special train from Edinburgh on September 1, 1877, laconically remarked: "It's a very long bridge." Emperor Dom Pedro II of Brazil came seeking progress adaptable to his country. Prince Leopold, Queen Victoria's youngest son, marveled not just at the bridge's elegance, but its "solid substantiality" [Koerte, 1991, p. 48]. Finally, in June 1879, the greatest accolade. Queen Victoria left her widow's seclusion to visit the Tay en route from Balmoral [Koerte, 1991, p. 49].

Others celebrated with photographs. Probably the finest one extant, by Scottish photographer George Washington Wilson, shows a haughty elegance, fragile piers and girders, the slender profile, "the obvious minimum of mass and the sweeping course across the Firth." But in Wilson's photograph, obscured by grandeur, is a portent of trouble. Five maintenance staffers are checking a pier for trouble [Koerte, 1991, p. 49, 51].

Magnificence was proving not only visually impressive but also profitable, despite a 48 percent cost over-run (a total estimated cost of 350,000 pounds in contrast to the 217,000 pound contract six years earlier) [Swinfen, 1994, p. 43]. Crossing the bridge became a popular outing. By cutting about an hour off the pre-bridge journey, the Tay was attracting passenger and goods traffic away from its Caledonian rival. By the end of its first year of operation, North British was estimated to be carrying 84 percent of the Edinburgh-Dundee traffic and 59 percent of the Edinburgh-Aberdeen traffic. Between Dundee and the Fife area, traffic had doubled. Goods hauled to Dundee, especially coal from the Fifeshire mines, had risen 40 percent.

Competitively, the bridge not only saved the North British, but made it supreme – commanding the country's largest rail operation, carrying more than 15 million passengers annually, resulting in a gross annual revenue of more than 2 million pounds. Shares rose 30 percent. In sum, the Bridge had done everything promoters had hoped for – and more. Then after 18 months of operation, it collapsed. The acid test of its viability and profitability, however, was demonstrated convincingly after the disaster. No one questioned replacing the Tay; just how to make it safer.

Winds of Tragedy

Winds howling up the Firth at hurricane force on 28 December 1879 and under-designing for maximum wind stress are the easy reasons for the collapse. But very seldom is the first, easily apparent reason the real one. Another theory was that a speeding train momentarily catching the fierce gale created utmost stress vertically and horizontally on the bridge – already dangerously compromised by design, poor casting, lax supervision, and political pressure. These reasons and blind euphoria that technology could always be trusted brought down the Tay just as surely as any gale. The easy to see but ignored, plus engineers' greatest fear – the unknown unknowns – coalesced into deadly chaos.

On the fatal night 90-mph gales, the worst in six years, lashed the Firth of Tay, churning the waters, tearing off the railroad station's roof, toppling chimney pots with a thunderous crash and spewing sand and pebbles through the air. Nothing seemed normal. One onlooker, familiar with Far East hurricanes, noted the unusual force.

Few of Dundee's 140,000 inhabitants watched the "Edinburgh" snake its way across the spider thread-like bridge. Unlike most nights, the storm, high fear, loud noises or havoc focused eyes on personal dangers. Some were busy barricading their homes against the storm, others were at church services or simply distracted at the crucial moment [Swinfen, 1994, p. 66]. So, none saw the red taillights, then sprays of sparks. Sparks did not necessarily signal trouble. They were just "normal friction of the wheel flanges against the force of the wind." Not this time. Others noticed a flicker of lights as the train entered the high girders. None saw the train disappear. None believed it had been swept into the water – girders, train and at least 75 passengers. In disbelief they reasoned the train hadn't crossed the Firth, had retreated, or was just slow. It had been expected at Tay Bridge Station at 7:15 p.m. Some consoled themselves with the previous train. Those aboard it told of wind gusts, sparks, and concerns about speed. But they arrived safely [Swinfen, 1994, p. 5]. Why not the "Edinburgh," too? Disaster never makes itself felt at once. The mind's natural inertia and disbelief enforce delay. Finally, several workers dared the dangers to crawl along the tracks and found nothingness. The high girders were just gone. An *Illustrated London News* cover illustrating David Swinfen's book shows the jagged edges and all around ominous water, rescue boats and an angry sky, but not without inspiring rays [Swinfen, 1994].

