Fatigue Design Diagram for Weld Joints on Aluminum Alloy Carbody Shells

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In order to develop some fatigue design diagrams, the authors carried out weld joint fatigue tests for an aluminum alloy carbody shell. The hollow extrusion weld joints of a doubled-skinned shell and two types of reinforced weld joints of a single-skinned shell were selected as being representative of carbody shell weld joints. The authors created a fatigue design diagram for the hollow extrusion weld joints by means of a statistical treatment of an S-N curve obtained from the fatigue tests using both small-size and full-scale test specimens. In addition, they used the full-scale test specimens in the same manner to develop a common diagram for two kinds of reinforced welds used on single-skinned shells. The diagrams were valid for evaluating fatigue strength from the stress range of materials near the weld joints.

Keywords: carbody shell, welded joints, fatigue strength, fatigue design diagram, fatigue test, aluminum alloy

1. Introduction

Fatigue damage that occurs to carbody shells – particularly when trains pass each other in tunnels – is due to the difference in internal and external pressures of carbody built to be airtight. Carbody shells adapted for high-speed traffic in recent years have been made of aluminum alloys. However, there is little published data on carbody shell fatigue strength and few examples of damage sustained in the course of daily operations. The aim of this investigation is to propose fatigue design diagrams made by S-N curves obtained from the results of fatigue tests for small-size and full-scale test specimens imitated to typical weld joints on the aluminum alloy carbody shells of recent years.

2. Fatigue design standards and fatigue design diagrams for welded joints

2.1 Standards in Japan

JIS E 4050 – Welded Joints of Aluminum Alloy for Railway Rolling Stock – is applicable as a national standard, but does not refer to any standard values concerning fatigue strength except for a notation stating that “where necessary the allowable stress taking fatigue into consideration shall be decided by a consensus among relevant personnel”. In addition, concerning airtightness strength, JIS E 7105 – Load Testing Method for Railway Rolling Stock – stipulates that “the stress for pressure testing shall be lower than the strength at N-cycles decided from the frequency of load”. And “the fatigue strength of weld joints depends on the types of welded

joints, the shape of the welds, etc. Merely, an evaluation concept is described. The strength at N-cycles is also similar.” are presented in – Test Methods for Static Load of Body Structures.” Standard values concerning the fatigue strength and the strength at N-cycles are unclear.

For definitive aluminum alloy carbody shell fatigue strength standards, the fatigue strength of butt-weld joints has been described partially in “Standards of Carbody Strength”¹⁾ that JNR's Vehicle Design Office produced in 1985. A Goodman diagram was drawn based on this. The JNR document noted that, “Where necessary, though fatigue is examined and strength judged by using them, a future review is required on the part of the numerical values of standards in welds.”

2.2 Standards and fatigue design diagrams in Europe and the United States

The various major standards that follow are applicable to fatigue design diagrams for aluminum alloy structures in Europe and the United States:

- (1) Fatigue design of new freight cars of Association of American Railroads (AAR)²⁾
- (2) Standards of Aluminum Association (AA)³⁾
- (3) British Standard 8118⁴⁾
- (4) European Recommendations for Aluminium Alloy Structures (ERAAS) of the European Convention for Constructional Steelwork (ECCS)⁵⁾

However, only (1) above adopted an N-cycles strength diagram that took into consideration the mean stress as in “Standards of Carbody Strength.” In general, a considerably high residual stress is generated in a structure's weld joints, and acts as a mean stress under cyclic stress. However, standards other than (1) have not taken into con-

sideration the mean stress for reasons of its minor effect on the fatigue strength by a difference of mean stress under a high mean stress and for the practical reason of the impossibility of measuring the residual stress of a structure's weld joints. Concerning the above-mentioned standards, fatigue design diagrams of each welded joint are prepared based on S-N curves, and the fatigue life assessed with the frequency of the varying stresses.

According to these standards, the fatigue strength of aluminum alloys welded joints under high cycles is not distinguished depending on materials because the effect due to the fatigue strength from the shape of the welded joints predominates and that from the materials may be disregarded.

