Research and Development of Fatigue Issues for Railway Steel Products and Future Prospects

Miyuki YAMAMOTO*

Abstract

Strength reliabilities, or fatigue issues, of railway steel products are very concerned matters for social safety and easiness. Since Nippon Steel & Sumitomo Metal Corporation has been supplying the railway steel products, such as rail, wheel, axle, and bogie truck, the research and development (R&D) fields in Nippon Steel & Sumitomo Metal are widely spread from material R&D with high fatigue performance to structural R&D by using numerical analyses and actual body endurance tests, furthermore, technology R&D of strength design methods. The present paper shows some recent R&D results and future prospects in these fields.

1. Introduction

It is said that the railway traffic system as we know today dates back to 1825 when the Stockton and Darlington Railway of England started commercial operation. In Japan, the first railway line was operated between Shimbashi and Yokohama in 1872. At that time, the maximum speed of trains was not higher than 60 km/h. However, with the progress of railways, train speeds have been increasing. In particular, since the opening of the Tokaido Shinkansen in 1964, train operations have been markedly accelerated. Today, thanks to the remarkable progress of railway technology, the maximum speed of trains has reached 300 km/h. Steel products have largely been used for many of the railway system components such as rails, wheels, axles, and bogies. Considering that the railway traffic system has an enormous influence on the public, the strength reliability of these components is an important matter associated with the security and safety of the public.

As for the strength reliability, one of the important study themes is the strength or fatigue characteristic of each railway system component that is subject to repeated loads during use. The reason why it is necessary to consider the fatigue characteristic carefully is that fatigue is a microscopic fracture[1] caused by the initiation and propagation of a crack due to a cyclic slip deformation of the size of a single grain, that fatigue occurs even under a stress smaller than the strength characteristic under a static load (e.g., tensile strength), and that it can suddenly lead to a fatal fracture without causing any macroscopic plastic deformation. Incidentally, fatigue characteristic is important not only to railways but also to many other machines and

structures. In the 1860s, Wöhler of Germany conducted a systematic experiment to evaluate the fatigue of steam locomotive axles and studied the stress(S)-life(N) relationship, which is used even today as the most basic fatigue characteristic data. Since he established the foundation for the study of fatigue,[2] the author feels a strong connection between fatigue and railway.

As a steelmaker, Nippon Steel & Sumitomo Metal Corporation manufactures various railway system components and supplies them to railway operators. For certain types of railway system components, the company even designs their shapes (strength properties) taking their fatigue characteristics into consideration. Therefore, it is engaged in the study of fatigue characteristics of materials and the development of high-performance materials. It also engages itself in numerical structural analyses indispensable for strength design, in product evaluation tests using model system components, and in R&D on advanced strength design techniques. The railway system components that are discussed in this technical review are rails, wheels, axles, and bogie frames. First, the materials used for them, the types of damage related to their fatigue, and the strength design techniques applied to them are reviewed. Next, examples of recent R&D results are presented. Then, the outlook for improvements in the strength reliability of these system components is described.

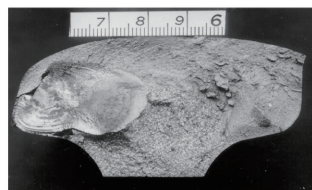## 2. State of arts of Railway System Components

2.1 Materials used for rails and types of damage to rails

Materials used for rails in Japan are specified in JIS.[3] They are high carbon steels of pearlite structure, whose chemical composi-

* Fellow, Dr.Eng., Technical Research & Development Bureau
1-8 Fuso-cho, Amagasaki, Hyogo 660-0891

Table 1 Rail steel specipication in JIS

Mark	Chemical compositions					Mech. properties	
	C	Si	Mn	P	S	TS	Elong.
	(%)	(%)	(%)	(%)	(%)	(MPa)	(%)
37kg	0.55-0.70	0.10-0.35	0.60-0.90	<0.045	<0.050	>690	>9
40kgN	0.63-0.75	0.15-0.30	0.70-1.10	<0.030	<0.025	>800	>10
50kgN							
60kg							
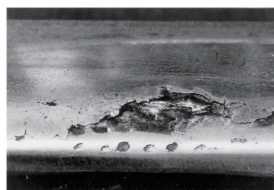
a) Flaking damage   b) Internal fatigue failure

