Suspension Bridges

In his introduction to this collection of essays on Engineering Disasters, Angus Buchanan defines “Disasters” as “serious disruptions to anticipated events”. Some may conclude that this is an unnecessarily wide definition as the import of the word Disaster, they would contend, is clear enough. But further reflection suggests that this is not so. The word Disaster can embrace a plethora of occurrences, not just the fate of the engineering project itself, and any loss of life which may have resulted, but also the financial implications and the consequent damage to the reputation of the engineers and contractors who executed the work in the first place.

P. G. Sibly and A. C. Walker analysed the circumstances surrounding the failure of several large wrought iron and steel suspension and other forms of bridge. Failures, they asserted, occurred against a background of increasing spans, greater slenderness, more confidence in design analysis and decreasing factors of safety. Concentration on certain design parameters, to the exclusion of others, led to those which were of lesser importance initially becoming more significant. Lack of attention to these led to the failure of the structures.[1] Sibley and Walker contended that each design concept had a life of about a generation before it was discredited, to be superseded by a new set of principles.[2] This hypothesis has its attractions. It assumes, however, a uniform pattern of behaviour across generations, countries and technologies in that a new technology is developed in response to the perceived weaknesses in the old, asserting that the problems which emerge with a particular technology are a function of an increasing lack of understanding or casual disregard of the principles upon which it is based. If they were fully respected and not over extended, failures would not have taken place. This assumes, of course that the technology was fully understood in the first place.

This essay posits that difficulties arise with a particular technology, not necessarily because it was extended too far, rather that it may not have been sufficiently understood in the first place. The example selected for consideration is the suspension bridge. Four such structures have been chosen, the bridge over the River Irwell in Salford, Lancashire, that over the Menai Strait in North Wales, the Tacoma Narrows Bridge in Washington State, U.S.A. and the Millennium Bridge over the River Thames in the City of London. All manifested, on initial consideration, similar engineering weaknesses, a conclusion which is not sustainable following a more detailed study of each disaster.

The great advantage of the Irwell bridge is that there is a graphic contemporary account of its failure, albeit in the Manchester Guardian newspaper, rather than a technical report. The bridge, which was built in 1826, was not a particularly large structure. It was just over 145 feet in length, the 18 foot 3 inch wide deck was hung from two bar link suspension chains, one on each side of the roadway. The drop height from the top of the suspension towers to the lowest point of the catenary chains was 12 foot 6 inches. In sum, it was a very conventional structure for the times.

The bridge failed on the 12th April, 1831. A company of soldiers, 74 in number, was returning to its barracks in Salford after a field day on Kersal Moor. About 60 men were marching four abreast when “the structure vibrated in unison with the measured step with which they marched, and, as the vibration was no means unpleasant, they were inclined to humour it by the manner in which they stepped. As they proceeded, and as a greater number got upon the bridge, the vibration went on increasing until the head of the column had nearly reached the Pendleton side of the river. They were then alarmed by a loud sound somewhat resembling an irregular discharge of firearms; and immediately one of the iron pillars supporting the suspension chains, viz. that which was to the right of the soldiers and on the Broughton side of the river, fell towards the bridge, carrying with it a large stone from the pier to which it had been bolted. Of course that corner of the bridge, having lost the support of the pillar, immediately fell to the bottom of the river, a distance of about 16 or 18 feet.” Most of the soldiers went into the river with the bridge. Fortunately no lives were lost. The writer went on to discuss the cause of the accident. It is clear from his detailed analysis that he did not understand what had happened.[3] The reality was that the soldiers marching in step had struck the natural frequency of the structure. The amplitude of the vibratory movement which resulted increased each time the feet, in unison, hit the deck of the bridge. It became such that the chains supporting the bridge came under ever increasing stress. In the event, it was a pillar rather than the chains which failed. It fell into the river taking the roadway and much of the bridge structure with it as described in the newspaper.

