FAILURES OF STEEL PARTS IN SERVICE

By

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Presumably, the matter of failure of metal parts in service would arise very infrequently, in the thousands of years mankind knew how to make use of metals, before the introduction of steam power. There is much evidence, however, that failures began to occur with distressing frequency from the time steam was applied to marine propulsion, and to railway engines early in the nineteenth century. Not that the steam of itself had anything to do with the failures, but its use as a prime mover implies normal working stresses higher than those employed when man, animal, water, and wind power were the sole means of making machinery go round. Not only were higher stresses used after the introduction of the steam engine, but the intermittent nature of the earlier prime movers would give place to long continued applications of the reversed stresses imposed by a steam drive.

The introduction of the steam engine also brought in its train many developments apart from Railway, and Marine engines. It was the direct cause of the industrial revolution from the beginning of the nineteenth century, when the demand for Cast-iron, and Wrought-iron began to grow at an ever increasing rate. Machine-tools were required to build the engines. The machine-tools, and the engines were built of Cast-iron and Wrought-iron. Engines and Mills were required for the Blast-furances, Foundries, Rolling Mills, and Steam-hammers. Cast-iron, and Wrought-iron bridges were required for the Railways, and so it went on, in ever widening circles, into the steel age. Thus we find, by 1850, what may be broadly taken as the first classic investigation into the failure of metal parts made in the previous half century. Sir William Fairbairn at that time began to investigate the strength of Wrought-iron bridges under repeated stress, on behalf of the British Government. His tests were carried out on full-scale bridge members, and for three-quarters of a century they remained the only full-scale tests. He submitted the Wrought-iron members to repeated bending, to simulate the passage of Railway trains, and from his results the common factor of safety of 5 to 1 arose. This factor of safety was based upon the tensile strength of the materials he was testing. Little did he know at that time, that scientific investigators, many years later, would discover a definite endurance limit which relates only to the tensile strength.

Some twenty years later, a German Railway-man began to test small samples of material in testing machines he devised himself, to simulate the working stresses the material would undergo in Railway practice. Wohler's long series of experiments was the forerunner of all our present-day "fatigue," or endurance testing.

It is not my intention to set out an historical record of the progress of our knowledge of the endurance of metal under repeated stress. Instead, I wish to use the two foregoing cases as dating the beginning of our knowledge, and to show you how, for many years afterwards, succeeding generations of astute engineers have completely failed to take advantage of existing information regarding the most imporatnt property their materials possess. In making the statement that the endurance limit is the most important property I am, of course, referring to constructional steels which are normally subjected to repetitions or reversals of working stress in use. Such steels comprise the great bulk of all steel made.

This failure to take advantage of existing knowledge has had surprising results, and I compliment the promoters of this Symposium upon their foresight in bringing the subject to the notice of Indian engineers. It is to be hoped they will, thereby, avoide the pitfalls other engineers have blundered into.

Possibly there was some excuse for the engineer of a generation ago treating the subject of "fatigue" with some misgiving, and unbelief. Until the twentieth century had got well started, it had not been proved beyond doubt that steel did not get tired in the course of time, and just simply break because it was exhausted. Such an explanation was frequently given, but it was hardly to be expected that the engineer would accept it when he had in front of him a steel part which had been going round, day in, day out, for possibly fifty years. Confronted with another steel part which had broken mysteriously within one year, he would naturally blame the quality of the steel, and nobody would be any nearer the solution of the trouble We now know that, in the great majority of cases, the fault rested with the engineer who had, unknowingly, included a potent stress-raiser in his design.

(*i*). Many of these stress-raisers causing failure were of a very subtle nature. For instance, my own grandfather built textile-mill engines, and he had an inkling of damping capacity eighty years ago. He was a strong advocate of the very long crankshaft journal as a means of preventing crankshaft failures.

In 1920-25 a well-known Marine Diesel-engine builder had several cases of broken crankshafts. On investigation it was shown that, in order to keep the overall length of his engine within reasonable limits, he had reduced his journal lengths to one diameter. The crankshafts were built-up, and fracture occurred at the stress raiser formed at the junction of the shrunk crank-web, and the journal. In this case, this weak stress-raiser was enhanced by the lack of damping as a result of the short length of the journal. He cured his trouble by shifting the torsional vibration nodes to a safe location by means of a fly-wheel.

(*ii*). Another instance arose in the course of an enquiry by a Marine Classification Society into the serious cracking of ships' hull plates within two or three years. It was explained that a certain type of ship was designed in 1895, and many ships had been built to that design in the next fifteen years. They had been outstandingly trouble-free and successful. Ships built to the same design between 1920 and 1930 had given a great amount of trouble owing to cracked hull plates. The steel-makers were blamed for poor quality steel made after the first War. When the steel-makers enquired whether any changes had been made in the design they were told "no". But, subsequent detailed enquiry showed that "minor improvements", had in fact been made since 1920 and that the cracked plates were all in the region of the "minor improvements". It appears that the ship-constructors had considered the hull too flexible in certain places, and had introduced stiffeners. These stiffeners had localised and concentrated the stresses which had previously been dispersed through flexibility. That is, whilst the mean stresses in the hull remained precisely as designed in 1895, yet owing to the effect of the stiffeners, the range of stress had been destructively increased.

