Fatigue Property and Design Criterion of Cast Steel for Railway Bogie Frames*1

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The fatigue design criterion for members of cast steel is not specified in the design standard of railway bogie frames in Japan. The objectives of the present study involve clarifying the fatigue property of cast steel used in railway bogie frames and proposing a fatigue design criterion for members of cast steel. Fatigue tests are conducted on test specimens with casting or machined surfaces under axial loading or plane bending. The results indicate that the fatigue strength of specimens with casting surfaces exceeds that of specimens with machined surfaces. The fatigue strength under plane bending significantly exceeds that under axial loading. The results are attributed to differences in the locations and geometries of cast defects where cracks originate. A fatigue design criterion for members of cast steel is proposed by the statistical evaluation of fatigue data. Furthermore, the validity of the proposed criterion is demonstrated via a full-scale fatigue test of bogie frames with members of cast steel. [doi:10.2320/matertrans.Z-M2019814]

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1. Introduction

Railway bogie frames are welded structures that use steel plates and members of cast steel. The use of cast steel is reasonable because it simultaneously enables material creation and shape formation. Cast steel is superior to cast iron in terms of ductility and weldability. This is the reason why cast steel is commonly applied in railway bogie frames. Figure 1 illustrates an application of cast steel members in railway bogie frame. As shown in the figure, cast steel members are employed as several main parts in a bogie frame. However, cast defects are inevitable in cast steel and affect fatigue strength. Casting surfaces also remain on cast steel members; therefore, the effect of surface quality is not negligible. It is necessary to consider the aforementioned properties of cast steel in fatigue design.

In JIS E4207,1,3 allowable stresses for the fatigue design of bogie frames are specified for the base material of the steel plate and welded part. On the base material of cast steel, the allowable stress is not specified as yet although several values are described in comments.1) Okino et al.2) proposed the allowable stress as 80% of the fatigue limit obtained from the fatigue test of specimens cut from cast steel members of actual bogie frames. However, the effect of cast defects, surface qualities, or probability of failure was not discussed.

The authors proposed the modification of the stress evaluation method in as-welded parts3) and the application of the fracture mechanics parameter to fatigue design by considering weld roots.4–6) However, the authors did not examine cast steel as yet.

The fatigue properties of cast steel have been evaluated by several researchers and are known to be sensitive to cast defects and surface qualities as previously mentioned in Ref. 7–14). Conversely, there is a paucity of data on the fatigue property of cast steel for bogie frames. The aforementioned influencing parameters are possibly different based on manufacturers. Hence, it is crucial to evaluate cast steel in more detail given that it is manufactured under conditions resembling that of actual bogie frames.

The objectives of the present study involve clarifying the fatigue property of cast steel used in railway bogie frames and to propose a fatigue design criterion for members of cast steel. Fatigue tests are conducted on test specimens with casting or machined surfaces under axial loading or plane bending. The results are attributed to differences in locations and geometries of cast defects where cracks originate. A fatigue design criterion for members of cast steel is proposed by the statistical evaluation of fatigue data. Moreover, the validity of the proposed criterion is demonstrated by a full-scale fatigue test of bogie frames with members of cast steel.

2. Specimens and Experimental Procedure

2.1 Tested material

The tested material was carbon steel cast as SC450. Table 1 shows its chemical compositions. The material was shaped by means of sand mold casting. Subsequently, it was heat-treated at 920°C for 30 min and then air-cooled. The aforementioned cast and heat treatment conditions were identical to those commonly employed for cast steel members.
of a bogie frame. With respect to the safety-oriented evaluation, cast defects and surface qualities in the non-critical region were duplicated as class 2 of JIS G 0581 and class 2 of JIS G 0588, respectively, in the material. Table 2 provides the mechanical properties and hardness of the material after heat treatment. The ultimate tensile strength was 573 MPa, which exceeded the lower limit of JIS of SC450. Figure 2 shows the optical view of the microstructure of the material after heat treatment. A ferrite-perlite structure was observed in the material.

