

Railways and materials: synergetic progress

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Railways were originally uniquely identified with the material of their initial construction and now are technically identified by the characteristic contact of 'steel wheel on steel rail'. Over 160 years ago failures of iron railway axles led to research into what we now know as metal fatigue. Accidents throughout the ages have acted as catalysts for research and improvements: this lecture will identify some key incidents. The change from iron to steel, following Bessemer's discovery of a method of bulk production and its implementation in Sheffield, resulted in fewer materials failures and enabled greater loads to be carried at greater speeds. Today's railways rely on a wide variety of materials from all the major classes of materials. The requirements of cost, weight, reliability, crashworthiness, maintainability and inspection are often in conflict as the service loadings imposed by the modern railway on materials have become more severe. It is not therefore surprising that despite our advances in knowledge and capabilities, costly failures still occasionally occur. Nevertheless, railways have benefited from, and contributed to, advances in material engineering way beyond the initial emphasis on iron.

As I was preparing for this lecture I chanced upon some railway journals of the late 1950s. As is often the case, the old advertisements were as revealing as the articles. The phrase shown in Fig. 1 caught my eye, '*Railways need steel – steel needs railways*', emphasising the relationship between heavy industry and the ability of the railways to transport goods such as steel and coal. Many of the advertisements were for railway products from companies in the

Sheffield area, ranging from locomotives made by the Yorkshire Engine Company, diesel railcars from Cravens and parts like axles and wheels from Baker and Bessemer, and Steel, Peach & Tozer (Fig. 2).

Over the past 50 years this Sheffield link with the railways has been considerably weakened, but still survives at least in part. The use of steel for the railways came many years after their origin and depended on the Bessemer converter first introduced to make steel in bulk in Sheffield in 1856. The early railway engines were *iron horses*, the railway itself *le chemins de fer* and *die eisenbahn* telling us of the original material which made the railway revolution possible and something of the rapid international spread of the railways. Many of the improvements of iron and later steel making came as a direct result of their use on the railway. In later years the railway has adopted materials as and when they have become available, as indeed it has made opportunistic use of many advances in technology which have themselves been made possible by drivers outside the railway industry. This paper, originally delivered in the form of the Hatfield Lecture at the University of Sheffield late in 2007, attempts to describe, in a qualitative manner, some of the relationships between the material progress of the railway and the progress of materials generally.

It is worth recalling the twin advantages of rail transport: that of speed and the ability to haul large loads with modest tractive effort. When the railways were introduced speeds in the order of 30 to 50 km h⁻¹ were an astounding increase on the maximum speeds possible by foot or horse traction. This great speed unified countries (indeed, many would claim that the day's return journey made possible by the railway defined the size of many European states), enabled news to be disseminated, allowed food and mail to be distributed, necessitated the introduction of a standard time and initiated the institution of fish and chips.

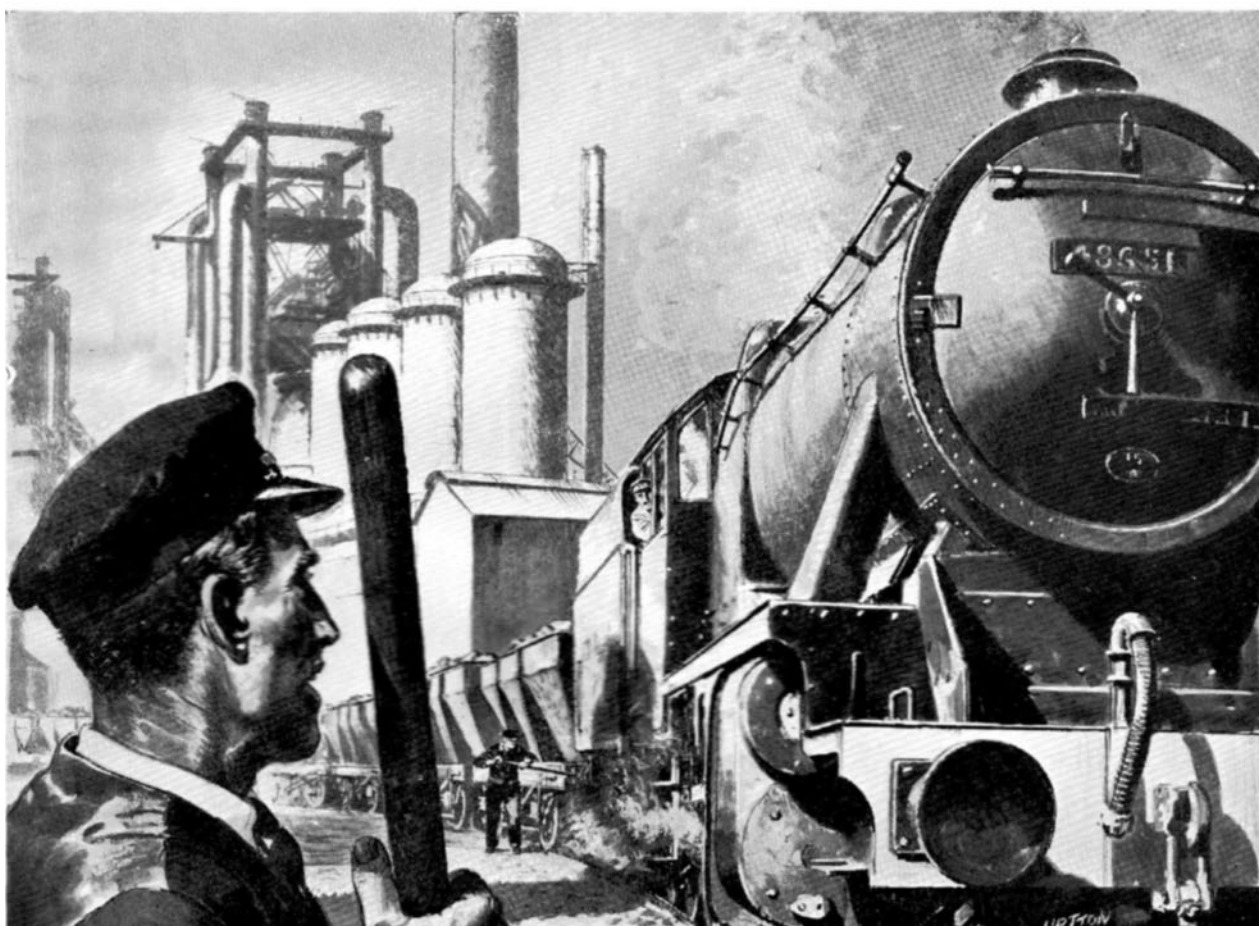
The low rolling resistance of a hard iron wheel on a stiff iron rail was the enabler of the haulage of large loads, previously only carried on canals at very low speeds. This advantage came with a price, that of the relatively low coefficient of friction between wheel and rail interface, which limits acceleration and braking capabilities, and, even today when lowered by the presence of leaves on the line, hampers operations. The iron way generally rested on a foundation of small stones, the ballast, so-called because the original small stones came from the ballast of ships at the seaward end of the Stockton and Darlington Railway. In fact the maintenance of the level and condition of the ballast is a major component of the maintenance costs of the railway. It deteriorates on the passage of a train by the attrition of the highly stressed contact points of the stones. As speeds and loads have risen to an extent undreamt of by the railway pioneers, increasing use is being made of foundations of concrete slab which have a higher installation but lower lifetime cost.

