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ARTICLE

Iron, Engineering and Architectural History in Crisis: Following the Case of the River Dee Bridge Disaster, 1847

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This paper establishes relations—historical, material and evidential connections—between two responses to a 'crisis'. The first features in the history of industrialised iron construction, specifically period reporting on the spectacular collapse of the River Dee bridge in Cheshire, England, in 1847. The second response highlights a blind spot in the historiography of modern architecture. Robert Stephenson became suspect when his cast- and wrought-iron railway bridge across the River Dee failed, resulting in death and injury and continuing uncertainty as to its cause. At the time the incident sparked national furore, setting off a coroner's inquest followed by a Royal Commission into the perilous state of Britain's bridges. The inquest jury concluded no one was to blame; rather, it was an accident brought about by use of iron, an uncertain and "treacherous" metal. This explanation has failed to satisfy contemporary materials specialists who have reopened the case, albeit under different terms of reference.

The paper examines the initial verdict, firstly, in view of aspects of the social context of evidence and proof prevailing at the inquest and, secondly, given historical writing on iron construction whereby the inquest's seemingly imprecise and arbitrary judgment is taken as sign of the subsequent progress of engineering as a practical and moral science. This paper adopts the leitmotif of 'crisis' to highlight a parallel history that challenges progressivist narratives of industrialised iron construction and modernist architecture. It invites reflection on the provenance and unstable forms of agency associated with engineering as a propositional and socially contingent enterprise.

Introduction

Histories of industrialised iron construction and modernist architecture have been partly shaped by assessments of technological artefacts over which an engineer or architect or indeed any recognizable *design* professional appears to have had limited, if any, control. Consider how the openings of some 19th-century iron bridges, like the inauguration of Isambard Kingdom Brunel's suspended tubular railway bridge across the River Wye at Chepstow (1852), were preceded by public demonstrations of their load-carrying capacity. It was as though seeing was akin to believing, with many tons of weight placed visibly upon bridge decks in the hope of convincing investors and potential users of a structure's reliable and safe performance and the trustworthiness of its engineer (*The Bristol Mercury* 28 February 1852). Robert Stephenson assisted in the opening of the Chepstow Bridge by publically inspecting the structure and concurring with the design. This was perhaps a favour in return for Brunel's testimony at a Royal Commission hearing after the 1847 collapse of Stephenson's cast and wrought-iron girder bridge over the River Dee that killed five people and injured a dozen more (Rolt 1989: 202–303).[2] (A fire on the Great Western Railway at Uxbridge had previously caused Brunel's bridge there to collapse.) According to one authority (Gagg and Lewis 2011: 1967), it was the failure of these structures that prompted Joseph Paxton to famously march men and roll cannon balls over the beams of the Crystal Palace (1851). Purportedly, this was done to reassure the public the exhibition hall would stand up, adding a dramatic performative element to the building's aesthetic reception (*Ipswich Journal* 15 March 1851).

Nikolas Pevsner provides a comparable, though literary, demonstration of the promise of new forms of iron construction. In *Pioneers of the Modern Movement* (1936, the book's narrative and photographic illustrations describing the functional aesthetic and inventive influence of 19th-century iron factories, warehouses and bridges. Pevsner's assessment of Brunel's Clifton Suspension Bridge (1831–64) stands out:

> [A]n architecture without weight, the age-old contrast of passive resistance and active will neutralised, pure functional energy swinging out in a glorious curve to conquer the 700 feet between the two banks of the deep valley. Not one word too much is said, not one compromising form introduced. [...] Only once before had such daring spirit ruled European architecture, at the time when Amiens, Beauvais, and Cologne were built. (128)

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There is little detail in Pevsner's story to make for a fuller account of factors bearing on the bridge's provenance and performance. Consequently, his readers are led not only to suspend disbelief that the structure could have been anything other than imminent, fit for purpose and beautiful for counterbalancing forces that were physically manifest by assemblies of stone and iron. They are also led to accept the structure as existentially meaningful, a precursor to architectural projects by Gropius and Myer.[3] Moreover, readers are allowed to forego understanding the complex history of iron construction, in which works of comparable 'architecture' (like some cathedrals, including Beauvais) collapsed under their own weight, brought low by little-understood forces or (perhaps counting for the same thing) the failure of their *engineering* relative to modern expectations for technical acumen and judicious design.

In view of the positive spin he gives to the story, Pevsner joins the company of Victorian moralist Samuel Smiles (1862), who caricatured the lives and times of British engineers, so that 19th-century engineering expertise is made subject to rule by either the spirit of the age or characteristically practical thinking (or possibly both forces in concert).[4] Either deceit serves to de-historicise the accidents that befell engineered works and their designers, more or less downplaying the broader crises that commonly followed death and injury and loss of property and profit.[5] Generally, history, including architectural history such as Pevsner's, has paid only limited, if any, attention to the social experience of accidents and the contingent and idiosyncratic aspects of technological change (Bijker and Law 1992: 2–4). When details are given they are commonly used to dramatize reports of outraged publics or help deduce the outcome of controversy. Readers are led to anticipate that controversy will result in the perfection of technology, the transformation of engineering into a discipline grounded in empirical science, or the emergence of authoritative regimes to guarantee public safety (Cooter and Luckin 1997: 1–16). Continuing critical commentary on the failure of Stephenson's bridge suggests that its meaning and significance remains variable, providing a measure of changing social, technical and ethical concerns.[6]

The coroner's inquest of the River Dee bridge collapse, complete with jury, expert testimony and eyewitnesses, appears remarkably modern in its form and conduct. Evidence was collected, firsthand reports recorded and drawings from the 'crime' scene prepared. However, the absence of a clear or agreed upon charge (manslaughter, professional negligence, human error?) makes the subject and purpose of the proceedings uncertain and its verdict questionable by modern standards of evidence and proof. The ambivalent status of iron as material evidence introduces an uncertain element into the political arithmetic in which authority is posed against creative license in the modernisation of the countryside by steam and rail and new modes of iron building. As the material of not only craft practices and trial and error, but also newly emerging and heterogeneous social networks of technical expertise, cast and wrought iron were highly visible, but inscrutable, signs of an age that was neither entirely understood nor its technology fully mastered.[7] Accordingly, to discover the range and kinds of factors that influence the adoption of new technologies, as Dreicer (2000: 130) observes, 'We need a bridge to understand a history that includes the full gamut of cultural and physical forces, including nationalist fervour, creative genius, and capitalist greed, a yearning for professional prestige [along with] tension and compression.' To Dreicer's advice one can propose that an *iron* bridge—particularly one that has failed—allows one to see these forces more clearly. This paper undertakes that task.

Following an overview of the disaster and inquest, the paper examines aspects of the crisis initiated by the River Dee bridge collapse. It draws particular attention to the influence of period newspaper reporting on the accident (**Figure 1**). Newspapers established an imaginative topography of risk that brought order to eyewitness accounts of the disaster. Reportage rendered the event sensational and made it subject to interpretation according to multiple and overlapping causal schema and probabilities. Questions about the performance and reliability of new or competing technologies and the competence of their proponents come to the fore. Consequently, newspapers helped form the archive that guides the contemporary scholar in their interpretation of the meaning of the disaster. In the second part of the paper, the crisis of the River Dee bridge collapse re-appears in slightly different guise. It appears as the object of aesthetic sublimation by the historian of technology who mostly presupposes the progress of building science. Ostensibly sparked by the same episode—an 'irruption of the unpredictable' (Castel 1991: 289) into the flow of historical discourses—this second case results in the effective 'neutralisation' (Figlio 1985) of aspects of the social experience of the River Dee bridge collapse. In the first instance, the 1847 inquiry was concerned with determining whether or not the deaths and injuries were 'accidental', a verdict which allowed for unforeseen or unknown circumstances and the blamelessness of the engineer. In the second, historical testimony is cross-examined by contemporary scholars (Lewis and Gagg 2004) equipped with knowledge of 20th-century engineering and building (including material) sciences. Missing or anomalous evidence is disregarded as instances of anachronistic, partial or impractical thinking. This latter 'progressivist' view that accepts *prima facie* the progress of building science is a morally problematic one. The disregard of missing evidence occludes awareness of a range of factors and agencies influencing the development of engineering as a discipline. It obscures engineering's role in the broader socio-historical process Hacking calls the 'taming of chance' (1990).