Fig. 1 Examples of fatigue damage appearance in rails

Table 2 Exchange cause of freight train wheels in North America (2005)

Why made code	No. of wheels		Ave. life
		Ratio	(year)
Administrative	398,039	57.1%	9.8
Good conditoin	375,244	53.8%	
Mate wheel	22,206	3.2%	
Others	589	0.1%	
Environment	199,168	28.6%	8.8
Out of round	2,699	0.4%	
High impact	111,709	16.0%	
Thermal cracks	3,322	0.5%	
Tread shelled	50,273	7.2%	
Slid flat	19,845	2.8%	
Others	11,320	1.6%	
Worn out	98,926	14.2%	11.0
Thin flange	23,830	3.4%	
High flange	62,001	8.9%	
Thin rim	10,573	1.5%	
Others	2,522	0.4%	
Wheel failure	766	0.1%	12.2
Rim spread	96	0.0%	
Flange cracked	244	0.0%	
Rim cracked	320	0.0%	
Rim shattered	106	0.0%	
Total	686,899	100.0%	9.7

tions and mechanical properties are shown in **Table 1**. The figures in the Mark column indicate rail weights per meter. The cross-sectional shapes of rails are also specified in detail in the same JIS. Also, rails weighing 60 kg are used for the Shinkansen.

On the other hand, in North America and Australia, increasing number of heavier-duty rails have been rapidly introduced to freight railways for transporting natural resources (coals, ores, etc.) to improve the efficiency of transportation. As high-strength rails suitable for those railways, Nippon Steel & Sumitomo Metal has already come up with eutectoid/hypereutectoid steel rails of pearlite structure, as described in detail elsewhere in this special issue.

The types of damage caused to rails include not only rail wear caused by contact with the wheels but also flaking (fatigue damage to the rail head surface) and shelling (fatigue damage to the rail interior).[4,5] Examples of flaking and shelling are given in **Fig. 1**. Flaking refers to rolling contact fatigue damage similar to the shelling that occurs on wheel treads described later. There is a concern that with the increase in freight mass, the incidence of flaking is also expected to increase. However, this can be effectively restrained by using high-strength rails. On the other hand, shelling refers to a fatigue failure originating in the rail interior 5 to 10 mm from the surface. The fatigue failure is ascribable to the presence of nonmetallic inclusions or the cross-section hardness distribution of the rail head.[6] However, in recent years, shelling has seldom occurred thanks to the improvement in steel cleanliness made possible by the progress of steelmaking technology and to the increase in the hardening depth of high-strength rails.

2.2 Materials for wheels, method of wheel strength design, and types of damage to wheels

As for the materials used for railway wheels and the method of wheel strength design, they are described in detail elsewhere in this special issue. Therefore, in this subsection, the author mentions only two points. Namely, in Japan, the materials used for wheels are nearly the same as those used for rails, that is, high carbon steels of pearlite structure specified in JIS,[7] and the method of strength design of wheels is the fatigue limit method considering the wheel web fatigue.

The types of damage caused to wheels include not only wheel wear caused by contact with the rails but also thermal cracking, spalling, shelling, flat-induced shelling, rim shattering, etc., caused by fatigue.[8] Unlike the rails on which the wheels run, the wheel treads are subject to braking loads. Thus, thermal cracking and flat-induced shelling under braking loads are the types of damage unique to the wheels. Other types of damage to the wheels are caused by almost the same causes or mechanisms as those that cause damage to the rails, even though their names may not be the same.

