ASSESSING FATIGUE CRACK GROWTH IN RAILWAY AXLES

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ABSTRACT

Railway axles are safety critical components. Designing in failsafe mechanisms is very difficult and the safety of the component is determined though a good understanding of the structural integrity and through effective management policies. This paper first reviews from a historical viewpoint the development of the design and management of railway axles, and then outlines state of the art methodologies to be employed in the successful management of railway axles. Advancements in fatigue fracture mechanics have permitted the development of statistical techniques which enhance the understanding of axle failures which occur relatively infrequently. Because of the extremely low number of in-service failures, there exists a possibility to increase the NDT inspection interval, and to even abandon certain inspection procedures, such as far-end ultrasonic scans, completely. There is some evidence to suggest that inspection procedures which involve a degree of disassembly of the axle actually introduce a risk which offsets the benefit associated with crack detection.

1 HISTORICAL PERSPECTIVE

Railway axles were one of the first components which were to subjected to large numbers of repeated cycles. Because of the loading geometry the axle is in approximately 4 point bending, and each time the axle rotates, an element of material on the surface of an axle goes from a compressive state to a tension state of equal magnitude. The large number of rotations that were experienced by early axles led to the first reported fatigue failures in which failure was observed at stress levels well below the yield strength of the material. These failures inspired the work of Wöhler [1] who discovered that below a limiting stress level the material could survive repeated cycles indefinitely. This stress level is commonly termed the fatigue or endurance limit. Current design standards all share common origins traceable back to Reuleaux, who was a German engineer and Professor. In 1861, he published, in German, The Constructor: A Hand-Book of Machine Design, which was enlarged in three subsequent editions. The forth edition was translated by Henry Harrison Suplee, and published in Philadelphia, USA in 1894. More recently, axle design guides have begun to converge. Europe has adopted common standards, EN 13103:2001 & EN 13104:2001, respectively for trailing and driven axles. These design guides are very general and accommodate allowances for a wide range of designs. Newer designs employing features such as inboard journal bearings and hollowed out axle centres also need careful attention when assessing the design for its susceptibility to fatigue.

Fatigue failures in railway axles are generally extremely rare. In the UK for example, axles fail at a frequency of 1-2 per year (average taken over the last 30 years). When

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compared with the number of rail breaks, which are of the order of several hundred in the UK per year, the investigation of failure mechanisms of railway axles rightly commands a low priority. Even though axles are statistically very safe, an industry exists to inspect axles at regular frequencies using ultrasonic and magnetic particle inspection techniques. Ultrasonic inspections occur relatively frequently and involve passing an ultrasonic sound wave into the axle and then measuring the reflections. The results are compared with a standard reflection trace measured in a structurally sound axle and an assessment is made of any deviations. The more sensitive magnetic particle exams are performed at major wheelset overhauls in which wheels and other components such as brake disks are completely removed from the axle allowing a thorough exam of the axle's surface to take place. Ultrasonic inspection frequencies are determined by computing the time taken for a crack, which can be detected with a good degree of certainty, to grow to failure. The inspection interval must be less than this, and usually is a fraction (1/3) of this time to allow the next inspection an opportunity to detect the crack should it be missed during the first inspection in which it becomes visible. Because of the nature of the problem, the probability of a fleet of axles containing even a single defective axle is quite low. The operators of the detection equipment are therefore presented with a large number of axles with only a very small percentage with defects. There are added human factors which put the operator in a disadvantage when faced with the large number of axles which presumably pass the ultrasonic exam. Furthermore, because some of the ultrasonic probes require that the axle box cover is removed, additional risk is induced through the possibility of failing to correctly reassemble the axle box, or through the introduction of contamination into the bearing housing. Axle box failures are also very serious and occur more frequently than axle failures. The safety benefit of ultrasonic inspections could therefore be completely countered by the additional risk introduced due to the procedures followed during the inspection. The magnetic particle exams which occur at major wheelset overhauls are very sensitive to the detection of surface cracks. However there is a case for advocating by default the withdrawal of the axle from service. This is especially the case when the axle design is simple. The cost of the replacement axle may be of the same order as the cost of performing the magnetic particle exam.

In summary, because of the safety critical nature of railway axles, considerable experience has been developed over many years in the design, operation and management of axles. In the forum of this conference it is acceptable to advocate a relaxation in inspection methodology, but in reality, the possibility of railway administrations adopting such a measure, especial so in the safety conscious UK, is unlikely in the foreseeable future.