Understanding fracture and fatigue

The early railways required iron components to be precision manufactured to tight tolerances and to be, as far as possible, defect free. The stresses to which components were subjected were largely unknown, either by calculation or experiment, resulting in a design process which was largely empirical and based on experience. Broadly speaking, parts were proportioned by erring on the side of caution, weight was unimportant and conservatism ruled. This approach has, to a great extent, survived until quite recently, but the demands made by high-speed trains, the need to reduce track maintenance costs and, even more recently, the need to reduce energy consumption, have led to the need for the adoption of much more sophisticated approaches which will be described later.

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Railways need steel—steel needs railways

ALL the way along the line (so to speak!) British Railways work in full collaboration with the Iron and Steel industry. Special trucks have been designed for the delivery of raw materials to the works; others for the delivery of finished iron and steel from the works. In fact, British Railways are always ready to consider designing special wagons for carrying all kinds of material in bulk.

From cars to caraway seeds

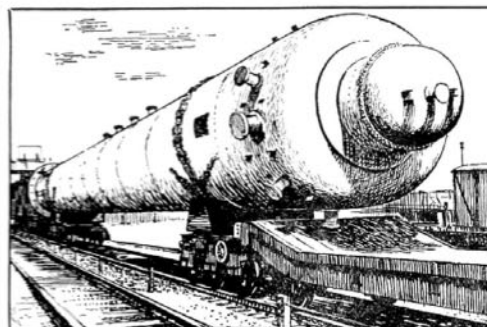
There is nothing British Railways cannot transport and everything is dealt with as a separate problem. For instance, bicycles, chemicals, furniture have special facilities; perishable goods have highly insulated containers—the most efficient of their kind in Britain.

Near-express speeds at night

Most of the freight work is done at night



Here we show steel plate being unloaded by magnetised grab.



A special wagon for this exceptional load—a depropaniser 128' long.

when the lines are quieter. And now more and more freight trains are being fitted with vacuum brakes. Not only does this make for greater safety it also means trains can run at near-express speeds, and so increase line capacity and improve punctuality.

Whatever your product, whatever your problem, you can rest assured that British Railways will give you excellent advice and

first class service. Just get in touch with your local Station Master or Goods Agent and your transport difficulties are over.

GREEN ARROW SERVICE Operating for both overseas and certain home freights in full wagon loads, this service enables you to register consignments all the way to the destination station or port for only 2/6d. Ask your local Station Master or Goods Agent for full details.