Too filled with pride and trust, hope and horror, many sought a miracle. Rather than sleep they stared at the Firth hoping the bridge would "re-erect itself," and the train would steam safely into Dundee [Koerte, 1991, p. 83]. Boat crews called out desperately across the water, but were answered with silence. At dawn the awesome news had to be faced. Ominous signs began appearing. A postmistress a few miles down the estuary at Broughty Ferry telegraphed, asking why mailbags were washing up on the beach. Later, bodies not still in the carriages began washing up, too. Could there be any clearer confirmation of the train's fate?

At first, railroad authorities sought to prevent panic by controlling information. Those waiting for the friends and family aboard the train were sent home with the belief it was kept back until the gale moderated. The attempt to suppress information failed [Swinfen, 1994, p. 8]. The first news to the outside world, ironically, went out over the still functioning CR telegraph:

> Terrific Hurricane
> Appalling Catastrophe at Dundee
> Tay Bridge down
> Passenger Train hurled into River
> Supposed loss of 200 lives. [Koerte, 1991, p. 83]

The only good news was the erroneous count; only 76 died. Just 46 bodies were ever recovered. None had any chance of survival. The morning after all appeared paralyzed. The scene was unreal, the silence deadly. "Smooth lead-like waters covered everything as if it had all been a bad dream" [Koerte, 1991, p. 82, 83]. The station was a wilderness of glass broken by the storm.

Later, stories were told – as part of folklore and at the investigations. One relates how the train should have been visible, but wasn't. What was wrong? Telephone and telegraph lines did not work, so Fife coast could give no answer. Crawling out on the bridge was a daunting prospect in total darkness and howling wind. Only a dire need to know would drive anyone out. The high girders were gone, their supporting iron columns broken off – stumps sticking forlornly out of the water as they still do today [Swinfen, 1994, p. 8]. The engine was salvaged; the carriages could not be except for wooden mementos – a knife, walking sticks, and other items.

Blame Enough for All

If ever the canard – success has a thousand fathers, failure but one – applied, it is to Sir Thomas. He was designated scapegoat, although recent studies say unfairly so. Three separate investigations in Dundee and London examined wind, design, production and quality controls, inspections, maintenance, and excessive speed. Two schools of thought, plus a common view popular then and now, emerged. First, the train itself brought down the bridge either when it canted over against the girders or actually left the track. Attempting to salvage his reputation, Bouch proclaimed this derailment theory – the locomotive and five coaches, derailed by vicious winds and excessive speed, pulled down the high girders. But his theory failed. The cars were too light and found submerged still within the girders.

Many believed the bridge itself collapsed, stressed by the storm. Its weakened, altered design had been further endangered by sloppy quality control. Still others held that additional wind resistance – the train blocking the flow through the high girders – contributed to the collapse. However, a recent computer analysis of the design concludes the collapse would very likely have occurred even without the additional wind resistance caused by the train. For not factoring in wind stress, Sir Thomas was blamed, but until the Tay nor had anyone else. Each element in the chain of causality explains the collapse and forms the museum of management mistakes.

Thomas Bouch: The designer was the immediate target for blame even by those partly culpable themselves. On Sunday evening he was a wealthy, highly respected engineer, knighted for the Tay Bridge, already at work on the second crossing over the Firth of Forth. On Monday morning his work and future lay in shambles [Swinfen, 1994, p. 73, 77]. It soon became clear he could be defended, but not saved. The attacks were too vitriolic. Parliament would not approve funds for the Forth Bridge while Bouch was still its designer. Bouch survived the Tay collapse by just 10 months, and the committee report by 4, dying on 30 October 1880.