As disaster struck…

Neither Pevsner nor Smiles wrote about bridges as technological systems encompassing material and human components subject to regimes of observation, calculation and control (Ellul 1980; Canguilhem 1994: 351–84). Neither recognised the necessary connection between technical performances and normalised behaviours, including imaginative conduct that could turn an 'acci-

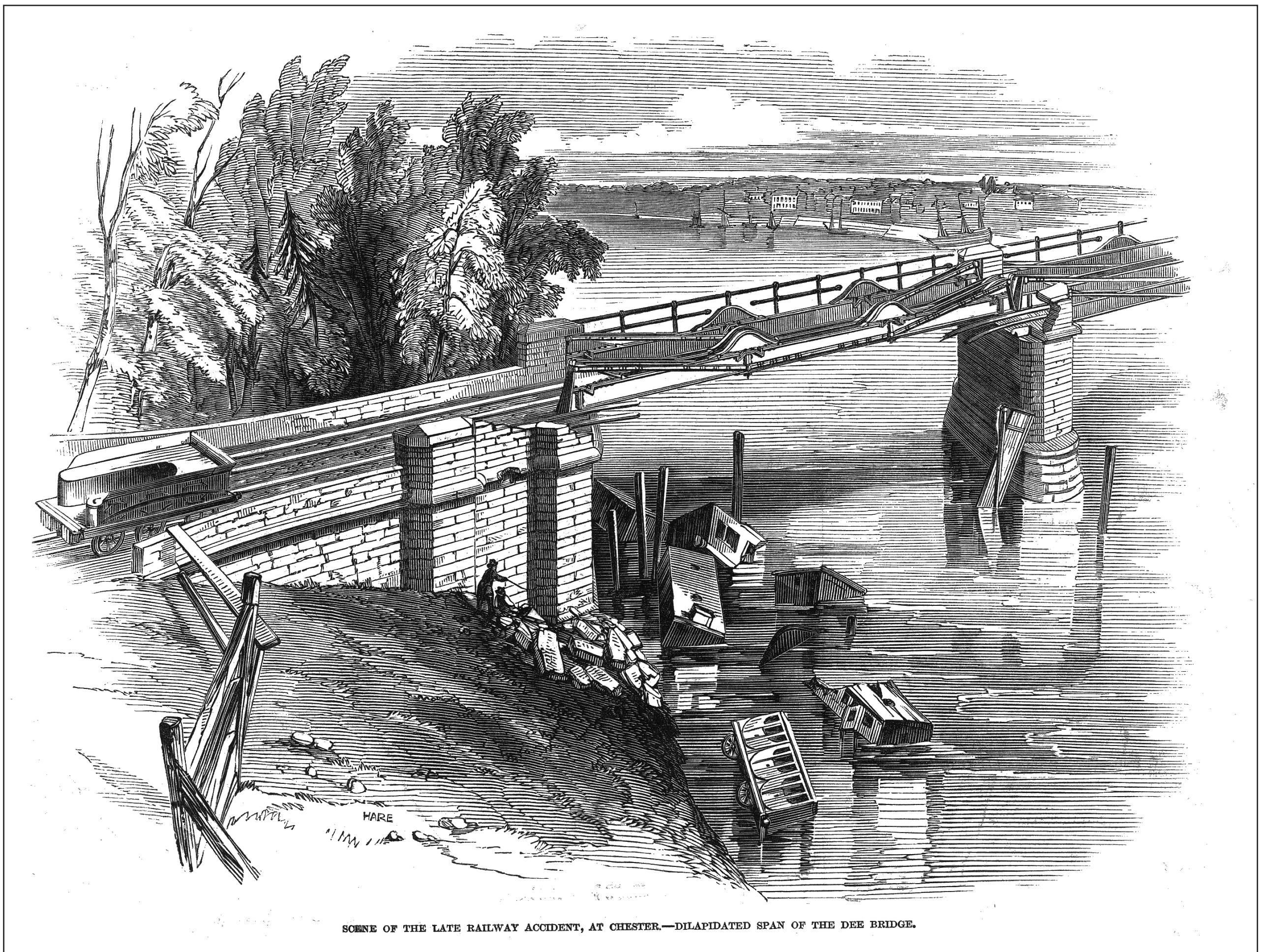

Figure 1: View of River Dee bridge disaster site in etching from *Illustrated London News,* 12 June, 1847. Courtesy of John Weedy.

dent' into a 'disaster', 'catastrophe' or 'crisis' of compelling social, political and moral significance (Williams 1990). While writing overwhelmingly Eurocentric and (clearly, in the case of Smiles) nationalistic histories of building technology, neither Pevsner nor Smiles acknowledged the influence of national cultures on technological change (Kranakis 1997). Largely absent on both accounts is a narrative where accidents happen and where constructed form, rather than following function in a determined and naturally progressive way, adaptive to novel purposes and circumstances, is instead caught up with uncertainty, risk and failure. Likewise the development of building technology is tied to the vagaries of reason and communities of only partly 'reasonable' subjects acting in complex material and social worlds (Davis 1983). It is a story where newly recognised risks resulting from novel materials and industries are as much a part of the dynamism of modernity as triumphant openings of visionary structures like Paxton's Crystal Palace. Consider the case of the River Dee bridge collapse.

On the evening of 24 May 1847, a southbound train travelling along part of the new railway connecting London and regional cities to Holyhead in Wales approached the River Dee just outside of Chester, at a speed later estimated to have been 30 miles per hour. Ahead lay the iron bridge designed by Robert Stephenson, one of several large spans required along the line, completed just six months before. Though overlooked for praise in *Pioneers of Modern Design*, the structure was no less technically ambitious than its near contemporary, Stephenson's wrought-iron tubular Britannia Bridge to Anglesey (completed in 1850) or Brunel's Clifton Suspension Bridge across the Menai Strait (inaugurated in 1861). The Dee Bridge consisted of three 98-foot spans set between masonry piers. Each span was made up of four cast-iron girders (two each for an up and a down line), and each of these was made by bolting together three shorter lengths of iron I-sections end to end, the composite formed by this series being reinforced by wrought-iron trusses. The rails were laid on timber sleepers carried by oak joists spanning the paired composite girders and supported on the lower flanges of the girders (**figures 2, 3**).

As the 60-ton locomotive and its tender crossed the third span, a portion of the structure began to collapse. The engine-driver, who later claimed he felt the bridge give way beneath him, applied steam and the locomotive and its tender pulled ahead, severing the link between the tender and carriages. The latter crashed into the river 40 feet below. The seemingly resourceful driver pressed on, managing to change tracks and crossing the bridge again in the other direction—on the yet undamaged northbound line to Chester—in order to warn other train drivers

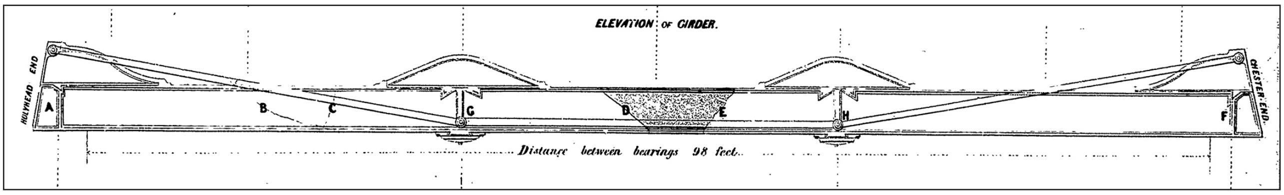

Figure 2: 'Elevation of one of the Girders over the River Dee' accompanies tables 'showing the deflexions taken upon each girder' with lines of fracture indicated from Simmons' report (Chester and Holyhead Railway 1847: 18). Image reproduction allowed courtesy of ProQuest and the HCPP database.