2.2 Specimens

Figure 3 illustrates the configuration of the test specimen. Specimens exhibited a central straight region with a square cross section of 16.5 mm × 10 mm, a length of 96 mm, and a round corner with a radius of 1 mm. The specimens were classified into three types (i.e., AC, CM, and AM) by the surface condition of their central straight region as summarized in Table 3 and Fig. 4. Specifically, AC exhibited casting surfaces on all four surfaces. Additionally, CM exhibited a casting surface on the front and back surfaces and machined surfaces on both side surfaces. Finally, AM exhibited machined surfaces on all four surfaces. Furthermore, AC and CM were cast into the raw material of the specimens as described in the previous section. The AM was cut from cross beams of the actual bogie frame, and exhibited almost the same chemical compositions and hardness as those of other specimen classes. In order to avoid the bending of specimens while mounting on the fatigue testing machine, the grip parts of the specimen were fully machined such that the centerlines of the grip parts were identical to that of the central straight part. The surface roughness of the casting surface of specimens was in the range of 7–10 µm of $R_a$ and 30–60 µm of $R_z$.

2.3 Experimental procedure

Fatigue tests were conducted by axial loading for all specimen classes and plane bending for only CM. In the axial loading fatigue tests, strain gauges were attached to all four surfaces on the central straight part of specimen. Subsequently, the specimen was mounted on the fatigue testing machine while adjusting its alignment by strain monitoring. In the plane bending fatigue tests, an identically shaped specimen was mounted on the fatigue testing machine such that the distance between two pins on the support side was 80 mm in the three point bending test, as shown in Fig. 5. The fatigue testing machines used in this study were electro-hydraulic servo controlled fatigue testing machines.
The stress ratios were 0.05 and 0.5 for the axial loading fatigue test and 0.05 for the plane bending fatigue test. The number of cycles for test termination was $1 \times 10^7$. The test frequency was in the range of 5–10 Hz. The test environment was room temperature and ambient air.

3. Experimental Result

Figure 6 shows the $S$-$N$ diagrams obtained from the axial loading fatigue tests. CM exhibits a lower fatigue strength than AC, with both stress ratios ($R_S$) as shown in Figs. 6(a) and (b). AM was tested only with the stress ratio of 0.05 and exhibited almost the same fatigue strength as CM.

Figure 7 shows the outer views of the fracture surface after axial loading fatigue tests. As observed in the images in the figure, most specimens exhibit fatigue fracture originating from cast defects. The origin (i.e., the cast defect located in the internal region in all AC) is adjacent to the machined surface in most AM and CM specimens. The aforementioned difference in the fatigue strength between specimen classes is potentially due to the size and/or location of defects corresponding to the origin. We will discuss the precise reason in next section.

Figure 8 compares the $S$-$N$ diagrams by different loading types. Figure 9 shows an outer view of the fracture surface after the plane bending fatigue test. As shown in Fig. 8, the plane bending fatigue test yields a significantly higher fatigue strength when compared with the axial loading fatigue test. As shown in the photo in Fig. 9, almost all specimens exhibit fatigue fracture originating from the casting surface of the tension side. The result suggests that the plane bending fatigue strength is seldom affected by the cast defects. This suggestion is supported by two facts. The first fact is that layers below the casting surface cool faster than internal regions in the casting process, and the high cooling rate in
solidification interferes with the generation of cast defects. The other fact is that the stress induced in the internal regions is lower than that on the casting surface of the tension side. Ohshima et al. and Hayashi et al. reported that the internal region exhibits a higher defect ratio and larger defect size than those in the region adjacent to the casting surface. This tendency corresponds to that in the present study.