BRITISH RAILWAYS

1 Synergies between steel and the railways illustrated in a technical press advert of the late 1950s

February 7, 1958

THE RAILWAY GAZETTE

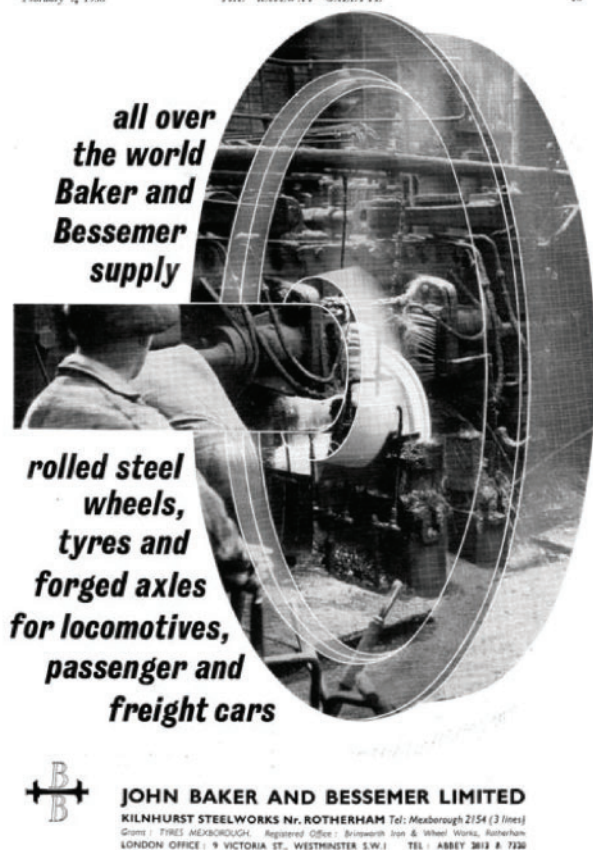
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December 12, 1958

THE RAILWAY GAZETTE

19

**all over
the world
Baker and
Bessemer
supply**



**rolled steel
wheels,
tyres and
forged axles
for locomotives,
passenger and
freight cars**

JOHN BAKER AND BESSEMER LIMITED
KILNHURST STEELWORKS Nr. ROTHERHAM Tel: Mexborough 2154 (3 lines)
Quart: 71903 MELBROOUGH Registered Office: Rotherham Road & Wharfedale, Rotherham
LONDON OFFICE: 9 VICTORIA ST., WESTMINSTER S.W.1 TEL: ABBEY 3013 & 7230

STEEL, PEECH & TOZER
A Branch of The United Steel Companies Limited THE ICKLES, ROTHERHAM, YORKSHIRE



Steel, Peech & Tozer Railway Materials
—wherever there are Railways

The Steel, Peech & Tozer plant produces tyres, disc wheel centres, solid wheels, straight and crank axles and laminated springs for railway locomotives, carriages and wagons; finished wheel and axle sets are produced at the adjoining plant of Owen & Dyson Ltd. These products are known all over the world.



2 Railway products from the Sheffield region

The frequency of broken rails on the early railways was reduced by slow improvements of the cast and later wrought iron (and much later steel) from which they were made and by 'beefing up' the critical dimensions. This approach did not work for the failure of axles which gave rise to the recognition of a new type of failure mechanism; that of fatigue.

Many investigations were prompted by the accident on the Paris to Versailles Railway in 1842 (Fig. 3).¹ This accident, caused by the derailment of an engine due to a broken axle, led to flimsy wooded carriages, with the helpless passenger locked inside, piling up on the wreckage of the engine and being set on fire by the spilt burning coals. Upwards of 70 persons were killed*, the first time a railway accident had caused major loss of life, and the news was a sensation throughout Europe and America.

*This figure is very approximate and is often quoted as being much higher. Forensic science in 1842 had not been extended to 'finger-tip' searches lasting several days. The known dead included Admiral Jules Dumont d'Urville, naval explorer and 'discoverer' in 1820 of the statue of Venus de Milo which remains in the Louvre to this day.

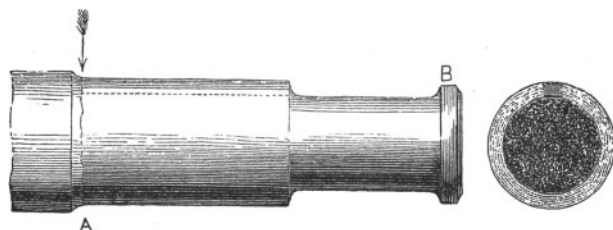
It was recognised that axles suffer a great many repeated stress cycles as they rotate and in the early days many fanciful theories were proposed to explain why failures occurred after periods of successful service. Popular amongst these were changes in the internal structure of the metal, so-called 'crystallisation' (for an explanation of why this erroneous idea took root, the reader is referred to the brief Appendix on the metallurgy of iron and steel). The more astute and careful observers of fractures, recognised the deleterious effect of stress concentrating features (Fig. 4), but it was to be over a century

later, in the early 1950s, that the link between fatigue and the initiation and propagation of cracks was finally established. In the 1860s, the pioneering experiments of the German engineer Wöhler² led to the identification of the fatigue limit for steels: that is an experimentally determined stress range below which, no matter how many repetitions may occur, no failure will result.

Very long service lives mean that the obvious principal design requirement against fatigue failure is that stress ranges should be below the fatigue limit.



3 The accident on the Paris Versailles Railway in 1842



4 A typical axle failure of the 1840s. The shoulder of the axle caused a stress concentration at which the fatigue crack grew

This apparently simple requirement is not as easy to apply as may be imagined, partly because the loading spectrum can contain many larger load excursions superimposed on a base line of constant amplitude loading, and partly because of competing deterioration mechanisms such as wear and corrosion which can erode the original design margin. Despite its long use, there is growing evidence that for lives longer than the conventional $10^6/10^7$ cycles at which the fatigue limit is determined, the safe stress range continues to be eroded down to 10^9 cycles³ and more; that is, at the very long lives typical of those required of axles and wheels.

