

Quality and Fatigue Strength Evaluation of Wheels for Railway Vehicles

Yoshinari YAMAMURA* Keiichi YOMODA
Chihiro KOZUKA Taizo MAKINO
Takanori KATO

Abstract

Railway wheels are one of the most important components of a rolling stock. Quality and design of wheels are required to ensure safety of the rolling stock since wheel damage will lead to serious accidents. Nippon Steel Corporation applies its own requisites in conjunction with JIS E 5402-1 in order to control wheel quality. In terms of fatigue design of the wheel web, Nippon Steel applies the loads to the wheel rim from the rail specified in JRIS J 0405. In addition, thermal stresses due to tread braking which affect the fatigue strength are also considered. In this report, our approaches to safety of the wheels with respect to quality and design are described.

1. Introduction

Railway wheels play an important role as undercarriage components. They are regarded as the most important components because damage on wheels may cause the rolling stock to derail, resulting in serious accidents. Wheels are engaged with an axle and used as a wheelset. A wheel consists of a rim, which will come into contact with a rail; a hub, which will be engaged with an axle; and a web, which connects the rim and hub (refer to **Figs. 1 and 2**). Rims support the weight of rolling stock and roll on rails as one role. They are also used as brake drums by pressing the brake shoes to the wheel treads for braking. Accordingly, they must have rolling fatigue resistance, wear resistance, and thermal crack resistance as their characteristics. In addition, hubs, which are coupled with axles, must have rigidity to secure holding strength. At the web, stress occurs due to reaction force from a rail per rotation of the wheel (mechanical stress) and thermal stress originating in brake heat occurs. Accordingly, the webs must have strength to endure such stress.

To ensure the safety of wheels, reliability from the viewpoints of product quality and design is required. With regard to quality, Nippon Steel Corporation determined its original quality management items and specifications so as to supplement JIS E 5402-1¹⁾ and has been working to improve product strength and production management.

There was a movement in Japan to standardize the quality of wheels that had actually been used in Japan and as a result, new

wheel quality standards were established after deliberation by the Japan Association of Rolling Stock Industries.²⁾

As regulations for evaluating the strength of wheel webs in designing, JRIS J 0405³⁾ includes regulations for mechanical stress. Nippon Steel evaluates the strength also considering thermal stress from brake heat so as to design wheels with higher safety. In addi-

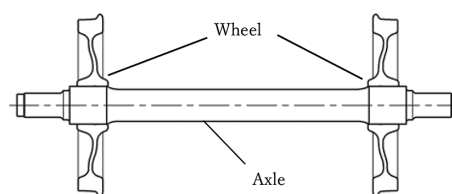


Fig. 1 Wheel and axle

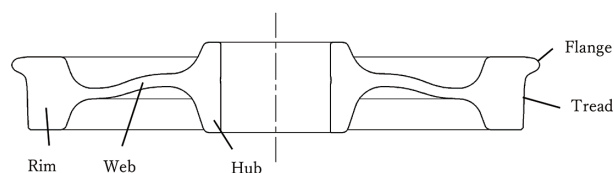


Fig. 2 Names of each part of the wheel

* Railway Wheel & Axle Design & Development Section, Railway Wheel & Axle Designing Dept., Railway Wheel, Axle & Bogie Div., Kansai Works 5-1-109 Shimaya, Konohana-ku, Osaka City, Osaka Pref. 554-0024

tion, to make strength evaluations more accurate, we performed fatigue testing to understand fatigue strength at wheel webs when mechanical stress and thermal stress worked simultaneously, which has made it possible to determine more appropriate allowable stress. Furthermore, in order to evaluate stress working on wheels more precisely, we have made it possible to analyze elastic-plastic stress in practical time, in place of conventional elastic stress analysis. This was enabled thanks to the advancement of analysis techniques in recent years.

2. Wheel Quality Management

As standards for the quality of wheels to be used for conventional line rolling stock in Japan, JIS E 5402-1 “Rolling stock-Solid wheel-Part 1: Quality requirements” (hereinafter, “JIS E 5402-1”) is available. In addition to the quality management items in the standards, Nippon Steel uses its own quality management items in manufacturing. In 2022, JRIS D 1202 “Rolling stock-Solid rolled wheels-Quality requirements” (hereinafter, “JRIS D 1202”) that additionally includes such original quality management items of Nippon Steel was established as the standards to supplement JIS E 5402-1.

When railway companies adopt new wheels (wheels manufactured by new manufacturers and/or wheels manufactured with a new manufacturing method based on a new condition or newly designed wheels), they need to refer to both JIS E 5402-1 and JRIS D 1202 in order to retain the same quality as wheels that have actually been used in Japan.