(*iii*). An old type of Marine reciprocating engine, working at very low stresses, has crossheads with projecting horns. In the case in question, the ship was 30 years old, and had given no engine trouble. At her last survey, the Inspector found these crosshead horns worn oval. He ordered them to be taken out, and built back to size by welding. To make a job of it, the welding firm turned the horns down to a diameter. Whilst doing the turning the machinist was instructed to leave a rough cut surface to which the welding would adhere more readily. Six months afterwards, the first horn broke off, and a new crosshead was made. The broken crosshead was cut up and investigated. This revealed the stress-raising rough machine cuts under the welding. A complete new set of crossheads was then ordered. In the time before the ship returned to her home port, two more welded crossheads broke. The fracture faces indicated that the normal working stresses were exceptionally low.

(*iv*). A very famous Atlantic Liner's tail-shaft showed defects at the top of the cone. The shaft was 24 inches diameter. Careful enquiry showed that after the previous voyage the rubber sealing-ring was found to be defective. Obviously, sea water had got to the shaft and had caused corrosion pitting. The shaft was condemned, and later broken open. In two return voyages at most, corrosion had initiated creeping-cracks extending 3 or 4 inches into the metal. This case was not a true case of "corrosion-fatigue". "Corrosion fatigue" was undoubtedly the initiating circumstance, but it was stopped when the sealing-ring was put right. Thereafter, the ordinary creeping-cracks propagated from the corrosion pits.

(*v*). Failures of Ships' tail-shafts by fatigue cracking from the square cornered Keyway were a common occurrence at one period. Keyways are now machined with generous fillets, and one rarely hears of a ship casting her propeller these days.

(*vi*). During the last War a tiny accident occurred, in an important Indian power-house, which might have had very serious repercussions. The generator shaft of a 25,000 K.W. set has a non-magnetic alloy end-bell retaining the windings. The junction between the bell, and the shaft body end, is made via an inch long under-projecting lip on the bell, and a corresponding over-projecting lip on the shaft body end. After two or three years working, the generator suddenly began to show distinct signs of running out of balance. The set was at once shut down, and examination showed that a small piece of the shaft lip, weighing no more than four onces, had parted company with the rest of the shaft. The fracture face of this tiny piece showed the typical creeping-crack markings. It was presumed that the non-magnetic alloy end-bell had very different elastic characteristics from the 0.35% Carbon steel shaft, and that with fluctuating speeds this end-bell would be imposing fluctuating stresses on the shaft lip. This explanation was tentatively cabled to the Turbine builders, who confirmed its correctness. A similar generator-set in South Africa had precisely the same experience a few months before. I believe this fault in design was temporarily corrected by machining the remainder of the lip off the shaft body, and so preventing the end-bell bearing on the shaft lip.

(*vii*). A small ship in New York harbour collided with the stern of the old Cunard White Star "Olympic". The rudder was forced round to the stops on the cast-steel stern-frame. Parts of the rudder had to be replaced, but no apparent damage was done to the stern-frame. Fifteen months after the accident, the stern-frame broke in two. The fracture faces showed creeping-crack marking. Litigation and renewal cost £.100,000, and the Court upheld the plaintiffs contention that a minute crack had been caused at the time of the collision, which had developed into a creeping-crack under normal working.

(*viii*). Diesel-engine fuel pump bodies were forged in a solid block from 30 ton Mild-steel. These began to fail in eighteen months time. It was assumed that Mild-steel was not strong enough, so replacements were made in 40 ton Nickel-steel; these failed in twelve months' time. The engine builder then accused the forgemaster of supplying bad quality steel, and he ordered 50 ton Nickel Chrome Molybdenum pump bodies from another firm. These failed in a shorter time. The pump body forgings are about 18 inches cube, and they are machined by drilling 2½" holes from sides at right angles, which interesect inside. The failure was noticed when oil seeped out through a fine hair crack which apparently had no connection with anything. This was a baffling case, and it was a long time before the thought occurred to break the bodies open under a steam hammer. Immediately, the story was revealed. Where the drilled holes interesected inside the body, a very sharp fin of metal was formed. This constituted a potent stress-raiser, and it cracked under the fluctuating pump pressure. The fractures all showed beautifully clear creeping-crack marks. From then on, Mild-steel was reverted to successfully, but the method of machining was changed.