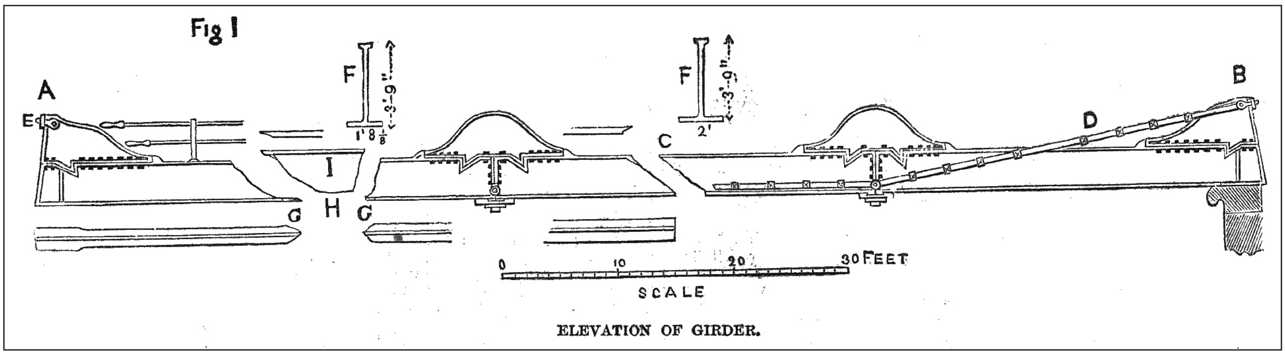

Figure 3: Elevation of broken iron girder, reproduced in *Illustrated London News* 12 June 1847. Courtesy of John Weedy.

and spare them the same fate. In the end five people died, including the fireman and four passengers, and more were injured. The incident shocked the nation and made for sensational newspaper reporting.[8]

The coroner's inquest into the incident began ten days after the incident. The investigation drew attention to Stephenson's role in the collapse, though professional negligence (an injury that was neither named nor formally charged) was only one source of uncertainty. Given the variety of eyewitness accounts and additional 'expert' testimony by military and civil engineers, acts of seeing were not necessarily productive of common and conclusive understanding. Stephenson claimed that the River Dee bridge collapsed owing to a mishap involving the locomotive—resulting in something akin to impact damage in general terms—rather than to a manufacturing defect in a cast-iron girder or weakness inherent in the metal. Spectators of the tragedy failed to corroborate his theory, some claiming to have observed a fracture open in the cast iron as the locomotive passed over a girder. The newspapers followed this debate closely. This early reporting may have influenced subsequent testimony, though this remains conjecture. The deference seemingly given to Stephenson's claims, despite his weak case (according to contemporary analysts), suggests that character assessment played some part in deliberations, along with the scrutiny of evidence, reports and drawings.

Finally, after two weeks of testimony, the jury found that no one person was to blame, concluding that the victims died by chance. However, jurors drew attention to the danger inherent in 'so brittle and treacherous a metal as cast iron' (*Liverpool Mercury* 18 June 1847 and other sources). For much of the 19th century, in the multiple arenas of iron and industrialised building—including iron shipbuilding (Winter 1994: 69) and later, tall building construction (Leslie 2010: 236–37)—cast and wrought iron were used with circumspection.[9]

The behaviour of iron was clearly read in multiple ways and thus indeterminately, with doubt and suspicion. One element supporting the circulation of evidence in this and other cases of 19th-century railway accidents was a field of surveillance formed by the intrusion of technology into Britain's rural and urban landscapes. According to one of the first newspaper accounts, the 'bridge and river presented a singular spectacle after the accident'.[10] However, along the River Dee on 24 May, 1847, the elements of a scene waiting for an accident, possibly a crime, to happen were already there. The newspapers provided an additional narrative and imaginative element. The prominent stage of the bridge and elevated track (illuminated by the late afternoon light) and the moment of a train passing, with its noise, spark and billowing smoke, anticipated an audience drawn from the surrounding population of rural labourers, travellers and other passers-by. Topography and the demography of an inhabited and industrialised landscape provided newspapers with rich terrain for sensationalised reporting. This and comparable scenes of national scandal helped define and promote a progressive agenda during the Victorian era. Scandals were followed with calls for cemetery and housing and sanitary reform, as well as the regulation of the railways —all subjects of official inquiries (Chadwick 1843a; Roberts 1850; Chadwick 1865). These reforms often demanded nothing less than the advancement of British science and building technology to complete humankind's mastery of nature and banish the risks that ignorance entailed. Newspaper reporting on the personal experiences of each of these types of disaster complemented the growth of statistics on death and injury that resulted in new classes of industrial accidents (Cooter 1997; Chadwick: 1843b).

The River Dee bridge first opened to local freight traffic on 4 November 1846, following its examination and approval by an inspector from the government's Board of Trade. Additional details emerging from the newspapers and inquest revealed that painters working on the structure had observed large deflections of several inches in the girders shortly afterward this examination. However, neither Stephenson nor his staff seemed to have been informed of the discovery. Just before the bridge was opened to the public, a small fracture was detected near the joint between two girders. Stephenson deduced it was the result of a casting defect. Piles were placed to temporarily support the faulty girder and a new section was cast as a replacement. On the morning of the disaster, six trains passed over the bridge without incident and Stephenson inspected the structure the same day. He was worried about sparks and cinders from passing trains falling on the oak sleepers and setting them afire (the apparent cause of the destruction of the Uxbridge Bridge on the Great Western Railway). Consequently, Stephenson ordered that five inches of ash ballast be laid over the timbers. The ash promised fire protection, but, as period testimony indicated and contemporary analysts have observed, the material added to each of the three spans an additional static (or 'dead') load, estimated to be eighteen tons. The ballast was laid in the afternoon, an operation completed just before the ill-fated train left Chester station at 6.15 pm. Many locals saw the accident and rushed to the aid of survivors. A number of observers provided accident inspectors with eyewitness accounts.

A small boy fishing in the river saw the accident, reported one newspaper. Hearing a train approach, he 'naturally looked up, and on its crossing the span nearest to him, he heard a crashing noise for two or three seconds' before seeing the four carriages fall down into the river 'in a string' (*The Bradford & Wakefield Observer* 27 May 1847: 5). Another spectator, Thomas Barlow, who was mending nets on the marsh below the Dee Bridge at the time of the accident, on the west side of the river about four hundred yards away, saw the train move onto the last span. He reported hearing 'a tremendous crash' and 'a large piece of girder fell from the middle buttress; also a lot of rubbish and the carriages; the last carriage dropped first, and the rest followed' (*The Morning Post*, London 29 May 1847: 3). A Chester publican and milkman, Thomas Jones, saw the accident from the elevated vantage point of the Grosvenor bridge about seven hundred yards away. He had put his milk cans down to watch as the train crossed the river. When it reached the furthest span, Jones reported seeing

> a crack open in the middle of the girder; the train and tender were about the centre; the crack opened from the bottom; the engine had passed the crack, and the tender was right upon it; the engine and tender went on, and I saw the tender give a rise up; the carriages gave a jump and fell backward; the last carriage went down first according to my judgment; the next I saw was the large stones fall off the wall on the Saltney side; I heard a crash when they fell; I am certain the girder opened up from the bottom. (*Manchester Times and Gazette* 19 June 1847)

This testimony came late in the proceedings, more or less coinciding with a report into the disaster ordered by the Railway Commissioners. Although Jones was further away from the bridge than other eyewitnesses, his observations were privileged, purportedly because they complemented these expert findings (Lewis and Gagg 2004: 183). Captain Simmons of the Royal Engineers was asked to investigate the incident. He was assisted by James Walker, another civil engineer. Their survey and assessment relied on site visits and detailed inspection of the damaged bridge and broken parts (**figures 2, 3**). It also called on another, more abstract and theoretically nuanced topography, in addition to the real-life accident scene. The former contributed to naturalising the domain of 'the accidental' over the course of the later 19th and early 20th centuries by subjecting random or providential events to assessment by reasoned observation and statistical measure (Green 1997: 39–46; Hacking 1987). This domain was opened when Stephenson's initial design and calculations were examined for accuracy and when tests were made of those girders that remained intact. These produced measurements of their deflection under static and live loads. To reproduce (though not exactly) the conditions prevailing on the bridge when it collapsed, a 48-ton locomotive was driven along the girders at about 20 miles per hour and additional movements in the iron observed.