2 FATIGUE DESIGN OVERVIEW

Successful fatigue design is dependent on an understanding of the material properties, the input loads, and how the structure responds to those input loads. Because of the interrelationship between each of these three design inputs, the degree of certainty to which fatigue behaviour may be predicted is dependent on the design input with the greatest degree of uncertainty. The first necessary task in any attempt to improve the fatigue design is the identification of the design input of which least is known. Refining a stress analysis computation in a finite element package may improve the precision of the result from ±5% to ±1%. This improvement is unproductive if the uncertainty of the boundary conditions (input loads) is ±10% for instance [2-3].

2.1 Stress analysis

The simple geometry of railway axles lends itself well to analytical stress analysis. Historically axles have been designed successfully with the use of beam theory, but even with the advent of computational tools such as finite element analysis, beam theory has not been replaced wholly in the design guides of axles. Only for more complex axles, for example, hollow driving axles with inboard bearing journals, is the use of finite element analysis justified. Figure 1 is an example of the input loads on a simple axle. Only those loads acting in the plane of the figure are shown and these arise primarily through the mass of the vehicle and through cornering forces, both with an allowance for dynamic effects. The bending moment due to the static weight of the vehicle is uniform between the wheel seats. The transfer of mass to the outer journal and outer wheel experienced during cornering results in a bending moment which varies linearly between the wheel seats, being highest in the vicinity of the outer wheel. For trailing axles with no braking mechanism, this is the extent of the analysis. Driving or braked axles require an additional calculation which introduces an out-of-plane bending and depending on the type of braking mechanism, additional in-plane bending. These moment vectors needed to be added using vector addition to find the resulting bending moment. Once the bending moment is known, the various sections and transitions along the axle can be determined and designed towards the maximum permissible stress. From the designer’s point of view, there is a conflict between achieving a low unsprung mass and a low design stress. Usually this is resolved by designing to the maximum permissible design stress.

2.2 Input loads

Of the three fatigue design inputs, possibly the most difficult to determine are the in-service input loads. Design guides do specify these but are generally for the worst possible case scenario. The axle may never experience the design guide input loads and for the majority of its life is operated at stress levels far below the maximum permissible stress. The worse case axle loading scenario occurs when all possible inputs are maximum; braking forces, cornering forces, vertical loading, and wheel nip, together with an allowance made due to dynamic effects. This approach is perfectly acceptable to ensure that the axle remains safely below its endurance limit, but more knowledge of input loads must be obtained if the input loads are to be used in a fatigue crack propagation analysis. If a fatigue crack develops sufficiently, and is growing, then performing a Paris law type integration using the maximum permissible stress as an input will result in an extremely conservative time to failure. An understanding of the real in-service conditions can only be obtained using measured data. This is expensive and difficult to achieve, but some data is often recorded for certification purposes of new rolling stock, or where there has been a problem with a particular fleet of axles. An illustrative example of typical data is shown in figure 2 (kindly supplied by AEAT rail). Because of the sinusoidal nature of the loading, the data is shown as a histogram of stress reversals. The maximum permissible stress is also shown in the figure, and illustrates how conservative the design guides actually are.

2.3 Material properties

The determination of material properties under laboratory conditions can be carried out with high precision. Standard rotating bending machines can be used to determine the endurance limit and the S-N curve, and compact tension specimens can be used to determine the fatigue crack propagation behaviour. Typical data for railway axles are usually represented by Paris Law constants and fatigue crack growth thresholds. Because the laboratory conditions are very different to the real axle environment, some care must be used when employing the material data. Real axles can be an-isotropic as a result of the manufacturing process. Specimens machined from real axles must therefore be machined carefully ensuring that the plane of crack propagation is the same in the specimen as it would be in the axle. Additionally, there are effects such as scaling which need to be accounted for. British Rail research investigated this by performing tests on whole axles and also on laboratory specimens. Corrosion can also be deleterious to the fatigue process in axles. Corrosion may accelerate fatigue crack growth through the process of stress corrosion cracking, and corrosion debris products may also act as a lubricant on the faces of the advancing crack, thus further increasing the rate of propagation.

3 METHODOLOGY FOR FRACTURE MECHANICS ASSESSMENT

This section briefly induces the methodology for performing a fracture mechanics assessment on railway axles. Details of the calculation have been omitted here for clarity. The necessary inputs for the fracture mechanics analysis include:

- Input loading histogram
- Stress analysis of a cracked beam in rotating bending to determine K as a function of crack length
- Material data: Threshold stress intensity factor range, fatigue growth law, load interaction model

The input loading histogram is ideally measured data, but could be computed using vehicle dynamics software. The problem of fracture of round bars loaded in rotating or non-rotating bending has received attention in the scientific literature [4-6 for example]. It is possible to represent the evolution of K as a function of crack length in accordance with:

$$\Delta K = \alpha \Delta \sigma \sqrt{\pi a} \ ,$$

where ΔK is the stress intensity factor range, $\Delta\sigma$ is the stress range[2], a is the crack length and α is a shape factor equal to 0.6 for rotating bending. Typical values for threshold stress intensity factor ranges are between $3-9\,\mathrm{MPa}\sqrt{\mathrm{m}}$ and crack growth represented by the Paris law:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left(\Delta K\right)^{n}.$$

With $C = 6.7\times10^{-4}$, and $n = 4.4$ typically to give a growth rate in mm/million cycles. The analysis is performed computationally and then combined to form a spectrum of failure times for a given initial crack size, as illustrated in figure 3. Given the NDT inspection probability of detection curve, this may also be used as an input and the inspection interval varied to obtain the probability of failure as a function of the inspection interval.