(*ix*). Shortly after the first War, double-reduction geared turbines became the fashion for the rebuilt British Merchant Marine. The gear pinions were made in oil hardened and tempered Nickel-steel. The early geared turbine ships gave no trouble with their gearing. But, as the number put into commission grew, broken pinions became common place. In one Company alone, five sister ships were in dock at one time awaiting pinion replacements. Their spare pinions were used to keep the sixth sister ship at sea. The failures were due to small sections of the helical teeth breaking out. Bad quality steel was adduced as the cause by the gear-cutters. The battle between them, and the steel-maker lasted for three or four years. Thirty years ago, we were not very sure of our ground in connection with stress-raisers, but the broken teeth all showed creeping-crack-markings. It transpired that the earlier successful gear-pinions were machined in three cuts; one roughing, one fine, and one polishing cut. As the pressure of work for the gearcutting machines grew, the number of cuts was reduced to two and then one only. This left deep scratch marks at the roots of the teeth which were, in effect, potent stress-raisers. It is of interest to note that the engineers said the working stress on these teeth was so low that theoretically a wooden pinion should have stood up. Yet here were dozens of 40 tons Nickel pinions breaking.

(*x*). An old Metropolitan Water Board pump crankshaft had been steadily pumping water for 45 years. On overhauling, the crank journal showed hair cracks on the surface running, some longtitudinally, and some at an angle. The crank was taken out and repaired by shrinking-in a new journal. The old journal was sectioned, and showed axial piping as the origin of the creeping cracks.

(*xi*). An L.N.E.R. main-line express loco of the most powerful type had been into the Shops for her first overhaul. She was taken out on a trial run before putting her back into service. On her return journey she put into a siding to allow a passenger train through. On being signalled to continue her journey, the engineer was unable to start her moving. He found a wheel-pin had broken off, and all the connected rods trailing on the ground. This pin was found to be piped, with creeping cracks radiating from the central defects.

(*xii*). Dozens of Marine Diesel-engine big-end bolts were breaking about twenty-five years ago. Their heads apparently, simply dropped off. We were then beginning to get wise to the stress-raiser. Examination revealed the same thing in every case. So that the bolt head should fit down snugly, the drawing showed a square corner between the shank and the head. The machinists had made an extra-special good job by machining this corner almost mathematically square. Replace bolts were made, and the junction of shank and head was actually under-cut. Since then, the design of these bolts is an object lesson on how to smooth out stress flow lines.

In themselves, these twelve cases, picked at random, have their own value as illustrations of what may be expected if stress-raisers are not avoided like the plague. But, I have introduced them for other reasons. Firstly, it will be noted there is only one case of failure through working stresses exceeding the endurance limit of the broken part. This single case is No. (*vi*) above, but the actual stresses could hardly be anticipated by the designer, and were of a most unusual nature. Out of hundreds of cases examined, I cannot recall another case of failure of sound steel in the absence of a stress-raiser, except in the case of shattering accident. Thus, this exception proves the rule that the great bulk of steel failures are due to the presence of avoidable stress-raisers. This rule holds good even in the two cases of metallurgical stress-raisers I have quoted. I shall leave it to others to tell you what the stress multiplication can amount to at the bottom of different forms of stress-raisers. I can, however, tell you that the extreme case definitely does not proceed to infinity. I myself propounded the theory in 1935 that even a fatigue cracked test piece has its own endurance limit. This implies that the bottom of a fatigue crack is not infinitely sharp, but has a radius of some dimension, whose material might heal under repeated low stress. This thought led the American investigators to their "damage and repair" series of experiments. These experiments in turn have led to the commercial practice of what may be called stress-normalising of high speed engines, etc. From a purely scientific point of view, the theory was a distinct contribution to our knowledge of the mechanism of "fatigue".

My second purpose in introducing these twelve actual cases, was to illustrate my point that little commercial use had been made of existing information regarding the effect of repeated stress upon machine parts. Twenty years ago whole sections of the engineering community in the West were falling into the same errors their fathers and grandfathers had made, and corrected. Perusal of some of the Papers, written by the early Gas-engine builders of seventy years ago, will show that they had their troubles, and they devised means of circumventing them. These means were rediscovered within living memory following investigation of the cases I have mentioned above. Certainly, we have much more precise scientific knowledge available to-day to help us. Even so, this knowledge still requires translating into the practical terms of everyday engineering if the young Indian Industry is to take advantage of it.

If I am permitted, I would offer the following suggestions. The actual endurance limit of highly finished test pieces from ferrous metals is not a matter of very great significance. The engineer can take it with assurance that it is about 45% of the tensile strength. There is in existence a wealth of experimental data upon plain polished pieces, and except for educational purposes there is really no need to spend time in duplicating these results. On the other hand, there is a very great need for the testing of models under repeated stress. These models may be small sized test pieces containing stress-raisers of known dimensions, or they may be small-scale, or full-scale models, subjected to the same stresses they will meet in service. Such tests have a direct bearing on design problems, and cannot fail to be of immediate application in design-offices. They would also serve to warn engineers in general of the disasters awaiting them if they do not pay due regard to the effects of stress concentrations, and abrupt stress flow lines. The National Metallurgical Laboratory would do a great service to Indian engineering if they emulated the German investigators, of the decade 1925/1935, in this connection.

I trust this Symposium will be the means of demonstrating the importance of its subject to Indian engineers, and that the National Metallurgical Laboratory will continue the praiseworthy propaganda it has started.