One by one, a number of possibilities, though clearly not all—including casting defects in the girders, excessive deflection of the cast iron under comparable loads and the failure of the wrought-iron trusses—were ruled out as the cause of the collapse. Their investigation allowed Simmons and Walker to theorise and propose that the dynamic condition precipitated by the moving train may have weakened the cast iron. This may have resulted in the crack, which Jones claimed to have observed, and an additional one, discovered in pieces of a second girder retrieved from the river bottom. The two engineers incorporated details from the eyewitness accounts framed by means of their empirical research and concluded:

> [W]hen a weight, partly permanent and partly passing, but together forming a very considerable proportion of the breaking weight of the girder, is in continuing operation, flat girders of cast iron suffer injury, and their strength becomes reduced. (*The Morning Chronicle* 15 July 1847)

According to Stephenson's theory the dynamic interaction of materials and machines played a role in the collapse. Simmons and Walker described a 'general' condition in which the breaking weight of any cast-iron girder *could* be reduced by repeated vibration, thus opening up a domain of probabilities. By contrast, Stephenson believed that a specific incident—an accident—occurred whereby the train derailed and then struck the inner side of the bridge, thereby causing a facture. If this latter case were true, it would mean the collapse was neither the result of a simple failure in the middle of the centre girder nor owing to the engineer's failure to size the girder properly for static and live (but not necessarily moving) loads. Stephenson obtained corroborative testimony from fellow engineers Joseph Locke, Charles Blacker Vignoles and Thomas Gooch. Nonetheless, despite such illustrious support, and while determining the deaths and injuries from the collapse were accidental (meaning their initial trigger was indeterminate), the jurors were also unanimous in their opinion that 'the aforementioned girder did not break from any lateral blow of the engine, tender, carriage, or van, or from any fault or defect in the masonry of the piers or abutments, but from its being made of a strength insufficient to bear the pressure of quick trains passing over it' (*Liverpool Mercury* 18 June 1847). Moreover, in a statement reproduced widely in the press, they considered it their 'duty towards the public' to

> call upon her Majesty's government to institute such an inquiry into the merits or demerits of these bridges as shall either condemn the principle or establish their safety [adding with remarkable precision] to such a degree that passengers may rest fully satisfied there is no danger although they deflect from 1 to 5½ inches. (Ibid)

The record of the coroner's inquest was conveyed to the public with remarkable speed and accumulating detail in newspapers published over the course of the proceedings. It is framed by and shapes a particular social context of evidence and proof, where the epiphenomenon 'iron' appears as a 'truth-effect'. This is where, as one scholar describes it, 'questions of truth reflect conflicting ideologies and political interests associated with unstable agencies' (San Juan Jr 1999: 81).[11] The public record of the River Dee bridge disaster frames multiple hypotheses for the cause of the bridge collapse. In so doing it catalogues the known properties and apparent behaviour of its cast-iron components as well as uncertainties requiring additional experiment and regulation of iron technology. The newspapers chronicle several forms of agency—the eyewitness, the expert engineer, the technician or operator of machines, the reporter and social commentator—as well as the activity of judicial authorities that gave rise to the proceedings in the first place.

The influence of the last of these alone is worthy of extended study. As Burney (2000) has shown, aspects of the English inquest had survived for at least half a millennium by the time of the disaster. The procedure's longstanding aim to ascertain the cause of death in uncertain circumstances was connected to the defence of popular liberties. In the 19th century, it became subject to an increasingly biological conception of population and governance. The inquest, Burney says, was

> an institution formally well positioned to take on the modern duties of inspection and information gathering, yet at the same time emblematic of the very participatory rationale to be displaced by the regime of expertise, the inquest was peculiarly sensitive to the tension between the demands of expertise and those of publicity. (Ibid., 2)

Over the course of the 19th century this tension was evident in multiple arenas and was not easily, if ever, resolved. In cases arising from death and injury in Britain's workhouses in the 1840s and in a range of workplaces in the 1860s, it was not the treachery of iron or any other one material accident that provoked public outrage and calls for reform (Ibid., 42, 47–50). Rather, it was the uncertain impact of a number of distinctive environments (including prisons, asylums and factories) on human health and morality that led to calls for inquests. Consequently, the institution of the inquest remained uneasily positioned as 'a tool of exposure and demonstration, on the one hand, and of procedural inquiry and explanation, on the other' (Ibid., 49).

Tellingly, the coroner attending the inquest into the River Dee bridge collapse concluded the proceedings by recording the jury's verdict of accidental death and injury, but not its opinion on the safety of cast- and wrought-iron bridges. Instead, the jurors' call for government interference in bridge design 'might be taken notice of by the gentlemen of the press, and would be forwarded by him to the Board of Trade' (*Liverpool Mercury* 18 June 1847). In other words, the work of the inquest was done when the verdict was rendered. Any other conclusion, including ones obliging regulation of engineering and iron industry, were for the press and other agencies to draw.

Two years after the inquest and its verdict, in July 1849, a Royal Commission was initiated to investigate the safety of Britain's iron bridges, though its findings appear to have done little to alter the progressivist bias in historical accounts of modern building methods and materials. Robert Stephenson, Brunel and others provided expert testimony. Both supported continued use of cast- and wrought-iron bridges, while Brunel delivered a blistering attack on what he perceived to be the Commission's intent to control structural experimentation by regulating the use of materials. With scant regard for these details, nor for this source of dissent, received wisdom has it that the rest is history. The limitations of cast and wrought iron were eventually fully recognised. Knowledge of material science and engineering was advanced by the River Dee bridge failure and by subsequent disasters. The collapse of Thomas Bouch's Tay Bridge in 1879 was particularly influential, the bridge's failure determined to have been caused by inadequate calculations for wind force, poor maintenance or shoddy workmanship (or a combination of all three factors) (Select Committee on North British Railway 1880)[12] (**Figure 4**). As conventional thinking has it, protection of the public good has become enshrined in new material standards and the improved education of engineers and building technicians. Thus was a wedge effectively driven between engineering and other professions, architecture in particular. Steel has now replaced iron in structural design. Legislation aimed at distributing professional liabilities for the constructed environment

Figure 4: Photograph of fallen girders after collapse of part of the first Tay Bridge, 1879. Reproduced under Creative Commons License from the National Library of Scotland Digital Gallery.

has taken over from authority derived from privileged birth, class or apprenticeship—or so the story goes.[13]

However, the verdict of both the jury at the River Dee bridge collapse inquest and the ensuing Royal Commission into Britain's iron bridges draws our attention to the play of forces behind the history of technological innovation and its normalisation through the regulating of those objects and materials of invention. Appreciating the uncertainty accompanying the verdict also prompts a reconsideration of the progressivist narrative of 19th-century building science and technology in which iron and its improvement has been positioned somewhere between wood and steel in an evolutionary chronology of construction materials (Mumford 1934: 120, 166–67; Condit 1988; Landau 1996: 40–61; Addis 2007: 295–300, 308–318).

The evolution of building with iron

The continued notoriety of the River Dee bridge collapse has inspired recent examination of witness evidence to determine just what went wrong. Two specialists in materials engineering, Lewis and Gagg (2004), studied the record of the inquiry and concluded that Simmons and Walker stumbled across evidence for the phenomenon now recognised as metal fatigue. The collapse, Lewis and Gagg write, was owing to 'a defect at a sharp corner in a flange on a girder' (177) which served to raise and localise stress in the metal. They note, perhaps with irony, and alluding to mixed aspirations for the design, that the offending corner formed part of a cavetto moulding between the flange (horizontal) and web (vertical) planes of the beam. This is a refinement traditionally carved in wood and it 'had presumably been added as an artistic flourish' (177).