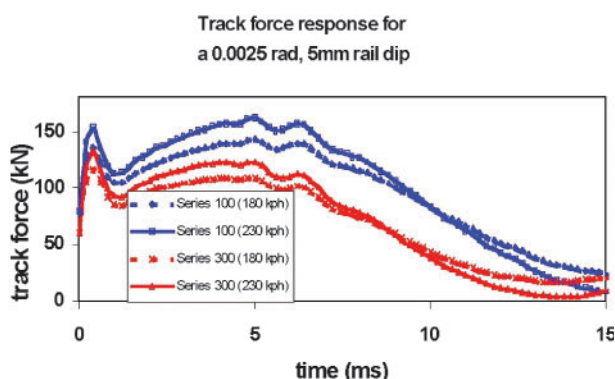
It is perhaps something of a surprise that despite so many years of study, fatigue failures of axles still occur. Although it might be assumed that the simplest solution would be to increase the size of axles to reduce stresses, the counter argument is that axles form part of what is called the *unsprung mass* of the vehicle which must be minimised to reduce the generation of dynamic stresses. Particularly as operational speeds of trains have been increased, the pressure to reduce unsprung mass has become more urgent.

It is worth pausing here to mention the nature of the forces at the wheel-rail contact and the generation of dynamic loads. At its simplest level, the contact patch between each wheel and rail must support that proportion of the vertical static load, the weight, which passes through it. Because of symmetry, this is known as the axle load (the wheel load equals half the axle load). In addition, along the direction of the rail, forces due to the acceleration, braking and traction at steady speed must be sustained. When a train passes through a curve, the lateral loads needed to generate curved motion must be considered, together with the load redistribution from inner (lower) to outer (higher) rail. All these loads are relatively easy to quantify, but the situation is made much more

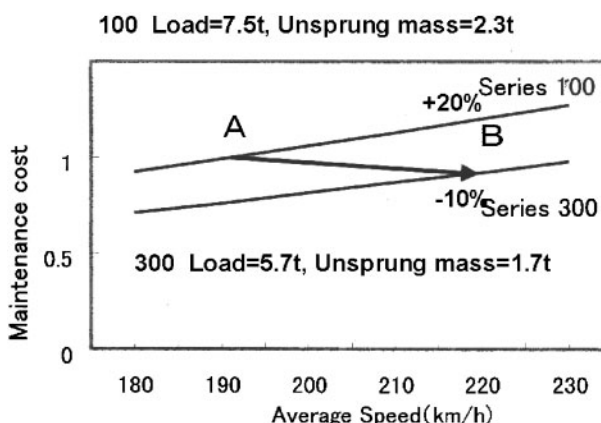
complicated by the generation of dynamic loads. It is now recognised that the magnitude of the dynamic loads induced by the passage of a wheel over a discontinuity in the rail, for example, a gap, dip, or damage patch, is determined by, of course, the magnitude of the discontinuity, the velocity, and by the axle load in combination with the *unsprung mass* of the vehicle, that is the mass below the main suspension in 'hard' contact with the rail.

An example, calculated using a simple model from data supplied by the Japanese Central Railway Company is shown in Fig. 5, which illustrates the forces generated as a function of time by the passage of a train over a small (5mm) dip in the rail head. Two trains

are shown, an old type (Series 100) and its replacement (Series 300). The intention was to increase the speed of operation from 180 to 230 km h⁻¹. The form of the response from both trains at both speeds is similar: with the dynamic forces showing two clear peaks with time, the so-called P₁ and P₂ forces. The dynamic magnification increases with speed and lies in a range approximately 2.5–3 times greater than the static force. Clearly these magnified forces have a significant effect on the fatigue of wheels, rails and axles. They are significant too in their effect on track maintenance. This is summarised on Fig. 6, which is a representation of the typical track maintenance costs as a function of speed for both types of train. The important characteristics of the new train are shown: a smaller wheel load (reduced from 7.5 to 5.7 t) and a smaller unsprung mass (reduced from 2.3 to 1.7 t), the reduction of which is a particularly sensitive way of reducing dynamic track forces. In the example shown, if the old train had been run at the required higher speed of 230 km h⁻¹, the track maintenance costs would have increased by some 20%. However, the new lighter train



5 Dynamic forces produced by the passage of trains over a rail head geometry defect



6 Generic effect of dynamic forces on maintenance costs

Table 1 Significant areas of fatigue in railways

| | |
|----------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Adjacent to wheel-rail interface | Wheels Rails Rail welds |
| Affected by forces generated at the wheel-rail interface | Bearings Axles Gearboxes Drive shafts Bogies Springs & suspension components Brake components Rail fastenings & supports Track foundation |
| Vehicles | Engine or motor components Body shells Couplings Internal components and fittings |
| Infrastructure | Bridges Signals Electrical supply components |

produces a saving of some 10% even at the higher speed. Obviously this is a somewhat simplified view of a complex situation which depends on many parameters. However, it serves to capture the essence of the dynamic load problem and illustrates the need for track and train designers to work in conjunction with each other. It serves also to illustrate the constraint of higher speeds and structural integrity. For high speeds it is necessary to drive down mass in critical components thus making them more prone to fatigue.

Although axles were the first components to fail by fatigue, it soon became clear fatigue was a much wider problem.⁴ Table 1 indicates some areas of application to railways, and, of course, more generally any component in any application subjected to cyclic loading is susceptible.

It soon became apparent that fatigue often acted conjointly with other failure modes, wear and corrosion being particularly important. The life of rails, for example, is a competition between wear and fatigue. Generally speaking a heavily loaded soft rail will fail by excessive wear: a hard rail will fail by fatigue. The introduction of steel rails in the 1860s (an introduction which was only accepted after a show of considerable reluctance by the conservative railway industry), allowed much longer lives because of the reduction in wear. Clearly a balance has to be struck between wear and fatigue. A so called *magic wear rate* is that which is just sufficient to wear out fatigue cracks at the same rate as they are initiated thus preventing them from growing to propagate into the depth of the rail (the same argument can be applied to wheels).