Although it was not specifically recounted, it is reasonable to assume, based upon the explicit and clear description of the failure, that the bridge vibrated in the vertical plane. It is very unlikely that the soldiers would have reacted in the way they did if the movement of the bridge deck had been torsional or lateral, as they would not have found the vibration as being “no means unpleasant” if either of these two movements had taken place. If they had, the soldiers would have found their balance disturbed.

I. K. Brunel was deeply involved in the design of the Clifton Suspension Bridge when the Irwell bridge failed. He pasted the press cutting from the Manchester Guardian into his diary without comment. As he was usually quick to express his views on technical matters, the fact that he did not annotate or comment on the report suggests that he did not understand what had happened. There was every incentive for him to study and analyse the Irwell incident as he was, with his father, working on the Clifton Suspension Bridge design at the time. He had been appointed Engineer to the Trustees very shortly before the Irwell failure, in March, 1831. His father, Marc, probably partly understood the problems created by side winds disturbing the decks of suspension bridges. There is evidence of this in his designs for the - two Île de Bourbon bridges but it is likely that his understanding was limited if Brunel’s design for the Clifton Suspension Bridge is an example of what Marc understood. The deck lacked rigidity.[4]

But Brunel was not alone. Most, if not all, of the early suspension bridges built in Britain lacked adequate rigidity in the suspended deck. Menai exemplified this design weakness shortly after it was built. The bridge across the strait between the Welsh mainland and Anglesey was completed in January, 1826. For the time it was of monumental proportions. The distance between the suspension points at the tops of the towers was 579 feet 10½ inches. There were 16 chains, each link consisted of five laminated wrought iron bars ten feet long, 2¾ inches wide and one inch thick. The overall length of the chains was 1,600 feet. There were four catenaries, one under each other, on each side of a central footpath which was four feet wide and four further like catenaries on each side of the roadway which was 28 feet wide overall including the footpath. The chain bars were united by coupling links consisting of six laminated plates, 16 inches long, eight inches wide and one inch thick. The whole chain structure was secured by pins. The height of the suspension towers was 52 feet, the deflection of the chains, that is the distance from the top of the towers to the lowest point of the catenaries was 43 feet. The roadway was suspended 102 feet above the spring high water mark from the coupling links of the catenary chains by one inch square wrought iron bars five feet apart. The 16 chains were anchored in the rock on each side of the strait.[5]

The weakness in the design was a lack of rigidity in the bridge deck. Although some stability problems due to wind loadings emerged while the bridge was being built, the inherent structural defects became extremely worrying by 1836 when undulations in the deck of nearly 16 feet occurred. These were apparently limited to movements in the vertical plane, no torsional movements were reported as occurred with the Tacoma Narrows Bridge in 1940. By 1836

Telford was dead so it fell to W. A. Provis, who had been the Resident Engineer, when the bridge was built, to put forward modifications to resolve the problem. He recommended that the deck should be substantially strengthened. Nothing was done about it until after a storm in January, 1839 which caused serious damage to both the deck and the suspension rods. Following this, Provis developed a much stiffer design. Work was put in hand and it was completed in 1840.[6] Despite the problems, no further major failures took place at Menai but, following the difficulties there and similar problems with suspension bridges elsewhere, they went largely out of fashion in Britain, although they remained in vogue in North America and continental Europe, to be replaced by alternative types of construction. The Britannia Bridge which Robert Stephenson designed to carry the railway across the Menai Strait was of a wrought iron tubular construction, as was that at Conway.[7] These two bridges were built between 1845 and 1850. When Brunel's suspension bridge across the Thames at Hungerford was removed in 1861, it was replaced by a rail-cum-footbridge of a trussed girder design. It was not until the second half of the twentieth century that major suspension bridges would be built in Britain again, in particular those across the Severn, the Forth and the Humber.