Throughout the bridge's conception, construction, and operations, warning-signals flashed – unheeded. Bouch himself was absolutely true to his reputation for "surprising cheapness of construction: unreliability, incorrect measurements, and lax, overly delegated supervision." With such a personal history, conclusions of the 1880 report should have surprised no one. He already had built nearly 300 miles (480 km) of railroad tracks in Scotland and northern England, and more bridges than any contemporary. Still, he was known as a chancer – his qualifications "shadowy" but excelling in breadth of imagination [Koerte, 1991, p. 19]. The Report found the bridge was badly designed, badly constructed, and badly maintained. Inherent defects "must sooner or later have brought it down" [Koerte, 1991, p. 84]. The Report blamed Bouch entirely for the faulty design; principally for lax construction, maintenance, and inspection.

However, even after more than a century, Bouch's culpability is not settled. In his 1994 book, *The Fall of Tay Bridge*, widely reported in the *Scotsman* and elsewhere, David Swinfen claims Bouch was unfairly made to shoulder all the blame. Swinfen, an historian and vice principal of Dundee University, uses fresh evidence from mathematicians and structural engineers to rehabilitate the designer so pilloried by the Board of Trade inquiry. Although wind stress and lateral stiffness received little attention until the Tay, according to Swinfen, Bouch did carefully search for the latest information. Two board of inquiry members at the design stage had assured Bouch wind would not effect open lattice girders. Recent computer studies show the bridge simply blew down. The bridge would have collapsed even without a train.

Swinfen also concludes petty jealousies, cost-cutting, redesign and supervisory shambles during construction should have forced some blame onto the North British Railroad, its directors and shareholders. NBR, which sought cheapness at the expense of durability, knew Bouch's reputation for cheap, light railway tracks. Nonetheless, the Board marked Bouch as a penny-pinching incompetent, "anxious to wriggle out of responsibility for the disaster" [Clouston, 1994]. Today, Bouch is remembered for the consequent over-engineering of the Forth Bridge and for "to bouch," or to make a mess of something.

Inspections: Lax and casual, particularly by the Board of Trade's Charles Hutchinson, these were culpable, too. Between 25 and 27 February 1878 he examined and tested almost every aspect of the bridge, except the key and fatal elements – wind stress and lateral stiffness. There was no convenient storm. Under questioning Hutchinson conceded his inspection had been superficial, but he had found nothing wrong – a don't look, don't find policy. He had been anxious to test for lateral stiffness of the piers and how high winds and a train in motion might affect them, but illness sidelined him until after the bridge was open [Swinfen, 1994, p. 81]. Could no one substitute?

One of Bouch's assistants, conscientious, but very careless, found "alarming cracks in the columns of the four piers below the high girders." Although just wide enough to insert a sheet of paper, some were 4 to 7 feet long (1.22–2.13 m). His test was high comedy. He wetted a piece of paper from his notebook with saliva, pasted it across the crack, and waited for the next train. No tears in the paper. No problems. The crack had not widened. To double-check, he pushed a thin wire, from the cap of a bottle into the crack. What a relief. It did not reach the pier's concrete core. *Ipso facto* the bridge is safe [Koerte, 1991, p. 100].

Such laxness would not be repeated at the Forth or the second Tay Bridge. No carefree social jaunt like the old days now, but a hard, serious day's work. The *Advertiser*, waxing somewhat nostalgic, according to Swinfen, noted that 10 years previously inspections were minimal, surrounded by pleasant companions, blithe talk, and ending with an elegant dinner [Swinfen, 1994, p. 95]. The Tay Bridge disaster ended all that. Now practical men after a hurried lunch sailed observantly around the piers.

Speed: Hutchinson attempted to blame racing locomotives. He stipulated 25 mph, but trains could go faster and often did, up to 42 mph (67 km/h) to race Firth ferries. Speed undoubtedly further weakened the bridge. Some reported a rattling of the girders and a prancing motion of the trains. But the "Edinburgh's" speed that fatal night was not known to be excessive.