4. Discussion of the Differences in Fatigue Strength among Specimen Classes

4.1 Effect of the defect size of the fatigue origin

Areas of the defect corresponding to the fatigue origin were measured from photos of the fracture surface via image processing, and the square roots of area were referred to as $\sqrt{\text{area}}$. The $\sqrt{\text{area}}$ was 2507–3912 μm in AC, 1406–5285 μm in CM, and 1733–4153 μm in AM. The data were processed by statistics of extreme value based on a Gumbel-type distribution, and Fig. 10 was obtained. As shown in the figure, the slopes of distribution of the extreme values of CM and AM with partially or fully machined surfaces are gentler than those of AC with fully casting surfaces. This tendency was caused by relatively small defects that were partially removed from the original defects by machining; this corresponded to the origin in fatigue in CM and AM. AM was distributed on the left-hand side of CM. This implied that the defect sizes of AM were generally smaller than those of CM. This was potentially due to the difference between the actual member and raw material cast for the specimen. In CM, comparatively large defects plotted in the right-upper area of the figure were inspected as the fatigue origin.

In Fig. 6, marks denoted “x” are present near plots of $\sqrt{\text{area}}$ exceeding 4000 μm, which exceeds the maximum defect size of AC. The noted plots that were fractured from these types of large defects exhibited low stress and short life in the S-N diagram in Fig. 6. However, if the noted plots were eliminated, the tendency described in previous section was recognized wherein CM and AM exhibited lower fatigue strength when compared with that of AC. Therefore, the difference in fatigue strength among specimen classes cannot be explained by only the difference in defect size.

4.2 Evaluation by fracture mechanics approach and the effect of the surface condition on fatigue strength

As described in the previous section, internal defects corresponded to the fatigue origin in AC with fully casting surfaces while defects adjacent to the machined surface corresponded to the origin in AM and CM with fully/partially machined surfaces. Given defects equal to cracks in terms of fracture mechanics, we estimated that the stress intensity factor (SIF) of the surface crack exceeded that of the internal crack by approximately 30% even if the both cracks exhibited the same area. This estimation potentially led to the difference in fatigue strength between specimen classes.

In order to validate the above possibility, we evaluated the fatigue test results by equally treating casting defects of the origin in fatigue tests as cracks in terms of fracture mechanics. Firstly, we calculate the SIFs by substituting $\sqrt{\text{area}}$ of defects of fatigue origin obtained in section 4.1 in following equation (eq. (1)) to estimate the SIF subjected to defects as follows:

$$\Delta K = F\Delta \sigma^* \sqrt{\pi \cdot \text{area}}$$

Here, $\Delta K$ and $F$ denote the range of SIF and a constant based on defect type, respectively; and $\Delta \sigma^*$ corresponds to 0.65 for surface defects and 0.50 for internal defects, respectively. Specifically, $\Delta \sigma^*$ denotes the nominal stress range on the cross section where the defect is located based on Murakami. However, the ratio of the defect on cross section of specimen in the study exceeded Murakami’s assumption, and thus we defined $\Delta \sigma^*$ as the stress range on the ligament section area, i.e., the area of cross section without the defect of origin. Specifically, $\Delta \sigma^*$ was calculated...
by correcting the multiplication of the stress based on specimen classes and a coefficient. The stress corresponded to the nominal stress in AC where defects of the origin were located in the internal region or the measured stress by the strain gauge attached on the surface where defects of the origin were locate in CM and AM. The coefficient corresponded to division of the cross section area by the ligament area. The validity of the correction was preliminarily verified by the result wherein the SIFs of a semi-elliptical crack in a finite thickness model proposed by Newman-Raju equation\textsuperscript{19} and by eq. (1) agreed with each other.

Figure 11 demonstrates the relationships between the SIF range $\Delta K$ and number of cycles to failure. The $\Delta K$ values of run-out plots with an arrow in the figure were calculated by using the defect sizes of the origin on fracture surface obtained by retests under a higher stress. As shown in Fig. 11, the evaluation by $\Delta K$ reduced both deviations in each specimen classes and between specimen classes with different surface conditions as shown in Fig. 6. The former deviation was generated by the difference in the defect size of the origin in each specimen while the latter deviation was potentially generated by $F$ in eq. (1), namely the difference in the $\Delta K$ between the surface cracks and internal cracks. Therefore, the difference in fatigue strength in the specimen classes resulted from the phenomenon wherein the location of the defect of origin was divided into the internal region and surface region related to surface qualities.