The details of early 19th-century iron construction often demonstrated opposing technical and aesthetic aspirations. These appear on bridges, but also on a number of building types (Anonymous 1856; Curl 1973: 24–28; Flores 2006: 14–15, 152–53). The moulding entailed here was normally associated with the fashioning of wooden beams, and comparable refinements appear on the iron used in mid-century factories, warehouses and storefronts (Bannister 1956). When commentators on the failure of the bridge mention the cavetto moulding they emphasise its negative impact on the statical properties of the iron beam in question. These properties are privileged over Dreicer's 'full gamut of cultural and physical forces' which must include aesthetic tendencies that may appear outdated, arbitrary or irrational. This emphasis therefore contributes to a partial and possibly anachronistic view of the past. In other words, the moulding speaks of changing building practices, but in its treatment by the materials specialists, it also becomes conspicuous in *not* being modern.

Engineering and architectural historians have often, though mistakenly, relied on a progressivist and at times evolutionary framework to explain the development of iron buildings from timber structures (Dreicer 2000). According to this scenario, iron buildings are clearly the logical successor to timber ones in delivering certain statical advantages. These include longer and more resilient spans, portrayed as self-evident outcomes waiting to be realised from beneath the deadening weight of history and convention—like the 'pure functional energy' Pevsner claimed was manifest by Brunel's Clifton Suspension Bridge. In philosophical terms, such an explanation calls upon 'an empiricist conception of knowledge' (Hindess 1977: 133) whereby empirical verisimilitude is established, in this case gradually, by means of trial and error, over time. Truth accompanies the congruence of the idea of an object (the function of a bridge, for example, or carrying capacity of a cast or wrought iron or steel beam) and the perception of its form or other sensuous quality. This conception is bolstered with hindsight, after a long period of experimentation—and disaster (Petroski 1982). It also relies on a conception of cumulative material invention whereby the substances of cast and wrought iron are ultimately transformed into *something else* entirely, something more theoretically abstract—compositionally specific and less tolerant of impurities—but also practically reliable, as, for example, the varying grades of steel are expected to be.[14]

Period engineers were themselves aware of unexpected progress that could come from trial and error, though obviously some errors were greater, more complex and uncertain in their explanation or tragic in their outcomes than others. Some engineers suffered for these differences. Thus, an evolutionary perspective on iron construction also commonly entails overlapping ideological, political and moral positions. Theodore Cooper (1839–1919) was assistant engineer in charge of New York City's first elevated railroads and an author of standard building specifications. He was the supervising engineer on the first Quebec Bridge when it collapsed after four years of construction (1907), just prior to its completion, killing seventy-five workers (Middleton 2001: 69–102). Cooper believed (1889) that 'the intelligent investigator does not decide upon the merits of any developed system by the failures which are necessary steps in its development. Without variations and failures there would be no evolution or survival of the fittest' (cited in Dreicer 2000: 132). However, as Dreicer observes, it is partly owing to the paucity of construction records for 19th- and 20th-century buildings that histories of engineers 'typically consist of anecdotes leavened by a belief in natural selection—belief adopted by the professional historians who read their writings' (130). Consequently, historians of engineering and construction technology have appropriated quasi-evolutionary theory 'to defend practices, hide uncertainties, and legitimize mistakes' (140). The same holds true for Pevsner who, though clearly more Hegelian in his idealism than Darwinian or evolutionist, could confidently state that 'engineering architecture in the nineteenth century was largely based on the development of iron, first as cast iron, then as wrought iron, later as steel. Towards the end of the century reinforced concrete appears as an alternative' (1936: 118). There follows a generalised and typically causal understanding of the past, a position akin to uniformitarianism where building materials such as these were caught up in a dynamic continuum. This is where, as in organic nature, 'everything is always or potentially changing and (…) nothing can be understood without its history' (Levine 1988: 16).

In support of *their* interpretation of events and mistakes in the story of the River Dee bridge collapse and inquest, Lewis and Gagg find it 'remarkable' that Stephenson's derailment theory was deliberated at length 'given the flimsy nature of the case' the engineer made for it (2004: 183). The materials specialists note that eyewitness testimony clearly indicated the engine tender had derailed as the locomotive pulled ahead and the track fell away beneath the carriages, but that this had 'occurred *after* the initial break in the centre girder, and not before' (183). Nonetheless, supportive testimony by Thomas Gooch and the other experts was allowed, the jurors were taken to the accident scene, and the 'remains of the train were scoured for any support for the theory, but very little could be produced.' In summing up the body of testimony for the jury, the specialists describe how the coroner 'went out of his way' to rule out negligence by Stephenson, 'let alone the possibility of manslaughter' (183).

The absence of evidence for the derailment theory may render the argument tenuous, given modern expectations for truth and empirical verisimilitude in judicial proceedings. However, the 'participatory rationale' (Burney) and the vagaries of expert knowledge shaping the inquest made it appear less tenuous at the time. Testimony based on firsthand experience (possibly mitigated by jurors having had access to progressively detailed reporting on the proceedings) mingled uneasily with deductive reasoning derived from theory and practical knowledge of the complex interaction of locomotives and iron rails and other elements of supportive infrastructure. Then again, one need only consider the challenge to any conclusive understanding faced by jurors today, in trials involving different forms and multiple sources of 'expert' testimony, to suspect that comparable uncertainty was also at work in times past. What is 'remarkable' about their view of the evidence given at the 1847 inquest is that Lewis and Gagg fail to fully acknowledge an important ethical context. This is one in which truth has been historically linked to different modes of reasoning, of which the empiricist conception and practice of knowledge associated with modern empirical science is only one style (Combie 1983). Likewise, it is a context entailing multiple subject positions, so that the agency of the engineer was far from static. Rather, the engineer's authority was vulnerable to contestation, even moral disapprobation.

Additional light can be thrown on the state of knowledge attending the River Dee bridge collapse by considering mixed expectations for the performance of another project. This is the Liverpool and Manchester Railway, which in 1825 existed only as plans on George (the father of Robert) Stephenson's drawing board and as the elder engineer's calculations for its locomotive and infrastructure. Mention of the inquiry instigated to obtain parliamentary consent for the scheme is included in the hagiographical account of the Stephensons' legacy, in Samuel Smiles' *Lives of the Engineers*. This was first published in 1861, thirty-six years after the inquiry and fourteen years after the River Dee bridge collapse:

> Mr. Stephenson stood before the Committee to prove what the public opinion of that day held to be impossible. The self-taught mechanic had to demonstrate the practicability of accomplishing that which the most distinguished engineers of the time regarded as impracticable. Clear though the subject was to himself and familiar as he was with the powers of the locomotive, it was no easy task for him to bring home his convictions, or even to convey his meaning, to the less informed minds of his hearers. In his strong Northumbrian dialect, he struggled for utterance, in the face of the sneers, interruptions, and ridicule of the opponents of the measure, and even of the Committee, some of whom shook their heads and whispered doubts as to his sanity, when he energetically avowed that he could make the locomotive go at the rate of 12 miles an hour! It was so grossly in the teeth of all the experience of honourable members, that the man 'must certainly be labouring under a delusion!' (161–62)

The Parliamentary Committee room provided an arena for debate where the variety and sources of authority and expert knowledge and the character of interlocutors were as much highlighted and called into question as the details of the new railway. In the chamber Stephenson confronts public opinion and more. The 'practicability' of the 'self-taught mechanic', in Smiles's words, confronts the expertise of accomplished professional engineers. His struggle to be heard and understood by a potentially hostile audience came at a time when dialect and elocution were common signs of character and trustworthiness. Stephenson's testimony also relies on the quality of his drawings and figures which, in the end, Smiles believes betrayed his cause. The Railway Bill for a Liverpool–Manchestor railway was not supported. The proposal was revised and returned to Parliament the following year without Stephenson's membership on the reconfigured team of advocates and eventually it won approval.