While students of civil engineering are limited to a written description of the failure of the Irwell Bridge, graphical though it may have been, those interested in the collapse of the Tacoma Narrows Bridge in Washington State, U.S.A. on the 7th November, 1940 have not only a fully detailed technical description of the bridge as built but also a report prepared by a board of engineers following its failure to study and so, hopefully, to understand what happened.[8] For those interested in the drama of the occasion there is also a film showing the bridge's last minutes culminating in its collapse. If Brunel had such of wealth of material to consider in 1831 with the construction of the Clifton Suspension Bridge looming, he would no doubt have filled many pages of his notebook with his analysis and thoughts on the Irwell Bridge catastrophe. With so much material available, it is not surprising that the Tacoma Bridge failure has been the subject of discussion and analysis for more than sixty years past. It can be said with confidence that, despite the enormous difference in dimensions, it has certain characteristics in common with the Irwell failure over 100 years earlier and the problems experienced with Menai.

The Tacoma Narrows Suspension Bridge opened on the 1st July, 1940. It was built extremely quickly. The total elapsed time from the receipt of the tenders to completion was 21 months.[9] The bridge failed 129 days after it was opened on the 7th November, 1940. A wind was blowing at 42 mph at the time. The structure normally only vibrated in the vertical plane. Such movements had occurred quite frequently during the later stages of the construction of the bridge. As a result, the construction site had become a tourist attraction and the bridge itself had earned the nickname "Galloping Gertie". However, on the day of the failure the deck began to oscillate in a torsional mode with the opposite sides of the deck out of phase. The movement became progressively more violent. The failure of the deck itself began at mid span. The stiffening girders, which ran the length of the bridge, and the lateral bracing buckled. As a result, an increasing number of the suspension rods snapped and parts of the deck fell into the water below. Eventually, virtually the whole length of the deck between the suspension towers ended up in the Narrows. The side spans remained although the cables sagged about thirty feet. The towers were bent backwards by the pull of these side span cables.

Professor F. B. Farquarson of the University of Washington, Seattle was on the centre span of the bridge taking motion pictures of the twisting deck just before the failure occurred. He was thus able to record the whole catastrophe as it took place, thereby giving great assistance to the engineers who were subsequently appointed to investigate and report on the failure of the Tacoma Narrows Suspension Bridge.[10]

When the contract to build the bridge was signed by the highway and bridge engineers, it comprised in addition to the text, some 39 sheets of drawings. The drawings of the sub-structure were signed off by Moran, Proctor and Freeman, Consulting Engineers and by Leon Moisseif, also a consultant engineer, for the superstructure, that is the body of the bridge itself. Some concern was expressed at the time of signing about the flexibility of the suspended structure by other professional engineers associated with the scheme, but the matter was not pressed.

The principal dimensions of the bridge may be summarised as follows. The suspended span was 2,800 feet long and the two side spans were 1100 feet in length each. The length of the centre span made it the third longest suspension bridge in the world when it was built. For a bridge of such dimensions the deck was distinctly narrow, comprising a roadway of 26 feet width with a five foot wide footpath on each side of it. This gave 39 feet between the cables and stiffening girders. The ratio of the suspended span to the width of the deck was thus 71.8:1.[11]. The piers of the Tacoma Bridge were 420 feet in height with plan cross sectional dimensions of 64 feet six inches by 117 feet six inches. Each cable consisted of 332 number 6 cold drawn galvanised wires. The diameter of each cable, under wrapping, when completed was 17⅛ inches, giving a net cross section area of 190 square inches. Stiffening girders, eight feet deep, were fitted under the bridge deck to give that part of the structure rigidity. The span to depth ratio was thus 350:1, a very high figure. There was apparently some concern about this aspect of the design as, originally, stiffening trusses, as opposed to girders, were proposed.[12] Previous experience indicated that the bridge, as designed, with relatively shallow stiffening girders, would oscillate. It was judged that any movement likely to take place was acceptable. A suspension bridge is not a rigid structure such as a conventional masonry arch or box girder structure would be. But by the time Tacoma Narrows Bridge was completed, substantial oscillations, as mentioned earlier, were commonplace.