Quality Management: Sir Thomas's former assistant Henry Noble was dedicated, but lacked know-how. He failed to report the loosening or chattering of key bars. When he did report great long cracks in iron columns and masonry of the piers, Bouch ordered band-aids rather than necessary surgery. They were bound by iron straps. Below water level, the scour of the river had gouged out great depressions on the foundations. That too was treated cavalierly [Swinfen, 1994, p. 62]. Falling, loosened and messy lugs, when noticed, were discounted as incidental. Rather, they were critical. One Court of Inquiry concluded that not the bars themselves, but the lugs on the cast iron columns to which they were attached, failed. Once the weakest bracing was ruptured, putting greater stress on the others, collapse would be inevitable [Swinfen, 1994, p. 77]. Astonishing neglect of quality control and maintenance "was a central cause of the disaster" [Koerte, 1991, p. 53].

Compromises: Cost and political pressures dictated the single track and high girders, but not without opposition. The *Advertiser* criticized the single track on grounds of stability and utility. What designer would think of running such a spider's thread over the river. It looked like a clothesline, far from a "magnificent and imposing object...an improvement to the noble scenery of the river." For more than two miles the route was suspended between the sky and the water on "about the width of a respectable dining table." That "assumed great faith in railway passengers to imagine they will trust themselves on this tight rope...at so great an elevation." Railway traveling "will become a gymnastic feat." Even though too late to influence plans, the *Advertiser* still campaigned for a double line to strengthen architectural security over a tidal river "liable to enormous floods" and "blasts of winds merciless in their fury" [Swinfen, 1994, p. 24, 25]. The structure was further weakened by the ultimately fatal high girders, purposely raised to accommodate Perth merchants' concern of being cut off from the sea. NBR sought cheapness at the expense of durability and safety.

Beaumont's Eggs: "Horrifying and dangerous negligence," a worse case scenario, reached their nadir at the Wormit Foundry. Its faulty casting of piers was an essential cause of the disaster. Wormit's most awesome scandal was camouflaging holes in castings with soft "Beaumont's Eggs." Some castings went to the job as "honey-combed as a Swiss Cheese." The soft, weak "eggs" were made of bee's wax, fiddler's rosin and very fine iron scraps melted together, then enhanced with lamp black. Workers filled the holes, then painted them over. Cosmetically the iron looked fine; realistically, it was fatal. Like spin masters today, a young Wormit manager eeled out information in his self-defense, by progressively denying use of the eggs, to knowing they existed, to having cast iron according to his own judgement. The great waste due to bad casting he spun into proof of his conscientiousness. The number of columns sent to the Tay stuffed with the "magic eggs" could only be guessed [Koerte, 1991, p. 95].

Portents: It behooves managers wanting to contain or avoid a crisis to read a fever chart of ills. Major tragedies announce themselves in many ways. Building bridges, even under the safest conditions, involves accidents, some fatal. The Tay seemed particularly accident prone. Two men drowned; many swept off the structure; a vent clogged and pressure built up until it blew out a plate. Girders broke loose while being towed. Others were blown down. In the worst incident, a pier sank into position over eight workers, a explosion ensued, water rushed into the cylinder. Weather was to blame as well as human misjudgment and machinery failure, but no public inquiry was held [Swinfen, 1994, p. 30].

Eventually, a new Tay bridge was built, but the old one was remembered in the proverbial expression, "I may see you on Tuesday unless the bridge fails." For a majority of the Scots the disaster "was nothing less than an act of divine judgement." The one voice louder than all others, a Divine warned, was "that of God, determined to guard his Sabbath with jealous care" [Koerte, 1991, p. 13]. Stern Calvinists saw God's revenge for traveling on the Sabbath. The disaster was no act of God, but of careless men and companies too eager for profit.

Legacy of the Tay Today

Like the Tay collapse, the sinking of the *Titanic* dashed messianic self-confidence among engineers. Hubris sank the invincible *Titanic* just as surely as icebergs. In just three hours it was transformed from "paradise to chaos," marking a watershed between the centuries. Sunk by "hype, haste and hauteur," it ended an uncritical era; produced an age of anxiety.