The Association of American Railroads (AAR) compiled data on the incidence of wheel replacement by cause. **Table 2** summarizes the results obtained in 2005.[9] As shown in the table, the causes of wheel replacement that are considered to be associated with fatigue ("environment" and "wheel failure") account for about 29% of the total, as compared with approximately 14% for "wear," and that the average life of wheels subject to shelling, thermal cracking, etc., is approximately 20% shorter than that of wheels subject to wear. Although authentic data are unavailable, the damage caused to solid wheel webs, which is given major consideration in wheel strength design, has not occurred in Japan.

2.3 Materials for axles, method of axle strength design, and types of damage to axles

Figure 2 shows an example of an axle for the Shinkansen. The axle is a multistep type having seats for fitting bearings, wheels, gears, etc., to form a wheelset assembly.

Table 3 shows the types, mechanical properties, etc., of axles based on the JIS specifications.[10] Axles are divided into four types. Types 1 to 3 are ones whose tensile strength has been increased by a suitable heat treatment, while Type 4 is an axle that has been subjected to induction heating and tempering after quenching and tempering. As for the chemical composition of steel materials for an
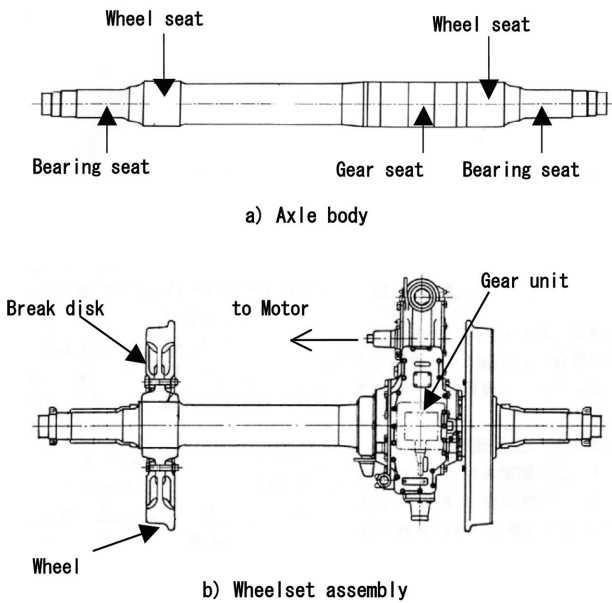
Fig. 2 Example of railway axle

Table 3 Railway axle specification in JIS

Sort	Mark	Mechanical properties				Heat treatment
		YS	TS	Elong.	Red.	
		(MPa)	(MPa)	(%)	(%)	
1	SFA55	>275	>540	>23	>35	Normalizing or
2	SFA60	>295	>590	>20	>30	normarizing & tempering
3	SFA65	>345	>640	>23	>45	Quenching & tempering (QT)
4	SFAQ	>295	>590	>20	>30	Induction heating QT

* Mechanical properties of SFAQ are those of before IHQT.

axle, the JIS specifies only high limits of P and S as impurities. At present, medium-carbon steels (C: 0.30 to 0.48 mass%, Si: 0.15 to 0.40 mass%, Mn: 0.40 to 0.90 mass%) are used in Japan. In Europe, low-alloy steels added with Cr, Mo, etc., are also used.

The strength design of axles is basically a fatigue limit design in which the safety factor calculated on the basis of the maximum stress (design stress) assumed to occur during vehicle operation and the allowable stress specified for each material and part is made higher than the reference safety factor established on safety achievements in the past. It is described in detail in the references[11,12] quoted at the end of the text. Therefore, in this subsection, only the design flow (**Fig. 3**) and procedure are explained.

First, as for the design stress, the bending moment and twisting torque at each part of the axle are obtained from all the forces acting upon the axles during vehicle operation, including the weight and inertia force of the car body and bogies, the reaction force from the wheels, the forces from the driving and braking units, the forces applied via the bogie frame, etc. Next, the bending moment and twisting torque obtained are converted into the bending stress and twisting stress, respectively, by using a technique based on the strength of materials theory.