Movements of up to 50 inches were recorded. Although these were serious, they were not judged to be dangerous: the structure was not at risk. But there was no room for complacency so studies of the vibration problems were put in hand. Models of the bridge were tested in wind tunnels. As a result of this and other studies, modifications were made to the design. Some, but not all of them, had been effected by the time the bridge failed. After the collapse a board of engineers was appointed by the Administrator of the Federal Works Agency to determine the causes of the failure and to make recommendations as to the best practice for future suspension bridges.[13]

The Report, when tabled, was some 140 pages plus appendices, the inclusion of which doubled its length. It was the latter which impressed The Engineer magazine most. There were copies of Leon S. Moisseiff's, the consulting engineer for the bridge superstructure, reports to Lacey V. Murrow, Chief Engineer and Director of Highways about the design of the bridge, letters of representation to the Public Works Administration and Reconstruction Finance Corporation, a Board of Consulting Engineers' paper approving the design of the bridge, observations by various witnesses on its failure, a mathematical discussion by W. D. Rannie of the Guggenheim Aeronautical Laboratory on the vibration of suspension bridges, a summary in some length of experimental investigations by Professor F. B. Farquarson of the University of Washington on models of the bridge and a further section by Dr. Louis G. Dunn, also of the Guggenheim Aeronautical Laboratory, describing experiments on the aerodynamic characteristics of the suspended structure of the bridge.[14] It is noteworthy that this report was prepared in less than ten months, an example of what can be done, given will and application: a sad reflection on like activities in Britain today.

Those called upon to report embraced the full range of disciplines needed to produce a comprehensive and exhaustive document. The most important finding was that the bridge was well designed and was in full accordance with the theories and practices of the day, In short, there were no errors, given the assumptions made and the design protocols followed.[15]

The excessive vertical and torsional oscillations were due to "the extraordinary degree of flexibility of the structure and its relatively small capacity to absorb dynamic forces".[16] Although aerodynamic forces had proved disastrous for lighter and shorter flexible suspension bridges in the past, it had not been realised that structures of the magnitude of Tacoma could be affected in this way, even though it was much more flexible than any other long span suspension bridge.[17] This conclusion is remarkable as it reads as though engineers had hitherto agreed that the sheer size of such structures as Tacoma would protect them, even though failures had occurred on lesser bridges designed using the same principles.

The vertical oscillations, the report concluded, were probably induced by the turbulent characteristics of the wind action. The amplitudes may have been influenced by the aerodynamic characteristics of the suspended structure but there was no convincing evidence that they were caused by aerodynamic instability as such.[18] At higher wind velocities torsional oscillations, once they had been induced, tended to become self reinforcing and to increase in amplitude.[19] This much is evident from the film of the failure of the bridge.

Although vertical oscillations played a major role in the failure, up to that date, such occurrences had caused no structural damage. As has been already mentioned, oscillations were first observed when the suspended deck was being erected and they continued at intervals thereafter. The resulting stresses in the stiffening girders were within acceptable limits, although under certain conditions very high stresses had been induced in the rods which dropped from the suspension cables to the deck, particularly at mid span.

It is reasonably certain that when the collapse took place, the first failure to occur was the slipping of the cable band on the north side of the bridge to which the centre suspension rods were connected. This slipping probably started the torsional oscillations which in their turn caused breaking stresses at various points in the suspended structure. The fall of the greater part of the centre span of the deck was precipitated by the failure of the suspension rods. This was followed by the sagging of the side spans which resulted in the overstressing and bending of the towers and side spans. Farquarson's film showed this progressive collapse of the structure quite clearly. The film's existence facilitated a definitive understanding of the sequence of events. To that extent, the engineers preparing the report were in a strong position.[20]