The authors proposed the endurance limit line and allowable value for the fatigue design of welded joints for railway bogie frames by considering weld roots\textsuperscript{4-6} This is specified in following equations and expressed as a function of SIF under the assumption that weld roots are equivalent to cracks:

\[ \Delta K_{th, P=50\%} = 6.52 - 3.30R \]  \hspace{1cm} (2)

\[ \Delta K_{th, P=2.3\%} = 4.45 - 1.48R \]  \hspace{1cm} (3)

Here, $\Delta K_{th}$ denotes the fatigue limit described by the range of SIF, $R$ is the stress ratio, and the suffix $P$ denotes the probability of failure. Figure 12 presents the relationship between mean value and amplitude of SIF. Experimental results in the study are plotted, and $\Delta K_{th}$ for weld root ($P = 50\%$, eq. (2)) and the allowable SIF for weld root ($P = 2.3\%$, eq. (3)) are also shown in the figure. As shown in the figure, the border between broken (solid) and run-out (open) plots of the study is higher than the line of $\Delta K_{th}$ for the weld root ($P = 50\%$, eq. (2)). Incidentally, Hayashi\textsuperscript{12} conducted a fatigue test of SC49 that is similar to the tested material in the study and indicated the maximum SIF at $R = -1$ of 4.9 MPa/\sqrt{m}. This is the value that is plotted on the vertical axis of Fig. 12 while it is in agreement with the line for $P = 50\%$ in eq. (2).

The above discussion suggests that eq. (2) and eq. (3) enable the evaluation and fatigue design of cast steel members in the case in which the size and the location of defects correspond to fatigue origin. In the future, if the size and the location of defects can be controlled or precisely estimated, then the aforementioned type of fracture mechanics approach is feasible. However, the approach is not yet applicable due to the aforementioned issue. Therefore, we discuss the fatigue design criterion based on the experimental results of the study by assuming the existing stress based fatigue design in the following chapter.

5. Proposal of Fatigue Design Criterion for Cast Steel Members

In this chapter, we derive the allowable stress as a fatigue design criterion for cast steel members via a statistical
evaluation of experimental data in the study. Subsequently, the following points are considered:

1. Cast steel members are essentially applied to bogie frames with a casting surface. Hence, experimental data on AC specimens fully covered with casting surfaces are employed in which internal defects correspond to fatigue origins. The data are obtained by axial loading fatigue tests. This implies a conservative evaluation in terms of the loading type and stress gradient.

2. Kinks of $S$-$N$ curve are not considered because fatigue origins correspond to internal defects. Fatigue limits are determined as the strength at $N = 1 \times 10^7$.

3. The allowable stress is derived based on the probability of failure of 2.3% as well as the fatigue design standard specified by the Japan Society of Steel Construction (JSSC), International Institute of Welding (IIW), and the authors for welded parts in bogie frames.

4. Variation in fatigue strength is assumed as expressed via a log-normal distribution.

5. A larger variation coefficient of the $P$-$S$-$N$ property under two stress ratios is applied to estimate the $P$-$S$-$N$ property under another stress ratio to ensure a conservative evaluation.

Figure 13 presents the $P$-$S$-$N$ diagrams based on fatigue failure data originating from the internal defects of AC specimens by an axial loading fatigue test. The diagrams are drawn based on JSMS standard. Variable coefficients in the diagrams correspond to 0.80% and 1.44% at stress ratios of 0.05 and 0.5, respectively. Subsequently, the variation coefficient is defined as the ratio of standard deviation (logarithmic value) to the fatigue limit (strength at $N = 1 \times 10^7$, logarithmic value) at a failure probability of 50% in the $S$-$N$ curve approximated to a power equation (i.e., a linear relation on the double logarithmic chart). A higher variation coefficient of 1.44% is applied to all the data including those under another stress ratio to ensure a conservative evaluation. Thus, fatigue limits are obtained at a failure probability of 2.3%.