With respect to the allowable bending stress, it is prescribed for each type of axle material and each axle part (fitted/non-fitted). For
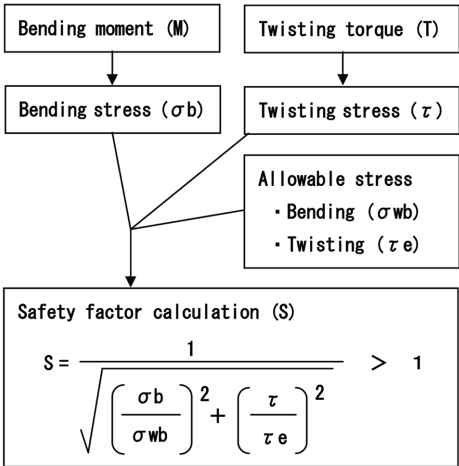

Fig. 3 Design flow of railway axle

the rotating bending fatigue limit of small test pieces, consideration is given to not only the size effect but also the fitting effect for each fitted part or the surface roughness effect for each non-fitted part. The twisting elastic limit[13] is used as the allowable twisting stress because a twisting stress occurs less frequently than a bending stress, and there is a phase difference between the bending stress and twisting stress. The safety factor of each of the axle parts is calculated using the formula shown in Fig. 3. This is to take the effect of superposition of bending stress and twisting stress into account. For each of the axle parts, a reference safety factor has been decided with due consideration given to the difference in vehicle types (Shinkansen, commuter, limited express, etc.).

Concerning axle damage caused by fatigue, fretting fatigue that occurs in the fitted part of a wheel seat is important. This is because under the fretting fatigue, the fatigue strength of the fitted part decreases more markedly than that of the non-fitted part because of the stress concentration caused by the fitting (macroscopic change in shape), microscopic stress concentration caused by tiny pits or irregularities produced by the fretting corrosion, and increase in stress caused by the frictional force from the fretting. According to the records of axle maintenance and repair conducted by the JR companies to keep track of the incidence of damage to axles in recent years, very few axles have been replaced because of magnetic particle flaws (small cracks occurring at the early stages of fretting fatigue).[14] In the past decades, no broken axles have been reported in Japan.

2.4 Materials for bogie frames, method of bogie frame strength design, and types of damage to bogie frames

Figure 4 shows the railway bogie frame, which consists of side beams; cross beams; and a structure for housing the motors, driving gear unit, etc. All these components are welded into a solid bogie frame. The welded parts are either finished with a grinder to obtain a smooth bead or left as welded. In addition, ordinary bogie frames are subjected to stress-relieving annealing in order to reduce the residual stress after the welding work.

Steel materials used for bogie frames are structural steels, as represented by SS400, SM400, and SMA490, and cast steels, as represented by SC450. Recently, structural steel plates about 8 to 16 mm in thickness have been in use. In addition, steel pipes for mechanical structure, as represented by STKM, have come to be increasingly used, especially for cross beams.
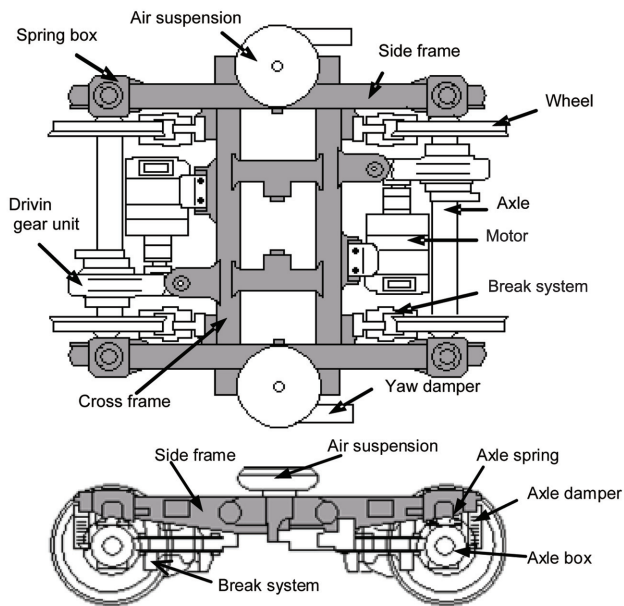
Fig. 4 Example of railway bogy truck