The report absolved the Public Works Administration and the Reconstruction Finance Corporation, as the body which decided to build the bridge and the organisation which financed its construction respectively, from any responsibility for the failure. They were entitled to rely on the experience and reputation of the consultants employed by the Washington Toll Bridge Authority. There was, therefore, no reason for either organisation to question the adequacy of the design. Further, both agencies had exercised thorough and competent supervision during the construction of the bridge. The quality of the materials used in the structure and the workmanship were both of a high order. The Report cast doubt on the remedial modifications which were in hand or planned when the failure took place. Essentially, what had been proposed was a system of diagonal stay ropes from the tops of the towers to the bridge deck. These would have, if installed, made the structure a hybrid combining the features of both a catenary suspension bridge and those of a cable stayed structure. The Report opined that this was a rational approach to the problems as they were seen to be at the time the remedy was recommended. That was that only vertical oscillation of the bridge deck had to be contained. It was, however, deemed that cable stays would have been unable to compensate for the extreme flexibility of the structure which was the root cause of the failure at mid span and the torsional movements which resulted in the subsequent collapse of the bridge. Some may conclude that the report was a "whitewash"[21].

The Report did, however, recommend that further experiments and analytical studies were desirable to investigate the action of aerodynamic forces on suspension bridges. But there was no suggestion that suspension bridges, as a genre, were put on hold until better understood: "there is no doubt that sufficient knowledge and experience exists to permit the safe design of a suspension bridge of any practicable span".[22] There was an element of contradiction in this finding. If the design features necessary to overcome the failure of the Tacoma Narrows Bridge were not understood, how could such a statement be made about “bridges of any practicable span” with such certainty?

In September, 1996 the Financial Times newspaper, whose address is Number One, Southwark Bridge, in association with the London Borough of Southwark, organised a competition to design a new footbridge across the River Thames to become the Millennium Bridge. Teams, each consisting of an architect, an engineer and an artist, were invited to take part. The competition attracted over 200 entries. It was won by Foster & Partners (Architects), Arup (Engineers) and Sir Anthony Caro (Sculptor).[23]

The site eventually selected for the bridge was from the foot of Peter’s Hill on the north bank to a point adjacent to the Tate Modern Gallery on the south bank of the river. In alignment, the bridge was to be effectively an extension of Peter Hill, a road which runs up to the south front of St. Paul’s Cathedral. So sited the bridge was within the zone of influence of St. Paul’s height restrictions. This placed constraints on the design of the bridge, in particular its elevation.[24]

The structure proposed was a shallow suspension bridge where the cables were located below the level of the deck to the greatest extent possible to optimise the views of the riverscape for pedestrians crossing the bridge. The two groups of four 120mm (4¾ inches) diameter locked coil cables spanned the river over two piers. The lengths of the three spans were 81m (265 feet 9 inches) for the north, 144m (472 feet 5 inches) for the centre and 108m (354 feet 4 inches) for the south span.[25] The drop height of the cables from their highest point to their lowest at the mid point of the centre span was 2.3m (7 feet 6½ inches).[26] The ratio of span to drop height for the centre span was therefore 62.61 which was around six times shallower than for conventional suspension bridges, the standards for which date from the early decades of the nineteenth century. This was a very radical design departure.

There were other unusual design features. Fabricated steel members, the transverse arms, were pitched at 8m (26 feet 3 inches) intervals along the length of the bridge. They spanned between the two groups of cables and supported the four metre (13 feet 1½ inches) wide deck. The centre span to deck with ratio was thus 36:1, a relatively small figure. The cable groups were anchored in reinforced concrete abutments on each bank of the river. The two river piers, which supported the whole bridge structure, each comprised a “V” bracket fixed to a tapering elliptical reinforced concrete body founded on two six metre (19 feet 8¼ inch) diameter caissons.[27] The design, when realised, was to be a slender structure without the inbuilt rigidity of some alternative design concepts. For this reason, amongst others, it was subject to a series of theoretical analyses. These included not only the characteristics of the bridge itself but also the effect of its construction on the flow of the River Thames. This latter study involved the use and appraisal of a 1:100 scale model of the proposed bridge in a test tank. So, in the development and testing of their design, Arup took into account all the factors which they deemed important or otherwise significant.[28]