Not surprisingly (given that Smiles tells it), George Stephenson's *idea* for a railway (if not his arguments for it) overcomes challenges to the engineer's credibility owing to commercial vested interests, class prejudice and the apparent technical ignorance of his interrogators. The Liverpool and Manchester Railway goes ahead. It achieves (and exceeds) the speed of twelve miles an hour, against the odds as they were conceived at the time. One can read between the lines of such Victorian moralising prose extolling the virtues, particularly the fortitude and perseverance of the era's heroic engineers. What is missing from Smiles' *Lives* is explicit mention of a social and political context in which not only is the rationality of such innovations at stake, but also the character of their chief proponents. Tellingly, Smiles fails to include mention of the River Dee bridge collapse in his story.

Conclusion

It is a paradox that Pevsner's *Pioneers of the Modern Movement* celebrates works of 'architecture' which were neither designed by an architect nor wholly understood by architects or any other kind of design practitioner at the time. Arguably, the variable and uncertain behaviour of materials forming these objects, specifically engineered structures like bridges, factories and warehouses, helped shape relations between forms of expertise-based authority and inventive practices—and equally between engineers and architects. Both sets of relations have proven to be ambiguous and prone to contestation at times, resulting from (and making for or intensifying) periods of crises accompanied by demonstrations, investigations and calls for reform. As Burney has shown in his work on the genealogy of the popular inquest, the legitimacy of expertise derived from science and professional training was not always given. In some cases, professional expertise was seen to threaten popular liberties (2000: 16–20). This threat also may have figured in protests against George Stephenson's plan for the Liverpool and Manchester Railway in 1825, along with clear vested interests held by landowners and some businesses.[15]

The River Dee bridge disaster aggravated a troublesome crack in the facade of Victorian industrial supremacy and technical expertise, a pretence that was only established by forgetting the details of this and other accidents. The collapse magnified wide-ranging uncertainty and fears prompted by technological innovation. Fears were expressed before and long after both the incident and the decade of 'railway mania'. In that period, the expansion, often forcible, of railway communication across the British Isles entailed widespread infringement of private property rights along with threats to life and limb (Lewin 1968; Kostal 1994; Sinnema 1998). As Kostal writes, the railway industry 'blurred what had been a stable division between the physical space of industrial production and consumption' (1994: 255). The record of mishaps and litigation (and, with increasing regularity in the 1850s and 60s, pecuniary compensation for victims) shows just how far railway companies would go to industrialise town and countryside so that

> Victorian society became exposed to the hazards of the industrial workplace. The railway had interjected a 'machine ensemble' between the traveller and the landscape. And when the machine went awry, the apparatus destroyed itself by means of its own power. Thus emerged what has been described as the 'technological accident' [Schivelbusch 1977: 24]. (Freeman 1999: 107)

The industrialisation of travel and the exposure of railway passengers and railway company employees (and company shareholders, indirectly) to risks arising from technological accident, death and injury reinforced the heterogeneous nature of Victorian society. This heterogenity was based on the forms of knowledge and individual character required of newly formed experts and other human components of Freeman's 'machine'. The chance failure of any one component set in motion judicial proceedings which were themselves undergoing change, so that justice was one 'truth-effect' of iron's unpredictability as an industrial material. Similarly, the delivery of justice was also socially differentiated. For instance, by the middle of the 19th century, while injured passengers were typically awarded damages, railway company employees were not, owing to an imbalanced interpretation of the concept of vicarious liability (Kostal: 255–56). Smiles introduced generations of Victorian readers, particularly school children, to the worth of genius, foresight and perseverance he believed characterised the lives of the great engineers like Stephenson and Brunel. However, the moralist failed to comment on Brunel's preference for illiterate engine drivers. Brunel argued that control of locomotives should be like the machines themselves: habitual, predictable and free from human idiosyncrasy. Addressing a Parliamentary Select Committee on Railways in 1841, Brunel spoke on the training required of drivers:

> It is impossible that a man that indulges in reading, should make a good engine-driver; it requires a species of machine, an intelligent man, an honest man, a sober man, a steady man; but I would much rather not a thinking man.[16]

These discriminations are important for understanding the history of iron construction and industrialised building. Specialist language and concepts like 'material fatigue' or the 'catastrophic failure' of structures may be useful for understanding the River Dee bridge collapse, but these modern terms can also be misleading. They engage the language, objective content and investigative protocols of scientific and engineering practices today and, in so doing, risk occluding social, including theoretical, contexts for understanding iron as an ingredient in emerging technological systems in times past. Historical anachronism shadows evolutionary explanations of design and construction practices (Forty 1986: 4). This is to say that the several witnesses to the River Dee bridge incident who claimed they saw cracks appear in the cast-iron girders just before the collapse were self-acknowledged and formally recognised observers of *some* kind of failure. They were thus experts in the matter to some degree, however minor by modern measures of technical acumen. Introducing additional uncertainty to this terrain of knowledge and action, multiple hypotheses were put forward to explain just what this failure could have been.

The relative brittleness of cast iron was well known at the time and encouraged iron's careful use, either alone or in combination with wrought-iron components. The composite trusses supporting the River Dee Bridge were also used to build the Manchester cotton spinning factory designed by architect William Whitaker. The building partially collapsed suddenly less than two months before the bridge failure (Gagg 2011: 1964; McBride 2012). Another 'fire-proof' iron cotton mill in Oldham had previously fallen in 1844, resulting in twenty-five deaths (13). Mill workers who survived the Manchester mill accident reported how the greater portion of the roof fell in 'with an awful crash, and [with] a report similar to the explosion of a boiler' (*The Morning Chronicle*, London 18 March 1847). A paper presented by William Fairbairn to the Institution of Civil Engineers (Great Britain) in April 1847 reinforced claims and language describing the 'treacherous' nature of cast iron (cited in McBride 2012: 10). However, such historical assessments of iron's seeming fragility (evidenced by collapsed bridges and buildings and blown boilers) are not entirely commensurate with circumstances resulting in what specialists of forensic engineering now recognise as material fatigue, a condition that was first, but imprecisely, identified in 1854 (OED). The concept was subsequently given theoretical elaboration in concert with practices resulting in the near (but not complete) normalisation of ferrous metal construction. Hence, it appears anachronistic that, though Lewis and Gagg believe the experiments conducted by Simmons and Walker for their Report demonstrated the 'problem of low cycle fatigue as well as the idea of a fatigue limit' (2004¨184), they reject the Victorian engineers' explanation that the physical 'structure of the metal changed fundamentally, repeated flexure producing "a peculiar crystalline fracture and loss of tenacity"' (184). Their rejection entails a narrowing of historical and social context so it more readily fits into an evolutionary schema accounting for the progress of engineering science and the moral training of engineers into reasoning subjects and designers of a particular kind.

Notes

1. The author gratefully acknowledges the assistance and comment on this paper provided by Joely-Kym Sobott. Research was supported, in part, by a grant from the Australian Research Council (ARC).
2. Rolt's account details Brunel's testimony at the Royal Commission on the Application of Iron to Railway Structures, including his characteristic stance against government bureaucracy and arguments against the regulation of engineering and iron industry.
3. Anderson (1971: 274) writes: 'In this as in most of his other writings, Pevsner seeks to identify what he calls "A Style for the Age." For Pevsner, the Age is at all times the hard reality which man must comprehend. As it happens, the Age called "modern" is not only a quite intractable given, but a given which is itself, according to Pevsner, a hard mechanistic mass civilization resulting from the full development of the Industrial Revolution.'
4. Smiles is best known for the four-volume *Lives of the Engineers* (London, 1862). Of comparable interest, Lionel Rolt was a prolific writer on the history of Britain's waterways, railways and industrial history and was equally idealist in his treatment of engineering and engineers. His biographies include *Isambard Kingdom Brunel* (London: Longmans, 1957) and *George and Robert Stephenson: The Railway Revolution* (London: Longmans, 1960).