Case studies of recent railway accidents

Rails

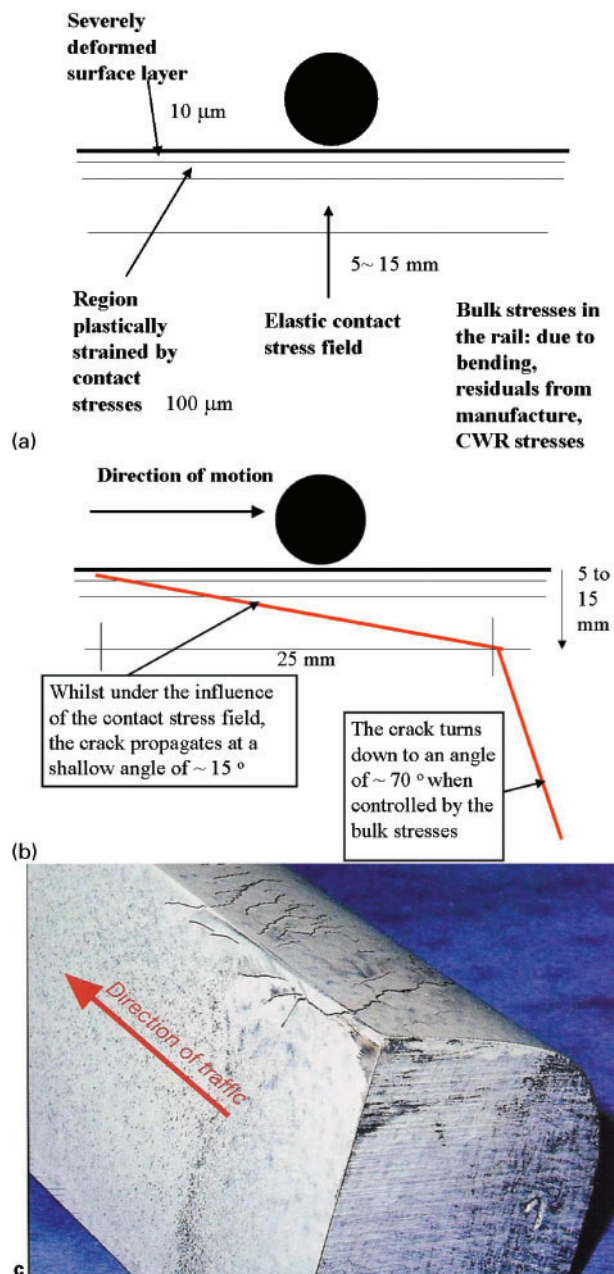
A single contact patch between the wheel and rail is typically the size of a very small coin: a large train is completely supported over a total area no larger than a compact disc. Clearly, the pressures at this key interface are very high, considerably in excess of the normal yield stress of the material. A complex series of events takes place with repeated passages of a wheel over a rail. The material in the immediate vicinity of the contact work hardens and deforms until its *ductility is exhausted** and a series of small cracks forms. The so-called *permanent way* is badly named: each passage of every wheel is an irreversible event, and with each passage, both wear and fatigue take place. Ideally, if the wear rate of the rail head or wheel equals or exceeds the rate at which cracks are initiated, then the cracks are 'rubbed out' before they can develop. However, if the crack development rate exceeds the wear rate, the cracks propagate deeper into the material, driven by the contact stresses. As the contact stresses diminish rapidly with depth into the material, the bulk stresses in the interior of the wheel or rail take over as the drivers of the crack. The possibility therefore exists of non-propagating cracks, if 'handshakes' fail to happen in the zones of transfer in the sequence of the change over of the governing stress from the surface

*This somewhat old fashioned term means that the yield stress of the material is raised to some limiting value by the repeated plastic deformation in the contact zone. The process is also referred to as ratchetting.

stress to the contact zone stress to the bulk stress (Fig. 7 a,b). This type of behaviour is paralleled in other fatigue situations when cracks initiate in high surface stress fields at, for example, sharp geometric notches, fretting patches and thermally loaded surfaces. In both wheels and rails, cracks can turn back upwards towards the surface leading to the formation of a detached flake (spalling).

As previously mentioned, the history of rail failures is as long as the railways. Cast iron was replaced by wrought iron, before itself being superseded by steel from 1860 onwards. In the last 30 years, the quality of steel manufacture has improved, virtually eliminating fatigue failures initiated from internal inclusion or hydrogen shrinkage defects in the rail head. Probably the most significant development since the introduction of the steel rail has been the use of welding to eliminate fish-plated gaps in the running surface and hence a potent source of dynamic loading. Rail are now manufactured in strings up to 250m long, thus simplifying the laying of track. The weld is itself a source of potential weakness: a large proportion of rail failures now occur at these joints. The thermit welding process is used in the field to join long rail strings. This process uses the exothermic reaction of a mixture of iron oxide and aluminium powder to connect the rails ends by what is essentially a casting. Flash-butt welding requires more equipment, but generally is capable of producing a more uniform weld and is sometimes used in critical location, for example, near points and crossings. Techniques are continuously being improved,⁵ but quality control under often adverse conditions is difficult and it is no surprise that defective welds are impossible to completely eliminate. Inspection techniques for welds have also improved, but are still not infallible. For example, there are currently over 130,000 welds installed in the UK railway infrastructure each year and it is estimated that there are in excess of 2.5 million in track. These very large numbers serve to emphasise the potential dangers caused by even an extremely low percentage failure rate.