Work started in late 1998 with an archæological survey of the soil structure on the sites of the two abutments. Once this study of what were potentially important historical locations was complete, the way was clear for the contractors to start piling in April, 1999. The superstructure of the bridge itself began to be erected in early 2000. The bridge was opened on the 10th June that year.[29]

About 80,000 to 100,000 people crossed the bridge on the first day. Video footage showed that there was a maximum of 2,000 people on the deck at any one time, giving a density of 1.3 to 1.5 people per square metre (1.09 to 1.25 per square yard). The bridge vibrated to an alarming extent. While no suspension bridge is absolutely stable and rigid, the lateral movement which caused the vibration of the Millennium Bridge deck under this loading was deemed excessive. Movements took place largely on the south span at a frequency of 0.8 HZ, the first lateral mode. Movement on the north span was rarer. When it took place, the frequency was just over 1 HZ, the first lateral mode. On the centre span the corresponding frequencies were just under 0.5 HZ and under 1 HZ, the first and second lateral modes respectively. All frequencies could have been dangerous and were embarrassing to those responsible for the design and construction of the bridge. Certain sections of the media, who had already exploited the unhappy circumstances of the Millennium Dome at Greenwich at enormous length, took the opportunity to pour scorn on another Millennium project which had run into difficulty. The bridge was closed while the phenomenon was studied and a solution engineered.[30]

The study had three priorities: 1. To compare the dynamic properties of the structure as built with the analytical predictions of its performance. 2. To quantify the forces that were being exerted on the structure by the pedestrians and 3. To design a retro-fit for the bridge which would reduce the movements to acceptable levels. Unfortunately, although lateral vibration due to pedestrian footfall had been encountered on occasion elsewhere, none of the reports available gave any reliable quantification of the lateral forces due to such pedestrians or any relationship between the force exerted and the movement of the deck surface.[31] So the study was ab initio. The movement was clearly caused by a substantial lateral loading effect which, as already mentioned, had not been anticipated during the design process. The loading was found to be due to the synchronisation of the footfall forces within a crowd of pedestrians. People found it easier to walk in time with the swaying structure even when the movement was very small. Having struck this frequency, the movement of the deck increased in amplitude: the lateral forces exerted by the pedestrians increased in response. There was thus a critical number of individuals which could cause the vibration to increase to unacceptable levels.[32]

Having determined the cause of the problem it was possible to use the findings of the study when designing bridges for the future. So, Arup enhanced their mathematical models and analytical techniques to incorporate these new insights into the characteristics of suspension bridges. But the problem the engineers faced was that the Millennium Bridge already existed.

They were constrained in the solutions they could apply as there was no way in which the bridge could be substantially redesigned and re-engineered. The solution, which some may describe as “a fix” lay in damping the lateral movements of the bridge deck. It was vital to all the parties involved, the architect, the engineers and the sculptor that this was done in a fully effective way so much mathematical modelling was carried out before a satisfactory solution was reached. A system of fluid visco-elastic dampers and tuned mass dampers sited in a bracing pattern was introduced into the bridge structure Arup also thought it prudent to dampen any vertical oscillations that might occur in the deck as well as the lateral ones, even though vertical movement had not emerged as a problem. These modifications to the bridge have proved successful and it is now in daily use.

One of the interesting findings of the Millennium Bridge study is that the synchronous lateral excitation the structure suffered was not due to any technical innovations introduced into the design. This could also have been said about the failure of the bridge across the Irwell at Salford in 1830: a time when structural engineering was much less sophisticated than it is today or, for that matter it could have been said of the Tacoma Narrows Bridge in 1940.