[5] Schapiro and Craven (1997: 158) write: '[the] tendency, to displace the analysis of an historical situation through a general psychological category, surfaces in the frequent references to the Zeitgeist and to the "essence" of the century as such. [Pevsner] advances from the representation of our time as a 'practical' and 'collective' century—somehow, the ordering structure of architecture reflects the *Geist* of rational planning in society—and forgets thereby the social conflicts and class divisions, all of which are subsumed under the collectively based sense of practicality.'

[6] Period and intermittent 20th-century commentary reveal broad interests in the subject by way of questioning the reasons for the bridge collapse. Early examples include two anonymous articles from 1847 in the *Journal of the Franklin Institute*. The contribution of the disaster and its resulting inquiry to the rise of modern engineering and its professionalization is a theme in contemporary literature (for example, see Sibly and Walker 1977; Buchanan 1985). 'Forensic engineering' is a term and sub-discipline allowing for varied interests in the history of disastrous episodes (Reynolds 2002). The necessary contribution of disaster and structural failure to the development of engineering knowledge is conveyed by a number of authors and specific chapters on the River Dee Bridge collapse, particularly Henry Petroski (1982, 1994a and 2012; also Scheer and Wilharm 2011). Studies of iron and material culture form an additional theme (Kemp 1993; Gagg and Lewis 2011). Additional social (including biographical, governmental and aesthetic) contexts for engineering failures appear in literature (Lewis 2001; Buchanan 1988; Gagg 2004).

[7] For a discussion of architecture and the aesthetic dimensions of this problem, see Muthesius (1970).

[8] Details of the incident and coronial inquiry were given wide coverage in the press. The account presented here is gathered from multiple period sources and by historians and scholars with expertise in engineering history and materials science who have attempted to explain the cause of the accident over the years. Overviews and analysis can be found in Lewis and Gagg (2004), Petroski (1994b: 81–98) and Hopkins (1970: 127–128).

[9] As Winter (1994: 69) writes about Victorian shipbuilding: 'Throughout the Victorian period, the language of disordered compasses [owing to their magnetic attraction to iron ship hulls] and lost ships was used to describe spiritual and intellectual uncertainties and the lack of clear, established conventions of authority [...]. One might have expected this vocabulary to have held only a metaphorical significance in issues of cultural authority, but their poignancy was enhanced by the loss of real ships and the disordering of real compasses.'

[10] The anonymous correspondent observed that 'various theories are afloat' as to its cause, but added 'as none of them rests upon a better foundation than mere rumour we pass them over' (*The Bradford & Wakefield Observer* 27 May, 1847: 5).

[11] Epifanio San Juan Jr. continues: 'Not that reality is a mere invention or fiction, but its meanings and significances are, to use the current phrase, "social constructions" that need to be contextualized and estimated for their historically contingent validity' (81).

[12] The Tay Bridge collapse is also notable for the novel use of photographic evidence in the ensuing inquiry.

[13] Petroski (1994) provides us with a variation on this tale. Beginning with 'simpler times and simpler engineering' where past 'analytical foundations' of engineering science 'are no longer matters of debate', he interprets case histories of historical bridge failures 'more for their lessons about the nature of design process than as an account of its manifestation in a particular artefact' (52).

[14] Mindful of the ontological implications of this second conception, it may be worth recomposing the history of iron construction in non-evolutionary terms, where three, more or less distinct ferrous substances (cast iron, wrought iron and steel) compete for acceptance in view of Dreicer's (2000:13) 'gamut of cultural and physical forces'. See Misa (1992: 124–132), who seems to adopt this perspective.

[15] Smiles (1861: 158) writes how canal operators threw everything they had into the battle against approval, conjuring up catastrophic visions of what further industrialisation of the countryside might bring: 'The public were appealed to on the subject; pamphlets were written and newspapers were hired to revile the railway. It was declared that its formation would prevent cows grazing and hens laying. The poisoned air from the locomotives would kill birds as they flew over them, and render the preservation of pheasants and foxes no longer possible. Householders adjoining the projected line were told that their houses would be burnt up by the fire thrown from the engine-chimneys; while the air around would be polluted by clouds of smoke. There would no longer be any use for horses; and if railways extended, the species would become extinguished, and oats and hay be rendered unsaleable commodities. Travelling by rail would be highly dangerous, and country inns would be ruined. Boilers would burst and blow passengers to atoms. But there was always this consolation to wind up with—that the weight of the locomotive would completely prevent its moving, and that railways, even if made, could *never* be worked by steam-power.'

[16] Testimony by Isambard Brunel, 'Report from the Select Committee on Railways; together with the minutes of evidence taken before them, and an appendix, and index', British Parliament Papers, 1841, Session 1, 68.

References

Addis, B 2007 *Building: 3000 Years of Design Engineering and Construction*. London: Phaidon.

Anderson, S 1971 *The Sources of Modern Architecture and Design* by Nikolaus Pevsner. (book review) *The Art Bulletin*, 53 (2): 274–275.

Anonymous 1847 The Late Failure of the Chester Bridge. *Journal of the Franklin Institute*, 44 (3): 149–157.

Anonymous 1847 Remarks on the Report of Mr. James Walker and Capt. Simmons, on the Late Failure of the Chester Bridge. *Journal of the Franklin Institute*, 44 (4): 217–219.

Anonymous 1856 Iron Buildings. *The Crayon*, 3 (3): 84.

Bannister, T 1956 Bogardus Revisited: Part I: The Iron Fronts. *Journal of the Society of Architectural Historians*, 15 (4): 12–22.

Bijker, W & **Law, J** 1992 Do Technologies Have Trajectories? In: Bikjer, W & Law, J (eds), *Shaping Technology/Building Society: Studies in Sociotechnical Change*. Cambridge, MA & London: The MIT Press.

Buchanan, R A 1985 The Rise of Scientific Engineering in Britain. *The British Journal for the History of Science*, 18 (2): 218–233.

Buchanan, R A 1988 Engineers and Government in Nineteenth-Century Britain. In: Roy MacLeod, R (ed.), *Government and Expertise: Specialists, Administrators and Professionals, 1860–1919*. Melbourne: Cambridge University Press. pp 41–58.

Burney, I 2000 *Bodies of Evidence: Medicine and the Politics of the English Inquest 1830–1926*. London: The John Hopkins University Press.

Canguilhem, G 1994 *A Vital Rationalist: Selected Writings from Georges Canguilhem*. New York: Zone Books.

Castel R 1991 From Dangerousness to Risk. In: Burchell, G et al. (eds), *The Foucault Effect: Studies in Governmentality*. Chicago: University of Chicago Press. pp 281–98.

Chadwick, E 1843a *Report on the Result of a Special Inquiry into the Practice of Interment in Towns*. London: R. Clowes & Sons.

Chadwick, E 1843b *On the Best Modes of Representing Accurately, by Statistical Returns, the Duration of Life, and the Pressure and Progress of the Causes of Mortality* […]. London.

Chadwick, E 1865 *Address on Railway Reform*. London: Longman, Green, Longman, Roberts, & Green.

Chester and Holyhead Railway 1847 Copy of report to the commissioners of Railways by Mr. Walker and Captain Simmons, R.E., on the fatal accident on the 24th May 1847, by the falling of the bridge over the River Dee, on the Chester and Holyhead railway; and minutes of the commissioners thereon. Source: Proquest and HCPP (House of Commons Parliamentary Papers) database.

Combie A 1983 *Styles of Scientific Thinking in the European Tradition*. Cambridge: Cambridge University Press.

Condit, C 1988 The Two Centuries of Technical Evolution Underlying the Skyscraper. In: Beedle, L (ed.), *The Second Century of the Skyscraper*. New York: Van Nostrand Reinhold. pp. 11–24.