The wear on the running surface of a rail can, in certain circumstances, produce a short wavelength shape change along the length of the rail, known as *corrugation*, which in turn leads to poor ride and noise generation.⁶ Controlled grinding is used



7 a. Depth of stressed zones, b. Geometry of crack propagation, c. Sectioned rail head showing crack development

to remove corrugations and/or to restore the accurate lateral rail head profiles that are essential for controlling the stresses in the wheel/rail contact. Combinations of high contact stresses upon which traction stress (along the rail) or cornering stresses (across the rail) are superimposed can lead to the initiation of rolling contact fatigue cracks.⁷ The particular types of these cracks caused by cornering are situated to the inside of the rail head and are known as 'gauge corner' cracks. If the wear and/or grinding rate is greater than the rate of development of fatigue cracks, the deterioration of the rail is benign. If, however, wear rates are low, it is possible for fatigue cracks to

grow down into the railhead. The cracks progress at a slow rate from the running surface, typically inclined downwards at a shallow angle of some 10°, until some 5 mm below the surface (Fig. 7c) they branch. If the branch crack propagates upwards, driven by plastic deformation of the thin tongue of metal above the crack, a part of the rail surface detaches or spalls – a form of damage that is clearly visible on inspection. But more dangerously, some cracks turn downwards into the head of the rail and these branches are extremely difficult to detect by conventional ultrasonic inspection techniques. It is claimed that eddy current methods may be more reliable,

but experience in the field is so far limited. If cracks remain undetected they can eventually grow in the zone of influence of the gross bending stresses in the body of the rail, turn downwards and propagate across the cross section of the rail and eventually become large enough to cause complete fracture of the rail.

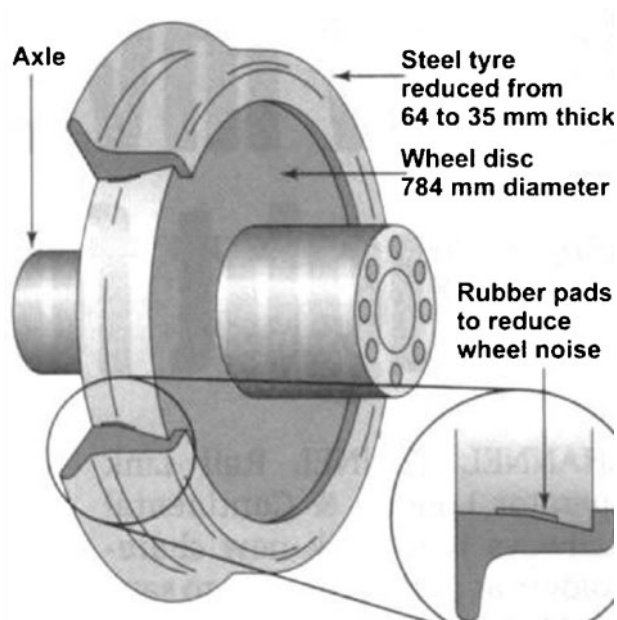
On 17 October 2000, a British train derailed at Hatfield, just north of London, killing four passengers. The immediate cause of the derailment was identified as a broken rail, and a subsequent examination of the UK network led to the discovery of more than 2000 sites containing potentially dangerous cracks. Severe speed restrictions were imposed whilst repair and replacement of track took place over a period of many months. In the long history of Britain's railways, no previous accident had caused such widespread public anger, managerial panic, disruption and eventual political crisis.⁸⁻¹⁰ The railway system had been privatised between 1996 and 1998, by fragmenting it into more than 125 companies and separating operations from infrastructure: the latter being of common feature of several other privatisations in other countries. This fragmentation of organisation was generally accepted as being the reason why, although the rail had been identified as being needed to be replaced, various inter-company delays meant that this had not happened. As a consequence of the Hatfield accident and its aftermath, Railtrack, the UK infrastructure company, was taken into receivership in October 2001 and was subsequently re-formed as a 'not-for-profit' company, Network Rail. More recently, changes in the organisational structure of the railway designed to reduce fragmentation have been announced.¹¹

A great deal of work, theoretical, laboratory based and experiments in service, has been performed on rail fatigue problem over the last two decades.⁷ There is now sufficient knowledge available to control this potentially dangerous problem, by a combination of inspections, grinding and contact stress reduction. The problem is such that many parameters, involving both the rail and the vehicle (wheel profile, suspension characteristics etc), need careful considerations. In railway systems where responsibility for the track and the vehicle has been placed with different authorities, care is needed to

ensure there exist mechanisms for those in charge of both sides of the wheel/rail interface to understand the complexities of the problem and to act in unison. The topic of fatigue at the wheel/rail interface, with particular focus on the rail, was extensively covered in a recent special issue of a specialist fatigue journal.¹² In this issue, after three scene setting review articles, there follow twelve research articles, three on monitoring, maintenance and non-destructive testing, four on damage, fatigue and fracture of rails, three on phenomena at the wheel-rail interface and, finally, two on new rail materials. The attention of readers is particularly drawn to this up-to-date overview of technical, scientific and practical aspects of fatigue at the wheel-rail interface.