4 CONCLUDING REMARKS

Railway axles are one of the few components which experience relatively simple cyclical fatigue loading. A long history of careful design has ensured that the number of failures of this safety critical component have remained small. Knowledge of fatigue crack propagation and probabilistic fracture mechanics has enabled a statistical approach to be adopted. A key input to this process is the measurement of real in-service loading data, which can more easily be obtained during the certification process of new rolling stock.

5 REFERENCES

1. Wöhler, A. (1858-1871). An account in English was published in *Engineering* 11 (1871) March 17, pp 199-200 and subsequent issues.
2. Hillmansen, S, & Smith, R A Intelligent measurement of the in-service rail vehicle axle environment, In Proceedings, Implementation of Heavy Haul technology for Network Efficiency, May 5-9, 2003, Dallas, USA, pp f.11-f.17, 2003
3. Smith, R A & Hillmansen, S, Monitoring Fatigue in Railway Axles, Proceedings of 13th International Wheelsets Conference (CD Rom), Rome,17-21, 2001
4. Carpinteri A., Brighenti R., and Spagnoli A., Fatigue growth simulation of part – through flaws in thick walled pipes under rotary bending, *Int. J. Fatigue.*, 22 pp 1-9 (2000).
5. De Freitas M., and François D., Analysis of fatigue crack growth in rotary bend specimens and railway axles, *Fatigue. Fract. Engng. Mater. Struct.*, 18 (2) pp 171-178 (1995).

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[2] The compressive bending stress makes no contribution toward the advancement of the fatigue crack, the stress intensity factor range is computed from $\Delta\sigma/2$ which because the stress ratio is –1 is approximately equal to the stress amplitude.

6. Lin X. B., and Smith R. A., Shape growth simulation of surface cracks in tension fatigued round bars, *Int. J. Fatigue.*, 19 (6) pp 461-469, (1997).

6 ACKNOWLEDGEMENTS

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7 FIGURES

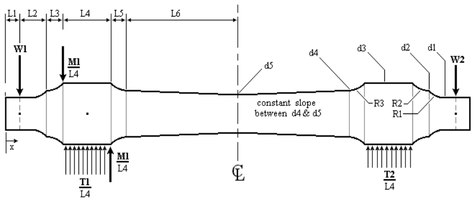

Figure 1. Schematic of a simple axle showing input loads and various sections and transitions

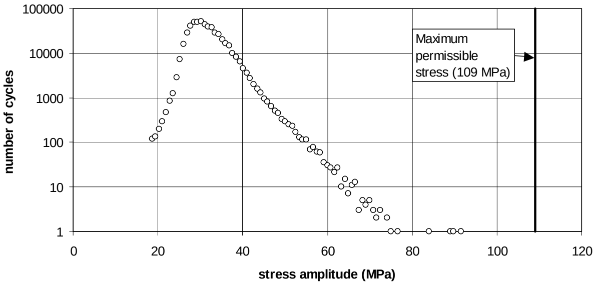

Figure 2. Typical axle loading histogram showing limiting design stress

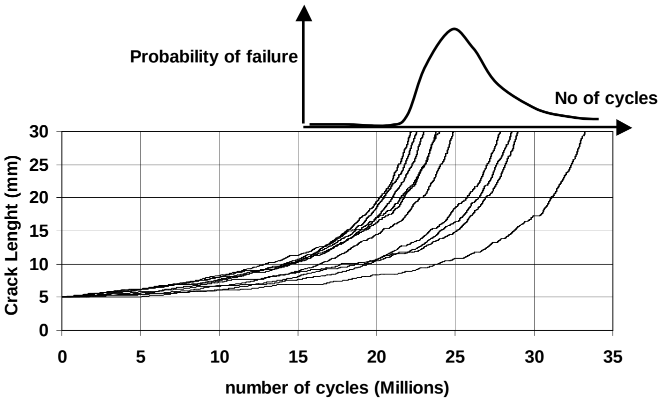

Figure 3. Illustration of how multiple simulations of crack growth can be used to determine probability of failure as a function of number of cycles