Cooter, R 1997 The Moment of the Accident: Culture, Militarism and Modernity in Late-Victorian Britain. In: Cooter, R and Luckin, B (eds), *Accidents in History: Injuries, Fatalities and Social Relations*. Amsterdam and Atlanta, GA: Rodopi. pp. 107–157.

Cooter, R and **Luckin, B** 1997 Accidents in History: An Introduction. In: Cooter, R and Luckin, B (eds), *Accidents in History: Injuries, Fatalities and Social Relations*. Amsterdam and Atlanta, GA: Rodopi, pp. 1–16.

Curl, J S 1973 *Victorian Architecture*. Newton Abbot, England: David and Charles.

Davis, I 1983 Disasters as Agents of Change? Or: Form Follows Failure. *Habitat International*, 7 (5/6): 277–310.

Dreicer, G K 2000 The 'Evolution' from Wood to Iron in the Construction of Bridges and Nations. *Perspecta*, 31: 130–140.

Ellul, J 1980 *The Technological System*, trans. by Neugroschel, J. New York: Continuum.

Figlio K 1985 What Is an Accident? In: Weindling, R (ed.), *The Social History of Occupational Health*. London: Croom Helm.

Flores, C 2006 *Owen Jones: Design, Ornament, Architecture, and Theory in an Age of Transition*. New York: Rizzoli.

Forty, A 1986 *Objects of Desire: Design and Society Since 1750*. London: Thames and Hudson.

Freeman, M 1999 'Trains of Thought': Steam Railway Capitalism and the Law in 19th-Century England. *Oxford Journal of Legal Studies*, 19 (1): 99–110. DOI: http://dx.doi.org/10.1093/ojls/19.1.99.

Gagg, C R and **Lewis, P** 2011 The Rise and Fall of Cast Iron in Victorian Structures—A Case Study Review. *Engineering Failure Analysis*, 18 (8):1963–1980.

Green J 1997 Accidents: The Remnants of a Modern Classificatory System. In: Cooter, R and Luckin, B (eds), *Accidents in History: Injuries, Fatalities and Social Relations*. Amsterdam and Atlanta, GA: Rodopi. pp. 35–58.

Hacking I 1990 *The Taming of Chance*. Cambridge: Cambridge University Press.

Hacking I 1987 Was There a Probabilistic Revolution 1800–1930? In: Kruger, L et al. (eds), *The Probabilistic Revolution*. Volume 1: *Ideas in History*. Cambridge, MA: MIT Press. pp. 43–55.

Hindess, B 1977 The Concept of Class in Marxist Theory and Marxist Politics. In: J. Bloomfield (ed.), *Class, Hegemony and Party*. London: Lawrence Wisehart.

Hopkins, H J 1970 *A Span of Bridges*. Newton Abbot, England: David & Charles.

Kemp, E 1993 The Introduction of Cast and Wrought Iron in Bridge Building. *The Journal of the Society for Industrial Archeology*, 19 (2): 5–16.

Kostal, R W 1994 *Law and English Railway Capitalism*. Oxford, Oxford University Press.

Kranakis, E 1997 *Constructing a Bridge: An Exploration of Engineering Culture, Design, and Research in Nineteenth-Century France and America*. Cambridge, MA: MIT Press.

Landau, S B 1996 *Rise of the New York Skyscraper, 1865–1913*. New Haven: Yale University Press.

Levine, G 1988 *Darwin and the Novelists: Patterns of Science in Victorian Fiction*. Cambridge, MA: Harvard University Press.

Lewin, H G 1968 *The Railway Mania and its Aftermath, 1845–1852*. New York: A M Kelley.

Lewis, P R 2001 *Disaster on the Dee: Robert Stephenson's Nemesis of 1847: The Collapse of the Dee Bridge*. Tempus: Stroud.

Lewis, P R and **Gagg, C** 2004 Aesthetics versus Function: The Fall of the Dee Bridge, 1847. *Interdisciplinary Science Reviews*, 29 (2): 177–199.

Leslie, T 2010 Built Like Bridges: Iron, Steel, and Rivets in the Nineteenth-Century Skyscraper. *Journal of the Society of Architectural Historians*, 69 (2): 234–261. DOI: http://dx.doi.org/10.1525/jsah.2010.69.2.234.

McBride, S 2012 Structural Analysis of the Collapse at Gray's Mill, Manchester. Unpublished Thesis (B.Eng.Civil Engineering), The University of Manchester. Available at https://docs.google.com/file/d/0BzzZJSKcC5SNTHBOdEl4am50bFE/edit?pli=1 [last accessed 20 March 2013].

Middleton, W D 2001 *The Bridge at Québec*. Bloomington, IN: Indiana University Press.

Misa, T 1992 Controversy and Closure in Technological Change: Constructing 'Steel'. In: Bikjer, W & Law, J (eds), *Shaping Technology/Building Society: Studies in sociotechnical change*. Cambridge, MA & London: The MIT Press. pp. 109–139.

Mumford, L 1934 *Technics and Civilization*. Chicago: University of Chicago Press edition (2010).

Muthesius, S 1970 The 'Iron Problem' in the 1850s. *Architectural History*, 13: 58–63, 128–131.

Petroski, H 1982 *To Engineer Is Human: The Role of Failure in Successful Design*. New York: St. Martin's Press.

Petroski, H 1994a *Design Paradigms: Case Histories of Error and Judgment in Engineering*. Cambridge: Cambridge University Press.

Petroski, H 1994b Success Syndrome: The Collapse of the Dee Bridge. *Civil Engineering*, 64 (4): 52–55.

Petroski, H 2012 *To Forgive Design: Understanding Failure*. Cambridge, MA: Belknap Press of Harvard University Press.

Pevsner, N 1936 *Pioneers of the Modern Movement from William Morris to Walter Gropius*. London: Faber and Faber; repr. as *Pioneers of Modern Design* (1949); (1975, Penguin).

Reynolds, K 2002 Forensic Engineering: A Reappraisal of the Tay Bridge Disaster. *Interdisciplinary Science Reviews*, 27 (4): 287–298. DOI: http://dx.doi.org/10.1179/030801802225005725.

Roberts, H 1850 *The Dwellings of the Labouring Classes, Their Arrangement and Construction* [...]. London: Society for Improving the Condition of the Labouring Classes.

Rolt, L 1957 *Isambard Kingdom Brunel*. London: Penguin; repr. 1989.

San Juan Jr, E 1999 Truth and Inconsequence: Who Speaks Now? For Whom? And for What Purpose? *Rethinking Marxism: A Journal of Economics, Culture & Society*, 11 (2): 80–85. DOI: http://dx.doi.org/10.1080/08935699908685583.

Schapiro, M and **David, C** 1997 A Critique: Pevsner on Modernity (1938). *Anthropology and Aesthetics*, 31 (Spring): 157–158.

Scheer, J and **Wilharm, L** 2011 *Failed Bridges Case Studies, Causes and Consequences*. Hoboken, NJ: John Wiley & Sons.

Schivelbusch, W 1977 *The Railway Journey: The Industrialization of Time and Space in the 19th Century*. New York: Urizen (English edn, 1979).

Select Committee on the North British Railway (Tay Bridge) Bill 1880 House of Commons Papers; Reports of Committees. Paper no. 311, vol. 12.

Sibly, P G and **Walker, A C** 1977 Structural Accidents and their Causes. Institute of Civil Engineers, *Proceedings*, 62 (2): 191–208.

Sinnema, P W 1998 Representing the Railway: Train Accidents and Trauma in the Illustrated London News. *Victorian Periodicals Review*, 31 (2): 142–168.

Smiles, S 1861 *Lives of the Engineers*, London: John Murray (rev. edn, 1879).

William, R 1990 *Notes on the Underground: An Essay on Technology, Society and the Imagination*. Cambridge, MA: MIT Press.

Winter, A 1994 'Compasses All Awry': The Iron Ship and the Ambiguities of Cultural Authority in Victorian Britain. *Victorian Studies*, 38 (1): 69–98.

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