The Millennium Bridge does, it can be argued, accord with Sibly and Walker’s hypothesis. Suspension bridge design was pushed to the limits to meet the constraints imposed on its architecture by the proximity to St. Paul’s Cathedral, in that the drop height of the cables to the length of the centre span as a ratio was very low by conventional standards and the way in which the deck was supported by the transverse arms was novel. These extreme design features revealed the lateral vibration phenomenon which then had to be addressed. To say that the structure which finally emerged is “unnatural” would be an overstatement but it is perhaps not too “passé” to argue that a structure, or for that matter any other engineering artefact, should look right, and if it does, it probably is right. Visually, the Millennium Bridge looks what it is, “stretched technology”, although, over time, it may become nearer to the accepted norm. The other issue is the extent to which a baroque building, such as St. Paul’s is, should influence the design of adjacent or nearby structures. While a clear and uninterrupted view of the Cathedral is of extreme importance, there could have been some relaxation of the planning criteria to permit a somewhat higher, high point in the Millennium Bridge without interfering to any significant degree into the eye-ability of the church from Bankside on the south bank of the river.

The four examples of suspension bridge selected for discussion as disaster situations span a period of 170 years. In no case was life lost. Two were patently engineering design failures resulting in structural failure, Irwell and Tacoma, one was a disaster waiting to happen until “fixed”, Menai, and the fourth was a public relations catastrophe, Millennium. For the failure of the Irwell bridge, a small structure, one is dependent on an account in the Manchester Guardian. It was obviously of interest to Brunel, otherwise he would not have cut it out and pasted into his diary; but he saw fit to make no comment: perhaps he had nothing to say as he had no personal experience of suspension bridge design or construction at the time. That said, the account is explicit enough to conclude that the soldiers marching feet hit the natural frequency of the bridge deck and superstructure and the failure occurred because of the excessive movement of the deck in the vertical plane which led to the failure of one of the supporting pillars. There had been problems at Menai by this date but the movement in the deck was undulating due to wind loading, a very different phenomenon A solution to this, the deck was substantially stiffened, was engineered by W. A. Provis, Telford's Resident Engineer, who had built the bridge in the first place. .After the failure of the Tacoma bridge had occurred, a major inquiry was initiated which called upon the experience and knowledge of a number of mostly disinterested parties, including Leon S. Moisseiff, various Public Bodies, Consulting Engineers and academics. It was not only well studied by the organisations and people just mentioned, the failure attracted world wide interest and there were many contributions to the discussion, not only from the United States but also overseas.[33] So, while the failure at Irwell is informed surmise, those at Menai and Tacoma Narrows are well understood. The vibrations at Irwell were due to footfall, the undulations at Menai and Tacoma Narrows were caused by side winds to which at Tacoma Narrows a torsional movement was added once the structure started to fail. It can thus be argued that Irwell, Menai and Tacoma Narrows should be treated as three distinct engineering phenomena.

The problems associated with the Millennium Bridge were different again. While structural failure was never in prospect, the vibration was of a disturbing nature. The movement induced by the footfall was a virtually unknown occurrence. It was lateral not vertical. The analysis of the problem carried out by Arup was exhaustive and a definite conclusion as to the cause of the problem was identified and a remedy was applied.

The four cases taken together, Irwell 1831, Menai 1836 and 1839, Tacoma Narrows 1940 and Millennium 2000 could be seen as being similar: all involved vibration of the suspended deck but each had a different cause. It must be accepted that suspension bridges are not, and cannot be, rigid structures and that their design must therefore take careful account of this if vibration problems are to be minimised, they cannot be designed out completely, such that they present no risk to the integrity of the structure. Each successive problem, when diagnosed, was shown to have a determining factor which was unrecognised or unknown when the design was initiated. This study suggests that more detailed studies are needed before making generalisations about the causes of engineering disasters.

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[1] The Prediction of Structural Failure, Ph.D Thesis P. G. Sibly, University of London 1977; Structural Accidents and their Causes, P. G. Sibly and A. C. Walker. Proceedings of the Institution of Civil Engineers, Part 1, 1977, 62, May 191 – 208.

[2] Design Paradigms, Case Histories of Error and Judgement in Engineering. Henry Petroski, Cambridge 1994, 169. "Petroski"

[3] Manchester Guardian 16th April, 1831.