2.1 Main characteristics of Nippon Steel’s wheel quality management

- (1) As wheel materials, continuously cast materials produced at Kansai Works Wakayama Area are used. Such materials have the excellent characteristics listed below.
 - A. Regarding the hydrogen content, which affects the brittleness of materials, we sample test specimens in the melting process at appropriate sampling timing and use appropriate analysis equipment in such a way that the measurement accuracy becomes the highest. This enables us to understand the residual hydrogen content accurately, which works well to suppress hydrogen embrittlement.
 - B. The content of Cu components, which affect hot forging performance, is low.
 - C. The quantity of nonmetallic inclusions, which may cause wheels to break, is small.
- (2) In wheel production, we periodically check quality even though this is not a prerequisite of JIS E 5402-1. We extract wheels five times per year for each steel type to check for variations due to changes in the quality management items over the years.

2.2 New quality management items determined since JIS E 5402-1

Table 1 lists the new quality management items that are included in JRIS D 1202 but not included in JIS E 5402-1. They were additionally determined by drawing on the characteristics of the wheel quality management at Nippon Steel.

While JIS E 5402-1 instructs that only shipping inspections be performed, JRIS D 1202 instructs that type inspections be performed to check the quality of new wheels and perform periodic inspections, which Nippon Steel conducts on a regular basis, to check

Table 1 Additional quality requirement for JRIS D 1202 in contact with JIS E 5402-1

	Quality requirement	Type test	Regular intervals test
1	Chemical composition (Check analysis)	○	○
2	Hydrogen content	○	○
3	Mechanical properties (After heat treatment)	○	○
4	Impact resistance characteristics	○	○
5	Hardness in the rim	○	○
6	Material cleanliness	○	○
7	Fracture toughness	○	○
8	Residual stresses	○	○
9	Hardness variation of rim divided into 8 circumferential sections	△	—
10	Fatigue strength of wheel web of wheel plate	○	—
11	Wear test	△	—
12	Circumferential residual stresses after tread-braking test	○	—
13	On-track test	△	—

○: Necessity

△: According to situation (Wheel corrugation, abnormal wearing, etc.)

whether the quality is maintained.

Type inspections are performed to determine whether the new wheels’ properties are within the specification ranges of the quality management items.

In periodic inspections, wheels are sampled five times per year for each steel type (SSW-QS and SSW-QR) to determine whether their specification values are within the specification ranges of the quality management items.

3. Method to Evaluate the Strength of Wheel Webs

For most of the wheels that are used on conventional trains in Japan, a braking method in which the brake shoes are pressed to the treads where the wheels are in contact with rails is used to reduce the speed. In this braking method, the temperature of the wheels increases due to frictional heat from braking, generating thermal stress. The mechanical stress due to reaction force from rails is high-cycle stress for which the stress intensity periodically changes as the wheels rotate. Meanwhile, thermal stress does not change much in one rotation of a wheel and thereby it is almost constant. Accordingly, thermal stress works as mean stress and does not work as fluctuating stress. However, the thermal stress is larger compared with mechanical stress (refer to Figs. 3 and 4). Its superposition on mechanical stress greatly affects the fatigue strength of the wheel web. Therefore, thermal stress may need to be taken into account in fatigue strength designing.

As standards for evaluating the strength of wheel webs, JRIS J 0405 is provided. However, JRIS J 0405 only describes evaluations based on mechanical stress and does not mention thermal stress due to braking. With regard to overseas standards, the European Norm (EN) 13979-1⁴⁾ and International Union of Railways (UIC) 510-5⁵⁾ do not include evaluations of thermal stress occurring at webs. The