In Fig. 14, fatigue limits at the 2.3% failure probability are plotted via the stress amplitude and mean stress separately converted from the stress range values in the fatigue limit diagram. The linear approximation based on the plots and lower limits of specification at a tensile strength of 450 MPa leads to the endurance limit line of the fatigue limit corresponding to 98 MPa at a stress amplitude at the mean stress of zero, i.e., the fully reversed condition in the figure as given by the following equation:

$$\sigma_{w,\text{al}} = -\frac{98}{450} \sigma_m + 98 \quad (4)$$

Here, $\sigma_{w,\text{al}}$ denotes the allowable stress amplitude [MPa], and $\sigma_m$ denotes the mean stress [MPa]. We propose the above equation as the allowable stress of the fatigue design of cast steel members in railway bogie tracks. The applicable range of the allowable stress is limited to cast steel members manufactured in accordance with a specification and casting plan enabling a greater or equal grade when compared with that of the tested material in the study. The cast steel members are assumed to be used with residual casting surfaces. Despite the assumption, if these are used with machined surfaces, attention should focus on the safety factor or modification of allowable stress.

The authors estimated the endurance limit line based on fatigue failure data originating from casting surfaces via a plane bending fatigue test in the same way as the axial loading. The obtained $P$-$S$-$N$ diagram is shown in Fig. 15. It should be noted that the kink of $S$-$N$ curve was considered...
because the casting surfaces correspond to the fatigue origin under plane bending in a manner different from that under the axial loading. The fatigue limit and variable coefficient are derived from the figure and plotted in the fatigue limit diagram. The fatigue limit under the fully reversed loading at a failure probability of 2.3% is obtained as 254 MPa from the diagram. This is 2.6 times the allowable stress of 98 MPa under the fully reversed loading as determined in eq. (4) by assuming that internal defects can correspond to the fatigue origin.

Allowable stress considering the effect of stress gradient corresponding to loading types, defect size, and its location is required as determined in the future. As described in the previous chapter, the fatigue strength can be evaluated by the stress intensity factor, and this implies the applicability of the allowable value for design as represented by the stress intensity factor based on fracture mechanics. Furthermore, the fact that defects can correspond to the fatigue origin suggests that defect sizes corresponding to the origin vary based on the number of products and their danger volumes. This should be discussed in detail with additional experimental data in a future task.

6. Validation of the Proposed Fatigue Design Criterion by Full-Scale Fatigue Tests

We proposed the allowable stress as the fatigue design criterion for cast steel members of a railway bogie track based on the fatigue test result of specimens in the previous chapter. The fatigue design criterion should be validated by the evaluation of full-scale members. In this chapter, two types of full-scale members, namely the motor bracket and cross beam were fatigue tested.

6.1 Tested full-scale members and fatigue test method for the members

Tested members for full-scale fatigue test and loading types are schematically illustrated in Fig. 16. The motor bracket shown in Fig. 16(a) corresponds to the welded structure of a cross beam with angular pipe shape and a bracket of cast steel. Both ends of the cross beam were fixed. A loading jig corresponding to a motor was attached to the bracket. A nearly fully reversed loading was subjected to the center of gravity of the motor in the jig. Tests were terminated when the number of cycles corresponded to $2 \times 10^6$.

The cross beam shown in Fig. 16(b) was manufactured as a member that was entirely composed of cast steel. Both ends of the cross beam were fixed. Cyclic three point bending ($R = 0.05$) was subjected to a point on the upper side immediately above a through hole distant from the center between two fixed points. Tests were terminated when the number of cycles corresponded to $1 \times 10^7$.

6.2 Cracking state in the full-scale fatigue test

Figure 17 demonstrates the crack initiation region and fracture surface view in full-scale fatigue test. In the test of the motor bracket, cracks were initiated at the fillet part on the bottom side of the brackets as shown in Fig. 17(a). The origin of the cracks corresponds to the casting surface. Cast defects were not observed at the origin.