Fatigue design diagrams are prepared moving parallel in a mean S-N curve only minus two times the standard deviation for all the foregoing standards (1) to (4). The vertical axis of these fatigue design diagrams means a stress range (the difference between the maximum stress $\sigma_{\max}$ and the minimum stress $\sigma_{\min}$) at varying loads. Stress σ is a nominal stress here, based on a section load obtained using the beam theory, framework analysis, etc. Therefore, when evaluating weld joints by the measurement stress, it is necessary to measure the stress in a smooth standard section where the shape is unaffected. In contrast, the horizontal axis of the diagrams is cycles N , and the fatigue design diagram is expressible by Equation (1):

$$\Delta\sigma^m \cdot N = C' \quad (1)$$

Where C' is a constant, and m is an exponent that shows the slope of a fatigue design diagram.

In References ^{1) 2)}, m is assumed to be $m+2$ in $N=5 \times 10^6$ or more, as shown in Fig. 1, and extends to $N=10^8$.

Fig. 1 Outline of fatigue design diagram

3. Fatigue test body of welded joints of carbody shell

An aluminum alloy carbody shell is composed of welding materials in variety of shapes. Paying attention to the fatigue strength of welded joints under the carbody as well as internal and external differential pressure changes on an airtight structural vehicle, the following parts were selected as typical welded joints, and the test bodies to imitating them tested.

3.1 Hollow extrusion welded joints on doubled-skinned shell

The latest aluminum alloy carbody shell is termed a doubled-skinned shell and is composed of hollow extrusions, as shown in Fig. 2. We investigated the welded joints that connect the hollow extrusions. The hollow extrusion welded joints on the boundary part of the side-roof construction are selected as being representative for the strength evaluation from parts where the maximum stress is generated in the airtightness test result. The edges of hollow extrusions are welded to each other by grooves formed between components. These were imitated on the fatigue test body, small-size test specimens that paid attention only to the welded joints, as well as full-scale test specimens that welded the two components as flat as possible, were prepared for ease of testing. These materials for the small-size test specimens and full-scale test bodies are of A6N01S-T5 used for hollow extrusions.

Welding a pair of plates of 3mm-thick plates together produced three kinds of small-size test specimens. The gaps in the components were 0, 0.5, and 1mm. In addition, there were test specimens on which the excess metal weld remained (termed an excess metal weld) and the excess metal weld was removed by a grinder (termed a grinder version). On the other hand, full-scale test bodies were obtained by cutting that into a width of 300 mm, after continuously welding two flat hollow extrusions. Excess metal weld and grinder versions of full-scale test bodies were also made.

Fig. 2 Fatigue test body for welded joints of doubled-skinned shell

3.2 Roof carline on single-skinned shell, reinforced welded joints on roof carline and side posts on single-skinned shell

A carbody shell with a framework structure that had mainly used large-scale extrusions instead of hollow extrusions is termed a single-skinned shell. This type preceded the above-mentioned doubled-skinned shell. The single-skinned shell structure is also used on doubled-skinned shells for the edge of the car with service equipment except cabins, and on pantograph-equipped vehicles. As the results of the investigation into the single-skinned shell, the shapes of welded joints were classified into two

Fig. 3 Fatigue test body for welded joints of single-skinned shell

forms in the triangular reinforcement welds shown in Fig. 3. Reinforced welded joints on the roof carline as well as the cantrail and reinforced welded joints on the side post and the side sill were selected as representative, the reason being that these joints are the parts that undergo the greatest stress during carbody airtightness tests.

Large extrusions on the singled-skinned shell that are cantrail combined with roof and are side sill combined with side plate are orthogonal framework structures to roof carline and side post respectively, with triangular reinforcements installed at the intersection part. The former use plug welding together with fillet welding at the intersection part and the latter installed by groove welding on the corner of the intersection. The former is termed reinforced welded roof carline joints throughout the remainder of this paper, and the latter, those on the side post. Because neither of the small test specimens regarded easily, only full-scale test bodies to imitate these were prepared for the fatigue test.

The test bodies of reinforced welded roof carline joints were composed of A7N01S-T5 carline (5mm thick), A6N01S-T5 cantrail (also 5mm thick), and A7N01P-T4 reinforcements (6mm thick). In contrast, the test bodies of the reinforced welded side post joints were composed of A7N01S-T5 side posts (3mm and 5mm thick), A7N01S-T5 side sill (20 mm thick), and A5083P-O reinforcements (6mm thick).