The strength design of bogie frames is a fatigue limit-based design carried out in accordance with the JIS procedure[15]—determining loading conditions, formulating a structural plan, calculating stresses in individual parts, and evaluating the strength. As a railway car runs, its bogie frames are subject to various types of loads. For determining the appropriate loading conditions, these loads are divided into static and dynamic loads. Static loads act upon the bogie frames, while the car is stationary. They include car-body weight, live load, etc. On the other hand, dynamic loads are applied to bogie frames as a result of vibrations of the bogie parts and driving/braking of the car. They act vertically, laterally, or longitudinally. In determining the loading conditions, consideration is given also to the occurrence of a twisting load due to cant change in a curved section and track misalignment. In calculating the stress in each of the bogie parts, the stress by individual load type is calculated. Although JIS does not specify any method of stress calculation, it is common practice to apply an FEM-based elastic stress analysis, whereby the stresses for the individual loads are combined and the mean stress and stress amplitude that are required for fatigue strength evaluation are obtained. The fatigue strength is evaluated by comparing the above resultant stress (mean stress and stress amplitude) with the allowable region enclosed by the allowable fatigue stress line in the modified Goodman diagram and the allowable yield stress line considered in terms of the maximum stress. Namely, the fatigue strength must be such that the resultant stress falls within the allowable region. For strength evaluation, three different allowable stress values are used for the base metal part, finished welded part, and as-welded part.

As the fatigue damage to bogie frames, there are cases in which a fatigue crack occurs on the base metal surface in a portion that is subject to a sharp change in shape or from a casting defect in a cast steel part. However, in many cases, fatigue damage originates in welded parts. The reason for this is as follows. In welding, the method of welding differs with the part to be welded. Therefore, the as-welded parts are susceptible to welding defects such as the undercut, and even the finish-welded parts can leave an unwelded root

at the back when one-side welding is applied.[16]

3. Examples of R&D on Railway System Components

3.1 Assessment of shelling damage to wheels

In this subsection, recent examples of studies on shelling[17,18]—the representative rolling contact fatigue damage to wheel treads—are presented. It has been known that shelling damage to wheels becomes especially conspicuous under wet conditions, the main crack that propagates in the direction of wheel depth and the branched cracks that propagate toward the wheel surface interact in a complicated manner to ultimately cause defoliation of the wheel surface layer, and that the wheel life under shelling damage decreases as the specific sliding increases and the material strength declines. However, the above knowledge is based on experimental results, and the underlying causes of shelling remain unknown.

Therefore, a disc model having an oblique surface crack and rolling on a flat plate was subjected to an FEM analysis to study the mode of crack propagation by evaluating the change in stress intensity factor at the front end of the crack. In the analysis, the direction of crack propagation (θ) and the driving force ($K_{\theta,max}$) for crack propagation under maximum tangential stress were evaluated, since the mixed mode of I and II prevails under contact stress.

As a result, it was found that $K_{\theta,max}$ has two peaks—for θ in the direction of disc depth and for θ toward the disc surface—as shown in **Fig. 5**. This corresponds to the fact that there are two modes of cracking (main crack and branched crack). It was also found that the peak value of K for θ toward the disc surface increases with the increase in specific sliding. This is one reason why the wheel life under shelling damage decreases with an increase in specific sliding. In another FEM analysis of the mode of crack propagation after branching, it was found that the main crack stops propagating after it reaches a certain depth, but the propagation of branched cracks is accelerated, considering that the stress intensity factor at the front end of the main crack decreased, while that of branched cracks increased. On the other hand, with respect to the influence of material strength, the higher the material strength, the smaller the peak value in the direction of depth, since the hydraulic pressure in the crack decreases. Thus, it was found that the main crack decreases in depth and the peak value toward the surface decreases accordingly, thereby helping to slow down the defoliation of the wheel surface layer.