[4] The initial design of the deck of the Clifton Suspension Bridge as detailed in the weeks following I. K. Brunel's appointment as Engineer to the Trustees in March, 1831 lacked stiffening and thus relative rigidity. By 1850 the design was somewhat changed. This suggests that Brunel had a better understanding of what was required. He probably took account of the difficulties which had been experienced on the Menai Suspension Bridge by that date, but even the 1850 iteration probably fell short of what was needed. It was left to John Hawkshaw and William Barlow to provide an adequate solution when the bridge was completed in the early 1860s. The Works of Isambard Kingdom Brunel, An Engineering Appreciation 1976, A. Pugesley (Ed.) 61, Fig. 11.

[5] William Alexander Provis, An Historical Account of the Suspension Bridge erected over the Menai Strait at Bangor in North Wales with a brief Account of the Conway Bridge, 1828, 24, 25, 14, 47: Charles Stewart Drewry, A Memoir on Suspension Bridges, 1832, 58 (73), 52 (68), 54 d(71), 55, 56 (73), Plate IV, Fig. 102.

[6] Michael Chrimes, SB1 Suspension and Cable Stay Bridges, SB2.3 Telford's suspension bridges, draft studies of which the author, through the courtesy and kindness of Michael Chrimes, Librarian of the Institution of Civil Engineers, has been given a sight.

[7] Robert Stephenson, the Eminent Engineer (ed.) Michael R. Bailey 318-327.

[8] The Engineer, 19th August, 1941, 128-130; 5th September, 1941, 144-146; 12th September, 1941, 162-164; 19th September, 1941, 180-182; 26th September 1941, 202-204. These articles contain a detailed description of the bridge and the circumstances surrounding its failure. For those readers interested in a deeper understanding of the Tacoma failure, it is suggested that they study the material in the issues of The Engineer mentioned.
[9] The Engineer 129.
[10] Failures in Civil Engineering Structural Foundation and Geo-environmental Case Studies – American Society of Civil Engineers 1995 – Tacoma Bridge “A.S.C.E”.40.
[11] The ratio of suspended span to width of the Menai Bridge was 20.7:1.
[12] A.S.C.E. 40; Structural Accidents and Their Causes, P. G. Sibly and A. C. Walker, Proceedings of The Institution of Civil Engineers, Part I, 1977, 62.
[13] A.S.C.E. 41.
[14] The Engineer 128.
[15] This meant, however, that although the design was adequate for a steady wind loading of 30 pounds/ square inch, no allowance had been made for the possible dynamic effects of such a loading.
[16] The Engineer 128.
[17] The Engilneer 128.
[18] By the 1940s wind tunnel testing was becoming an increasingly powerful tool in aircraft development but it had not reached the level of sophistication it was to achieve in the years which followed, particularly with the arrival of supersonic flight. So, although models of the bridge had been tested aerodynamically, there was a substantial element of subjectivity in this assessment.
[19] The Engineer 128.
[20] The Engineer 128.
[21] The Engineer 128.
[22] The Engineer 128.
[23] The London Millennium Foot Bridge, P. Dallard et al, The Structural Engineer Vol. 79, no. 22, 20th November, 2001. “Dallard” 17.
[24] Dallard 17.
[25] Although the bridge was designed and constructed using metric measurements, these have been converted to the Imperial system to facilitate comparison with the earlier bridges cited in this paper.
[26] Dallard 17.
[27] Dallard 17.
[28] Dallard 18.
[29] Dallard 18.
[30] Dallard 20,21.
[31] Similar phenomena had been encountered on the link bridge, a steel truss on unbraced vertical columns built in 1978, span 45 metres (147 feet 7½ inches) from the National Exhibition Centre to Birmingham International Railway Station, the Grove Suspension Bridge at Chester originally built in 1923, span 100 metres (328 feet 1 inch) and the Auckland Harbour Road Bridge, a steel box girder construction completed in 1995, the span of the north section was 190 metres (748 feet 0 inches).
[32] Dallard 21.
[33] Since the failure of the Tacoma bridge in November, 1940, the films must have been seen by tens of thousands of engineering students at Universities and Engineering Schools world wide.