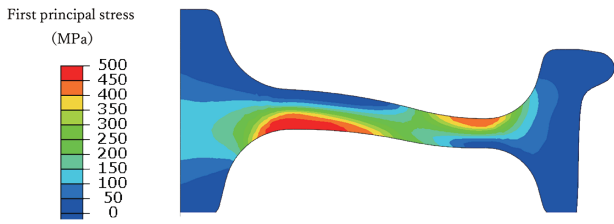


Fig. 3 Thermal stress distribution obtained by FE analysis

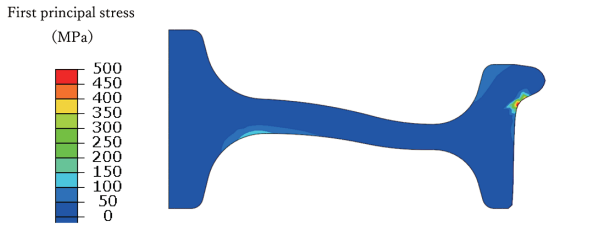


Fig. 4 Mechanical stress distribution obtained by FE analysis

Association of American Railroads (AAR) S-660⁶⁾ provides standards for evaluating thermal stress on webs through elastic stress analysis but does not include fatigue strength evaluations. Nippon Steel has been analyzing thermal stress on webs through elastic stress analysis for many years and, as described above, we have been regarding it as mean stress in fatigue strength designing. Using this strength evaluation technique, we developed new A-type corrugated wheels as brake heat-resistant wheels,⁷⁾ and the use of the product began in 1994 in Japan and overseas. The recent advancement of finite element analysis techniques has made it possible to use general programs for elastic-plastic stress analysis. This encouraged Europe to start utilizing elastic-plastic stress analysis to evaluate residual stress on wheel rims that occurs as a result of braking. Consequently, to make more logical fatigue strength evaluations in line with the current techniques' levels, we started utilizing elastic-plastic stress analysis to calculate the thermal stress on wheel webs and using the obtained results to evaluate the fatigue strength. This paper reports the evaluation technique. In addition, an allowable stress diagram is required to evaluate fatigue strength. However, the allowable stress diagram included in current JRIS J 0405 lacks data on the high-stress ratio, which is required when thermal stress is considered. Therefore, we performed additional fatigue testing and proposed a new allowable stress diagram that was created based on the results.⁸⁾ The details will be reported in another report entitled the "Railway Wheel Web Allowable Stress Diagram."

4. Wheel Web Strength Evaluation Technique Considering Thermal Stress Due to Braking

Figure 5 shows the flowchart for calculating the fatigue safety factor of a wheel to be evaluated.

(1) Analysis model creation

To eliminate differences in the calculation results originating in analysis models, the strength evaluation areas, element types, meshing method (including element sizes), and boundary conditions were determined in detail (refer to Fig. 6).

(2) Analysis of wheel temperature after wheel tread braking

With regard to temperature analysis targeting brake heat, conditions are determined based on results of investigations of the temperature on the sides of the wheel rims of currently-used rolling

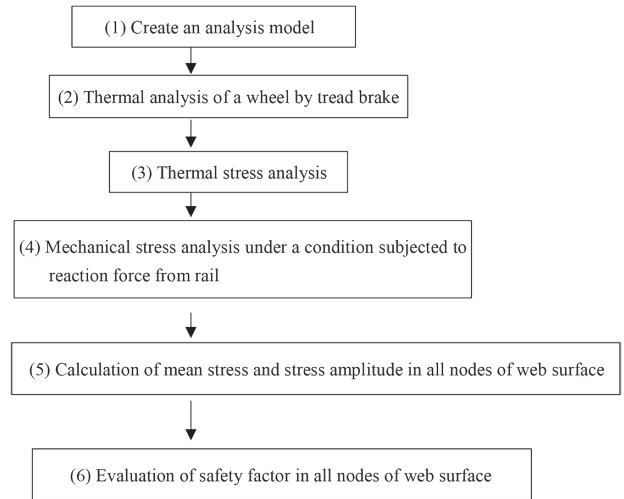


Fig. 5 Evaluation flowchart of fatigue strength of wheel web

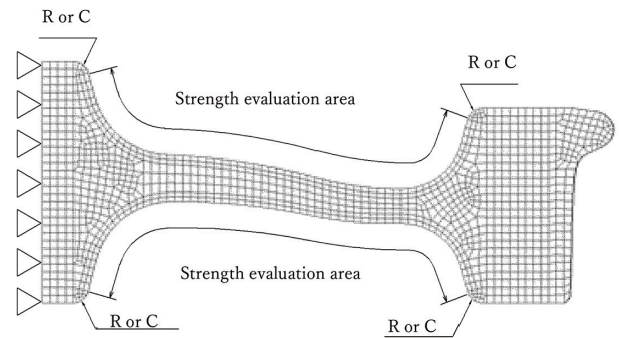


Fig. 6 Strength evaluation area, meshing and boundary condition

Table 2 Conditions for heat transfer analysis

	Heat quantity per second (kJ/s)	Period of heat (s)
Braking frequency is high	19.6	1 200
Other than above	11.9	

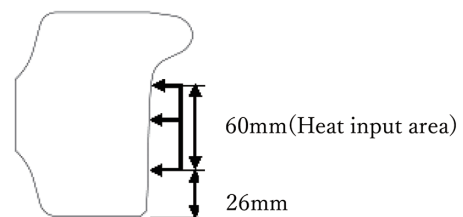


Fig. 7 Heat input area in heat transfer analysis

stock measured with thermo labels. Temperature analysis conditions are determined for two cases: One in which braking is frequently applied and the temperature of the wheel rims is high and another case for the other travel conditions. Specifically, conditions are determined such that the temperature 10 mm below the tread of a new wheel will become 230°C or 150°C. Table 2 and Fig. 7 show the analysis conditions. Before determining these conditions, a braking bench test was performed to confirm that the temperature of the side