3.2 Fatigue characteristic of press-fitted axle under variable stress

Concerning the fretting fatigue characteristic of press-fitted axles, it is necessary to clarify the influence of variable stress on the occurrence of fretting fatigue cracking, since the stress amplitude is always variable under the actual working conditions of the axles.
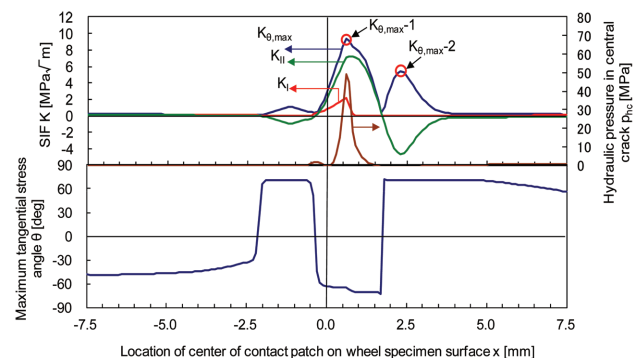
Fig. 5 Change of stress intensity factor[17]

Therefore, a small induction-hardened axle was subjected to a three-point bending fatigue test to study the influence of variable stress on the occurrence of fretting fatigue cracking in the press-fitted axle. In the fatigue test, a two-level, multi-step stress pattern was used, and both stress level and highstress-to-lowstress frequency ratio were varied. In addition, a multilevel, multi-step stress test was conducted to evaluate the influence of number of stress levels. As parameters for evaluation, modified Miner's damage value (D) and equivalent stress (σ_{eq}), which were expressed by the following equations, were used.[19]

$$D = \sum_{i=1}^{k} \left(n_i / N_i \right) \tag{1}$$

n : number of cycles of repetitive loading
N : life obtained from the S-N curve under constant stress amplitude
i : i-th stress, k : number of stress levels

$$\sigma_{eq} = \left(\sum_{i=1}^{k} n_i \cdot \sigma_i^{-m} \middle/ \sum_{i=1}^{k} n_i \right) \tag{2}$$

m : gradient of S-N curve under constant stress amplitude

Figure 6 shows the test results summarized in terms of equivalent stress. It was found from the test results that under a variable stress, the axle cracks with a smaller number of cycles of repetitive loading than the number under constant stress amplitude, and that the said tendency becomes more conspicuous with the decrease in equivalent stress. Assuming the variable stress conditions under which actual axles are put, the value of D at which the axle cracked in the test was calculated. As a result, it was found that $D = 0.02$. It is generally known that the phenomenon whereby the value of D decreases so sharply occurs when the frequency of stress variations under the fatigue limit is high. Therefore, it is necessary to pay attention to the fact that a similar phenomenon will occur in the fretting fatigue of press-fitted axles.