Both the *Titanic* and Tay replaced untamed euphoria with paralyzing horror. As later generations would remember where they were when the Challenger 10 explosion was etched beautifully against the heavens and in people's minds, people in Dundee dated events before or after the Tay. Its ghosts weave through current debates on UK bridge maintenance and privatization. And, as Swinfen's book documents, responsibility is still in contention.

Even a great disaster brings progress. The first Tay Bridge enormously increased passengers and freight, hence income to North British, income too great to forego. Infrastructure such as the Tay Bridge station and connecting lines were worthless without another bridge. After tasting the convenience of the bridge crossing, passengers were loath to return to cumbersome ferries. And, Dundee had lost its water supply. So, an encore was played out: tussles over design between conflicting interests, and again between Dundee and Perth. Disputes were resolved by cash and lowering the spans over sea channels from 88 to 77 feet. The second bridge appeared more stable and solid. Its girders were doubled in number, tentative or experimental methods were eschewed for fully accepted principles. The new span would be strong and durable. Inspections were no longer a casual jaunt, but a hard day's work, taken very seriously. Testing too was much more thorough and careful. Finally, the first scheduled train left Dundee for Fife at 5:05 on 20 June, 1887 [Swinfen, 1994, p. 86, 95].

The Tay legacy also lives on in its lessons and warnings, as well as general historic obtuseness and concept of failure. Henry Petroski asks if bridge failure can be expected "now and then." His answer emulates Santayana in engineering terms. Neglect of the past, Petroski writes, is embodied in short-term historical memory – hubristic thinking that "one's own generation's engineering science and technology have progressed far beyond...one's professional progenitors, even mentors." Earlier bridges became pretty pictures, not examples, models, or portents. Such short-sightedness spells disaster time and again [Petroski, 1995, p. 386].

Petroski's 30-year cycle of failure demonstrates communications and generational gaps that widen as engineering science and analytic tools develop as well as public tensions between means and wants, between function and form. Though it ebbs and flows as surely do the waters over which many a monumental bridge is built, the ongoing push and pull between designer and financier, between engineer and architect, between engineering and art," gains attention only when design questions bob to the surface – or in disaster. Bridges, symbolic and evocative, are the most visible and vulnerable arenas of this contest. The acid test? Bridges "must stand against weight and wind and want." Even the most beautiful bridge, if neglected in structural design and maintenance, if it falls, becomes an "ugly pile of concrete and steel." Every bridge is a legacy to its environs and its users [Petroski, 1995, p. 396].

Others see light rather than shade, a more future oriented optimism than doubts about technology. Historians have learned to be careful. Barbara Tuchman warned against unwarranted nostalgia for pre-World War I days. It all looks so wonderful, so safe and ordered only when viewed across the horror of an abyss that destroyed a world that in truth never existed. So too in bridge building. Disasters were not invented today. Spectacular disaster, black days went hand in hand with progress; untamed euphoria with paralyzing horror. Victorians "hardly ever questioned technology." Nothing could really go wrong if plans were properly executed and supervised. Accidents could be rationalized as acts of fate made to appear under control. It was easier then; numbers of victims were smaller and limited to one locality. Today, the oxygen of instant global communication of a crisis anywhere creates unusual and existential fear. Technical progress has "broken the shackles of human control" to become the "arch evil of the time," no longer receptive to rational argument [Koerte, 1991, p. 11].