Wheels

Spalling damage due to fatigue is relatively common on railway wheels. It leads to poor running conditions and high dynamic impact loads. In most cases this damage, if caught in its early stages, can be removed by re-turning the tread of the wheel. Similarly, out-of-roundness (polygonisation) or wheel flats, caused by sliding, can be machined out before damage becomes too wide spread. Turning is used in the first instance to re-profile the wheel, in order to improve contact patch conditions which are particularly sensitive to the local geometries of the wheel and rail at the site of the contact. In the past, wheels were usually manufactured by shrink fitting a tyre onto a hub. The famous 'wheel tappers', who older reader may remember, were looking principally for loose tyres rather than for cracks as is often supposed. Modern practice is to make wheels of a monobloc construction, with a relatively thin web, curved in the plane of the wheel to give lateral strength through geometry. Failures in the web are rare. However, despite all our knowledge of stress concentrations, a recent wheel fracture on a high-speed train running on the main East Coast route of the UK, initiated at a hole that had been drilled into the web of the wheel in order to attach a balance weight. The wheel disintegrated, but the train was fortunately able to come to a halt without causing any casualties (an good example of fate being kind, and the failure not unleashing a catastrophic series of events). This obviously dangerous method of balancing has been ceased. The wheels are now



8 Construction of the resilient wheel which failed at Eschede 23 June 1998

balanced by eccentric machining of the interior underside of the rim in a manner which achieves balance by removing a small crescent shape of material smoothly blended into the profile, thus avoiding any stress concentrating discontinuities.

The much-publicised accident to the German ICE train on 23 June 1998, which resulted in more than 100 fatalities, was caused by a fatigue fracture on the underside of a wheel rim separated from the disc of the wheel by rubber pads (Figs. 8 and 9).

This design, much used on vehicles operating at lower speeds, has the supposed advantage of reducing the transmission of noise and vibration from the wheel/rail contact into the body of the vehicle. The so-called resilient wheels were put into service without, in the author's opinion of the evidence available to him, adequate

fatigue testing. Other opinion has been published.¹³ In particular, the amount of material that could safely be removed from the tread to re-profile the wheel was not determined. The wheel that eventually fractured had been re-profiled on several occasions and the tyre thickness had been reduced from its initial value of 64 mm to 35 mm. As more and more material was removed in successive turning operations, the tyre became, in effect, a more flexible thinner ring. The squeezing of this ring caused by the rotation of the wheel, led to high bending stresses on the inside of the tyre. This increased bending would not have happened in a solid wheel. The inspection techniques were concentrated on the outer tread of the wheel, the usual site of contact fatigue damage in a solid wheel. It appears that the inadequate testing had not been continued sufficiently to produce



9 The failed tyre (rim) of the Eschede wheel. The fatigue crack is self evident

failure, therefore the site of potential failure was unknown and not adequately covered by the inspections. The root cause of this disastrous failure was not lack of fatigue knowledge, but the inability to anticipate a problem caused by a flexible wheel of significantly different design from a standard wheel, compounded by inadequate testing prior to the introduction of a the new design into service.

Carriages

It is worth recalling some of the developments in the construction of carriages. The name comes, of course, from the design adapted from horse drawn passenger vehicles. Wood was the early material used in the superstructure, the heavy under-frame and running gear were made of iron, later steel. The main materials of construction of the whole are now steel, both mild and stainless and aluminium. The interior is fitted out using a wide variety of materials, including many types of plastics and some composites. The flammability of wooden coaching stock has already been mentioned, but an even greater danger lay in the relatively weak superstructure being overridden in a end-on collision by the heavy stiff under-frame acting as a knife. Before carriages were more substantially built, attempts were made to prevent overriding by serrated panels on the vertical ends of the vehicles, which were supposed to engage and prevent further vertical misalignment. Gradually, carriages became more like rigid tubes with the whole of the structure contributing to the strength, and the under-frame disappeared, except for some support for break away bogies. This arrangement stood up to collisions with remarkably little overall deformation, but with very little ability to absorb the collision energy. The result was that passengers were often badly injured by the violent deceleration causing them to be thrown about inside or be ejected from the vehicle.

In the early 1990s, British Rail recognised this problem and a major investigation was performed in order to improve designs for crashworthiness.^{14,15} A statistical analysis suggested that the most effective safety improvements could be made by designing into the carriage structure energy absorbing capabilities at the coach ends. Large deformation non-linear finite element analyses were validated against full scale crushing tests in the laboratory and eventually,

highly instrumented full scale impact test of whole trains were performed. In addition, research was carried out to make the interior design passenger friendly. The crashworthy design recommendations arising from this work have for some years been adopted as required standard by the British railway authorities and have prompted similar work in many other countries. This type of large scale research and development, of which the author was proud to be chairman, is extremely difficult to be carried out in a fragmented railway.

Infrastructure

Space prevents extended discussion on material problems with railway infrastructure. Bridge collapses have been few: the Tay Bridge being the most famous and noteworthy. This has been the only railway accident in the UK in which all train crew and passengers were killed. In common with many accidents it led to increased technical understanding; in this case of wind loads on structures. Although this failure has been studied extensively over the intervening years, recent new investigations by the Open University^{16,17} have suggested that fatigue may have played a part in weakening the structure.