3.3 Evaluation of strength of bogie frame welded sections

In the one-side welding of a bogie frame, there is a possibility of occurrence of an unwelded root at the back of the one-sided weld. Since fatigue damage is likely to occur in such an unwelded root, it is necessary to evaluate unwelded roots (if any) and reflect them in the design and manufacturing of bogie frames properly. Therefore, T-shaped welded joints of the SM400 steel plate having four different root lengths were subjected to a tensile and bending fatigue test with two levels of load ratio. Then, the fatigue limits obtained by the
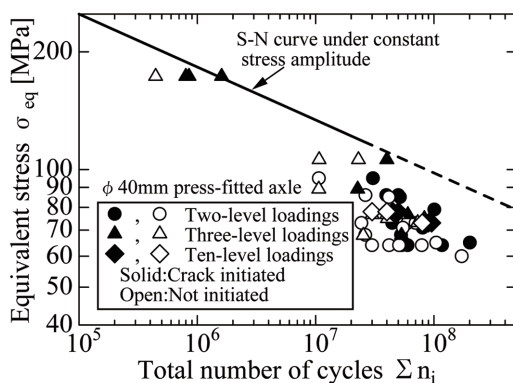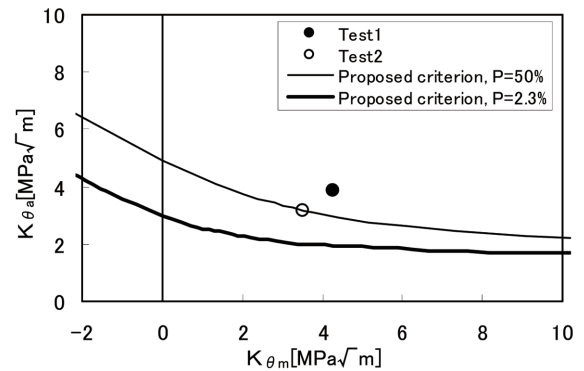

p. 7 Comparison of strength criterion to test results[20]

fatigue test were evaluated using the stress intensity factor (K_θ) in the direction of principal stress, which was obtained by an FEM analysis with each root modeled as a crack, and a strength criterion defined as the relation between K_θ mean and K_θ amplitude was derived.

Figure 7 compares the fatigue characteristic of a spring cap weld evaluated by a fatigue test using a bogie frame side beam that contained a spring cap weld with the strength criterion. The fatigue test results agree well with the strength criterion for the 50% fracture probability. Thus, the validity of the proposed strength criterion could be verified.[20] To permit the application of such an evaluation technique in practical design, FEM analysis methods in which the realistic scale of calculation and the required accuracy of calculation are compatible have been studied. These techniques won a Technical Award from the Society of Materials Science, Japan, in 2007.

4. Outlook for Future

It is expected that the demand for strength reliabilities of railway system components will become increasingly sophisticated in the future. For example, in North America and Australia, the use of heavier-duty freight railway systems will be further promoted to improve the efficiency of freight transportation, while the social demand for reduction of weights of railway systems as public transportation facilities will become strong in view of the aggravating energy problems. Without significant improvements in the strength reliabilities of railway system components, these objectives would be unattainable. Nippon Steel & Sumitomo Metal, which manufactures various railway system components, studies the fatigue characteristics of materials used for those components and develops new, high-performance materials. It also engages in extensive R&D on numerical structural analyses required for strength design, strength evaluation tests using actual components, and advanced strength design methods. The R&D activity in such diverse fields accounts for the company's competitive edge. It is important to not only develop technologies in each individual field but also maximize the synergy between technologies in different fields.

4.1 Synergy between rail and wheel

The latest technology pertaining to rails is the high-strength rail of the hypereutectoid pearlite structure. It is expected that the technology will be further developed in view of the ever-increasing demand for heavier-duty rails. Shelling, which is a type of damage associated with rail fatigue, occurs in wheels too. Since the mechanism of shelling has been clarified appreciably, as described in 3.1, it is to be desired that the knowledge thus obtained should be reflected on the development of new rail materials. On the other hand,

Fig. 6   Result of variable stress fatigue tests[19]

the direction of technology development for wheels is different from that for rails. For example, efforts have been made to add suitable alloying elements and optimize the heat treatment in order to come up with heavier-duty wheels. This is because the performance requirements of wheels differ from those of rails. For example, unlike rails, the wheels are thermally affected by the braking loads, and the entire wheel material requires strength design. However, since the wheels are always in contact with the rails, it is necessary to press ahead with R&D on them, including basic studies.

As mentioned at the beginning of this technical review, railway systems have a history of 190 years. They have become increasingly globalized, especially in the developing countries. The basic railway system that employs rails and wheels will not change drastically in the future. Therefore, new R&D themes on rails and wheels will come up one after another. From the standpoint of simultaneously optimizing both of them, it is considered possible to continue enjoying the synergy of R&D efforts in the fields of materials, evaluations, and designs.