Museum of Management Mistakes

Unlike exhibits in most museums, desiccated and drained of all *sturm und drang* of their vital days, the Tay Bridge collapse raises issues elemental in quality control today. Dr. W. Edwards Deming's principles of total quality control, or Volvo's pod production that gives responsibility to those who do the work, need constant reiteration. Supervision by shoeleather – on the scene, constant, attentive inspection – is demeaned too often by cosmic-thinking executives. Warnings of trouble are missed. In "Making a Success out of a Museum of Failure" Antony Anderson ponders how lessons of failure can be transmitted to following generations. Using the Tay as his news peg, Anderson, an electrical engineer at the University of Newcastle on Tyne, notes "engineering success is built on lessons learned of failure." Most "could have been avoided." Relevant information was usually available, but neither to the right people nor was its significance appreciated [Andersen, 1991, p. 54]. Busy managers too often don't want to see specks of trouble, so allow them to grow too large to handle. Nor is failure unique, Anderson writes. It replicates, but never exactly, similar events or common principles. Not only do managers not look back, but when they do, Anderson explains, they study only "the smoking mass of debris," not similar machines or systems still operating well.

Reasons for failure reveal themselves slowly, raggedly. What may appear as a technical cause actually had its origins in degradation of management systems. Operating practices changed ever so slightly, transforming what was once safe into danger. Management may fail to see the danger of current practice, or be unwilling to finance training or safety measures. Failures may repeat themselves as staff changes dilute hard-won experience [Andersen, 1991]. No news of danger or accidents is translated into good news. Milk-run successes lulled once vigilant managers into complacency. Quality and safety can be maintained only by repeatedly passing on hard-won knowledge and experience – distilled from the past as portents of trouble.

Anthony Anderson's solution is a Museum of Failures – especially big ones such as the Tay Bridge, but also damage caused by sparks and poor electrical contact, computer viruses, and products introduced before their time. Other sections would cover human factors, expert opinions later proven absolutely wrong, and a failure maze to sharpen concepts. To counter those who might deem his museum "a bit ambitious," Anderson [1993] quotes words from the Rye Parish Church in Sussex:

> Upon the wreckage of thy yesterday
> Design thy structure of tomorrow [Andersen, 1991].

To Anderson this is the essence of a constructive attitude to failure. As historians, we might only wish he were heeded.

One executive noted engineers routinely design and test for the unknowns. However, the devilishly elusive unknown-unknowns, hidden, far off the planning radar scope, as wind and stress were for Bouch, are the greatest danger. Even a few bad events can set in motion a fatal chain of unintended consequences. An engineer's penchant to simplify, or an analysis that breeds risk-free, overly optimistic assumptions court disaster particularly if they match the temper of the times, as did Bouch's at the Tay Bridge [Ames, 1996].

But, it is a new techno-hubris that most links us back to the Tay. Challenger 10 and Chernobyl are just two dramatic examples. How much uncritical faith are we putting into computers and Internets? How many executives saw only Internet advantages to spread their message widely and instantly, not the downside risks of false or unverified information? In addition to specific lessons, the Tay teaches us that looking back is essential to profit, success, or even survival ahead. Saying this to business historians is like a clergyman preaching to the already converted, but the MBA students I teach focus on the present, even more the future, with laser-like intensity and narrowness. They seldom look back, corporately, personally or generally; seldom do they use the past for competitive advantage. As I researched this paper, I was repeatedly impressed how many of the issues more than a century ago are issues still.

Anniversaries of the two Tay Bridges and the Forth span produced not just remembering and celebration, but a poignant sense of *deja vu*, questions of maintenance and privatization. The neglected Forth Bridge "looks mess-stained, rusting and uncared for." Once again, a Bouch inspired span became a symbol of "general unease about public squalor and neglect." Lead oxide paint flakes from the bridge's main support. Spectres of privatization brought fears that the area once opened by railroads would now be bypassed and the need for the Forth and Tay railroad bridges diminished. This would "cause enormous damage to the economy of Fife," already suffering Scotland's highest unemployment rate [Mclean, 1995].

Today the belching smokestacks of Dundee's jute industry are gone. The landscape appears less austere and wild. The second Tay Bridge traces the course of its predecessor "sweeping widely across the Firth." It transmits "a strangely restrained" and peaceful aura, "a matter of fact crossing of an estuary between green hills" [Koerte, 1991, p. 7].

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