In the test of the cross beam, cracks were initiated at the surface edge of through holes as shown in Fig. 17(b). Cast defects were not observed at the origin.

6.3 Comparison between the results of the full-scale fatigue test and proposed fatigue design criterion

In full-scale fatigue tests, stresses were measured by a strain gauge attached on the surface of crack origin. Stresses are plotted on fatigue limit diagram in Fig. 18. The allowable stress from eq. (4) proposed in the previous chapter was drawn as a solid line for comparison purposes. In the figure, cracking plots are located at a higher stress region than the proposed allowable stress. This was attributed to the fact that
comparatively large cast defects were less likely to correspond to the crack origin in full-scale fatigue tests than in the axial loading fatigue test because stress gradients in the tested full-scale members were potentially at a medium level (between those of specimens with plane bending and axial loading). Incidentally, the endurance limit line determined from full-scale fatigue tests was also denoted as a broken line in the figure. The fatigue limit under a fully reversed loading was obtained as 146 MPa from the endurance limit line, and this was 1.5 times the allowable stress of 98 MPa. It was clear that the proposed fatigue design criterion provided a conservative estimation, and this indicated the validity of application to the fatigue design of cast steel members in railway bogie frames.

7. Conclusion

In order to propose a fatigue design criterion for members of cast steel, fatigue tests were conducted on test specimens with casting or machined surfaces under axial loading or plane bending. We considered the allowable stress for fatigue design in terms of statistical fatigue property and effect of loading types. The following results were obtained:

(1) With respect to the result of axial loading fatigue test, specimens with fully casting surfaces exhibited higher fatigue strength when compared with those of specimens with fully/partially machined surfaces. The reason for the result can be attributed to the location of cast defects corresponding to the fatigue origin based on fracture mechanics.

(2) Fatigue strength under plane bending significantly exceeded that under axial loading as described in (1). The result was attributed to the following reason: specimens with plane bending exhibited fatigue fracture originating from the casting surface of the tension side. This implies that plane bending fatigue strength was seldom affected by cast defects.

(3) Fatigue limits at 2.3% failure probability were obtained from the statistical evaluation of fatigue data with origins corresponding to the internal defects of specimens with fully casting surfaces. The linear approximation based on the plots and lower limits of specification for a tensile strength of 450 MPa leads to an endurance limit line of the fatigue limit corresponding to a stress amplitude of 98 MPa at a mean stress of zero. We proposed a fatigue design criterion with the endurance limit line corresponding to the allowable stress.

(4) Full-scale fatigue tests of motor bracket and cross beam for a railway bogie frame were conducted. Fatigue limits of both members exceeded the proposed allowable stress. Therefore, the proposed fatigue design criterion validated the fatigue design applicability of the railway bogie frame.

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Appendix

The authors supplemented the adoption of the fatigue limit (strength at $N = 1 \times 10^7$) at 2.3% failure probability for the allowable stress. Specifically, JIS E4207 indicated that the allowable stress for welded parts is close to the value of 2.3% failure probability for strength at $N = 2 \times 10^6$. We applied it to the S-N data for cast steel in Fig. 13. Strengths at $N = 2 \times 10^6$ corresponded to 219 MPa and 155 MPa for stress ratios ($R$) of 0.05 and 0.5, respectively. The values of 0.1% failure probability above strengths were 186 MPa and 122 MPa for stress ratios ($R$) of 0.05 and 0.5, respectively. The aforementioned values exceeded the strengths at $N = 1 \times 10^7$ at 2.3% failure probability of 164 MPa ($R = 0.05$) and 115 MPa ($R = 0.5$) that were adopted for the allowable stress in the present paper. This tendency does not change even if S-N diagram was redrawn in semi-logarithmic diagram. The result suggests that the allowable stress proposed in the present study was more conservative than the stress determined based via the existing specification for the fatigue design of bogie frames.