4.2 Future direction of development of strength design methods

Nippon Steel & Sumitomo Metal implements the strength design of railway system components, such as wheels, axles, and bogie frames, by employing techniques based on the evaluation of fatigue limit. The existing design techniques pose no special problems. However, to meet the ever-growing demand for lighter system components, it is necessary to introduce a new viewpoint. Namely, to reduce the weight of any component while securing its strength reliability, the strength design needs to be more sophisticated. In the fatigue limit-based design of any component, the design stress is the maximum stress that is estimated to occur in the component while in use, and the material strength is the fatigue limit under constant stress amplitude. However, the stress that actually acts on the component is a variable stress, and the fatigue characteristic under a variable stress is different from that under a constant stress amplitude.

Therefore, the future direction toward the strength design method is to introduce the evaluation of fatigue characteristic taking the variable stress explained in 3.2 into account. To this end, it is indispensable to first clarify the appropriate pattern of the variable stress and to then understand the influence of this pattern on the fatigue characteristic. For the former purpose, several methods have been developed, including a technique to directly measure the stresses occurring in axles in use over a long period of time[21] and a technique to evaluate the dynamic stresses occurring in bogie frames by numerical analysis.[22] In the future, these methods should be refined, and a sufficient amount of data on variable stress patterns should be collected and accumulated. For the latter purpose, since the variable stress patterns to be studied are varied and the fatigue characteristic is a statistical variable that requires a probabilistic study, it is important to accumulate and review numerical data on fatigue damage taking the failure probability into account by a long-range, well-planned approach[23] in the future.

4.3 Collaboration with the customer

The strength reliability of railway system components is secured by the efforts of not only the manufacturers but also the users of these components. Namely, periodical maintenance implemented by individual customers is important because it permits the detection and repair of such defects in the form of broken or cracked components, which can lead to a major railway accident. So far, it seems that we, the manufacturers, have often paid excessive attention to maintenance results and focused on R&D aimed at solving problems

in detected defects. In the future, we should also pay attention to maintenance and consider implementing R&D on techniques to efficiently secure the strength reliability by integrating the processes of design, manufacturing, and maintenance.

One of the specific tasks to tackle is to optimize the period of maintenance. As described above, the conventional strength design is based on fatigue limit, leaving the concept of life out of consideration. Therefore, it does not provide any useful information as to an optimum maintenance period. On the other hand, the strength evaluation that takes the variable stress into consideration can help in optimizing the maintenance period, since the modified Miner's damage value (D) used in the evaluation is an index closely associated with life.

Another conceivable task is to tackle R&D to enhance the efficiency of maintenance work. At present, magnetic particle examination and ultrasonic examination are most commonly used. If a more accurate flaw detection technique is developed, it should become possible to monitor the progress of fatigue damage more precisely. Furthermore, if difficulty is involved in the inspection or repair of some component because of its construction, it might be advisable to review the maintainability of that component from the design stage or even propose a better maintenance method and procedure in the design stage. In any case, the R&D mentioned above requires a closer collaboration with the customer than in the past, and hence, it is necessary to identify and perform specific tasks that help meet the customer needs.

5. Conclusion

Considering rails, wheels, axles, and bogie frames as railway system components, this technical review has outlined the materials used for them, the fatigue-induced damage to them, and the strength design method applied to them. It has also presented recent examples of R&D on railway system components. In addition, the synergism of rails and wheels, the future direction to take for strength design, and the collaboration with the customer that are required from the standpoint of enhancing the strength reliability of railway system components in the future have been discussed. We wish to make the recent amalgamation of Nippon Steel Corporation and Sumitomo Metal Industries a good opportunity for us to take a great stride forward in the field of railway systems.

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Miyuki YAMAMOTO
Fellow, Dr.Eng.
Technical Research & Development Bureau
1-8 Fuso-cho, Amagasaki, Hyogo 660-0891