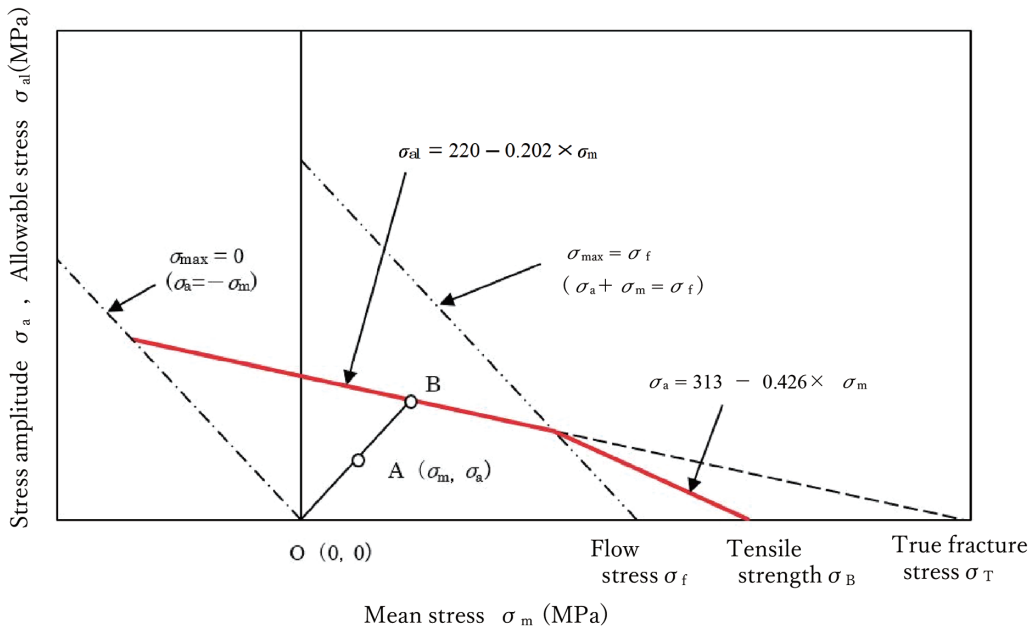


Fig. 9 Allowable stress diagram

References

- 1) Japanese Standards Association: JIS E 5402-1 (Rolling stock-Solid wheel-Part 1: Quality requirements), 2015
- 2) The Japan Association of Rolling Stock Industries: JRIS D 1202 (Rolling stock-Solid forged and/or rolled wheel-Quality requirements), 2022
- 3) The Japan Association of Rolling Stock Industries: JRIS J 0405 (Rolling stock-Verification of the fatigue strength of the solid wheel web), 2014
- 4) BS EN: 13979-1 (Railway applications. Wheelsets and bogies. Monobloc Wheels. Technical approval procedure - Forged and rolled wheels), 2003
- 5) UIC: 510-5 (Technical approval of monobloc wheels - Application document for standard EN 13979-1), 2003
- 6) AAR: S-660 (Wheel Designs, Locomotive and Freight Car - Analytic Evaluation), 2007
- 7) Yamamura, Nakata, Anjiki: Development of Brakeheat-proof Corrugated Wheel, Sumitomo Metal Industries, Ltd. 46 (4), (1994)
- 8) Kato, T. et al.: Transactions of the JSME (in Japanese). 87 (895), 20 (2021)
- 9) The Japan Association of Rolling Stock Industries: JRIS J 0405 (Rolling stock-Verification of the fatigue strength of the solid wheel web), Fig. 2 (written in English), 2014



Yoshinari YAMAMURA
 Railway Wheel & Axle Design & Development Section
 Railway Wheel & Axle Designing Dept.
 Railway Wheel, Axle & Bogie Div., Kansai Works
 5-1-109 Shimaya, Konohana-ku, Osaka City, Osaka Pref.
 554-0024



Taizo MAKINO
 Dr. Eng., Leading Researcher
 Steel Research Laboratories



Keiichi YOMODA
 Quality Management Div.
 Kansai Works



Takanori KATO
 Dr. Eng., Chief Manager, Head of Dept.
 Railway, Automotive & Machinery Parts Research Dept.
 Kansai R & D Lab.



Chihiro KOZUKA
 Senior Manager
 Railway Wheel & Axle Quality Design Section
 Railway Wheel, Axle & Bogie Quality Control Dept.
 Quality Management Div.
 Kansai Works