Concluding remarks

Before concluding, it must be emphasised that the impression created by the content of much of this paper, that railways are particularly prone to accidents, is completely false. Fewer passengers have been killed in the whole long history of Britain's railways, than are killed every year on our roads. Statistically, by any measure such as deaths and injuries per kilometre travelled, per hours exposure or per journey undertaken, railways are an extremely safe form of transport. Nevertheless, accidents often act as catalysts for research and development to improve performance in the future. That this is true can be seen from some of the accidents described above.

The railway has advanced incrementally, but cumulatively hugely, so that the modern railway is highly sophisticated in its use of materials. For example, a modern high-speed train for service at speeds in the order of 300 km h^{-1} , must be extremely light in order to minimise the dynamic loads. It must also be strong in a crashworthy sense. It must be airtight to prevent

passenger discomfort due to air pressure changes caused by passing trains or the entry and exit of tunnels. The interior must be air conditioned, the seats must be both light and comfortable, non-flammable and hard wearing. All these and other requirements stretch materials selection to its limits and pose problems for manufacture akin to the aircraft industry. The huge amount of hard wiring, up to 20km in a 25m long carriage, is not only expensive to manufacture but adds substantially to the weight and efforts are being made to reduce its use. More and more effort is being made to produce low maintenance track which is matched to the dynamic requirements of the vehicle. The bridges, viaducts and embankments over which our trains must pass, must be guaranteed safe by automated inspection techniques. The increased deterioration caused by climate change must be measured and infrastructure additionally stabilised. All these represent challenges in various ways to materials engineering and will continue the synergies between the railways and materials into the future.

Appendix

It would be appropriate for a Hatfield lecture to attempt to mention, however briefly, something of the role that metallurgy has played in the development of rails.

The earliest metal rails were formed from short (less than 1m) lengths of plate (hence the name 'platelayer') cast in iron. The brittleness caused many fracture problems. The carbon content was high (2–4%) and impurities such as sulphur and phosphorus made a less than reliable product. The basic acceptance test was a dropped weight, but this was not correlated with any measured service loads. Quality improvements gradually permitted the use of longer and more reliable rails and cast iron was often replaced by wrought iron. Barlow by 1850 was able to comment on his use of 15 ft lengths of wrought iron rail and was enthusiastic of their qualities.¹⁸

Wrought iron was characterised by a high slag content which was worked into long stringers along the length of rails and axles during manufacture. To some extent these slag stringers acted as composite fibres, promoting corrosion resistance and acting as crack stoppers in the relatively soft iron matrix. Fractures produced by bending exhibited a fibrous or woody structure

emphasised by the slag stringers. It was the startling different appearance of fatigue fracture surfaces from ductile fracture surfaces that mislead the early investigators into thinking that the material has 'crystallised'.¹⁹ Wrought iron could only be made in relatively small quantities, so the early bridges were made from cast iron beams. It was the failure of such a bridge over the Dee at Chester in 1847²⁰ which nearly caused the premature and ignominious end to the engineering career of Robert Stephenson, but more importantly led to the appointment of a Royal Commission to inquire into the use of iron in railway structures.²¹ The Commission report contains a wealth of detail of the then current knowledge of iron and details some important experiments which led to the idea of an elastic limit and tests on large beams which were the first fatigue tests on structural members.

The age of steel rails began with an experiment in Derby station on the Midland Railway in 1857. The pearlitic structure, based on a carbon–manganese composition, was essentially the same metallurgically as that of steel rails in use today.^{21A} As the years have gone by improvements have been made by very accurate control of the chemical composition, potentially embrittling elements such as sulphur, phosphorus, nitrogen and hydrogen have been reduced to very low levels and the steel has been made cleaner with far fewer stress-concentrating inclusions from the steelmaking and casting process. When the first British Standards were issued at the beginning of the 20th century, four of the first batch of eleven were on rails or railways, giving an indication of their importance on the country's industrial development. BS11 of 1903 called for a minimum tensile strength for rail steel of 618 MPa. Numerous revisions since then have led to the requirement of 710 MPa for normal grade and 880 MPa for the so-called wear resistant grade.

Even higher strengths in the order of 1300–1400 MPa have been achieved by reducing the spacing between the pearlite lamellae by controlling the growth rate. Originally manufactured for heavy haul goods application, particularly in North America and Australia, these premium rails are now being selectively used in tight curve heavy wear situations of European railways. Alloying elements such as chromium and nickel can be used to

further improve properties, as can heat treatment, introduced at working in 1985. Selective heat treatment can be used to produce a hard rail head on a more ductile web and flange.

More recently, the problem associated with the relatively low fracture toughness of rail steel has been addressed by the development of low carbon carbide-free bainitic rail steel, produced by careful choice of alloys and an intermediate cooling rate. The alloying additions are made to prevent the formation of carbides, resulting in very fine interlath films of austenite which are retained between ferrite plate. The structure is composed largely of low carbon carbide-free bainite with some retained austenite. A minimum of a twofold increase in fracture toughness and a four times reduction in wear rate has been measured in laboratory tests. Further details²² and test results continue to be reported^{23–25} but take up by the railways has been exceedingly slow. Amongst the many reasons for this are the continuing conservatism of the railway industry, the pressing need to reduce costs mitigating against a more expensive product, the long life of existing rail limiting the opportunities for wide scale replacement and, perhaps, most importantly, a continuing lack of clarity about what exactly is being designed against. This latter point returns to a theme of the paper, that the need for measurements of real loads in operational service is essential prior to a deep understanding of the mechanical environment in which our railways operate. Only if the mechanical and metallurgical sides of the equation are studied in consort will true progress be made.

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