4. Fatigue test experiments

4.1 Fatigue test on hollow extrusion welded joints

4.1.1 Fatigue test on small test specimens

A residual stress is thought to be the mean stress exists in welded carbody shell joints. However, the stress ratio R was assumed to be $R=0.1$ of 0 neighborhood for reasons such as easiness of test and, in the diagram showing the

fatigue strength at N -cycles of welded aluminum alloy joints, there is little decrease in the area of $R \geq 0$ while the fatigue strength decreases remarkably from $R=-1$ to $R=0$. A nominal stress range – the difference between the maximum load and the minimum load divided by the nominal section – was assumed for the fatigue design diagram. We carried out the fatigue tests using servo-hydraulic testing machines at the test frequency of 15Hz, even when not fractured, the maximum of number of cycles- N was 10^7 times.

The total number of small test specimens used was 57, broken-down as follows:

- (1) Excess metal weld: 25 (0 mm gap: 7, 0.5 mm gap: 10, 1mm gap: 8)
- (2) Grinder version: 32 (0 mm gap: 7, 0.5 mm gap: 13, 1mm gap: 12)

A center axis along the length of the test piece was matched by inserting spacers in the grips according to the size of the weld gap.

4.1.2 Fatigue test on full-scale test bodies

It is difficult to test many test bodies, because the test speed is reduced due to testing machine performance restrictions when examining of full-scale test bodies. Thus, the fatigue design diagram was made with the small test specimen, as described in Section 4.1.1, and respective six full-scale test bodies each of the excess metal weld and grinder versions were tested with the aim of supplementing and verifying the diagram's findings. Fatigue tests applying load to the test body by three points bending were carried out at the stress ratio $R=0.1$, as shown in Fig. 4(a). We measured the stress with a strain gauge placed on a smooth surface on the welded joint's base material, and adjusted the load to reach a prescribed examination stress. The test frequency was 3 Hz, and the maximum cycle, 2×10^6 .

4.2 Fatigue test of reinforced welded roof carline and side post joints

As described earlier, it is impossible to investigate a number of aspects in the test using the full-scale test body. Therefore, we verified the validity of the fatigue design line by making a comparative study of the fatigue design lines obtained from S-N curves in tests carried out overseas. There are nine tests, involving reinforced welded roof carline joints, and six for reinforced welded side post joints.

We carried out fatigue tests applying a load to the test body by four points bending at a stress ratio of $R=0.1$, as shown in Figs. 4(b) and (c). In addition, we measured the stress with the strain gauge placed on a smooth surface on the welded joint's base material at each reinforced point. The test frequency was 3 Hz, and the maximum cycle, 2×10^6 .

(a) Hollow extrusion welded joints

(b) Reinforced welded roof carline joints

(c) Reinforced welded side post joints

Fig. 4 Fatigue test methods on full-scale test bodies

5. Results of fatigue tests and fatigue design diagram proposal

5.1 Welded hollow extrusion joints

5.1.1 Results from small test pieces and fatigue design diagrams

Figure 5 shows the fatigue test results for small test pieces. The S-N curve was obtained by the least squares fitting according to the presence of excess metal weld, because the difference in test result due to the difference in weld gap was not entirely visible. Only -2 times the standard deviation move parallel in this S-N curve, and the fatigue design line is proposed in the cycle number area of 5×10^6 to 10^8 , at which the inclination m of the strength line of time was assumed to be $m+2$. As a result, the difference made by the presence of excess metal weld

(a) Excess metal weld

(b) Grinder version

Fig. 5 Fatigue design diagram for small test pieces of hollow extrusion welded joints

(a) Excess metal weld, gap 0mm

(b) Grinder version, gap 1mm

Fig. 6 Small test piece failures

is small. Crack initiation sites are the weld roots regardless of the presence of excess metal weld, as shown in Fig. 6. In this, it is the main cause not to receive the influence of the surface shape.

5.1.2 Results from full-scale test body and discussion on fatigue design diagrams

The results of the fatigue test of full-scale test body are plotted in the form of fatigue design diagrams (S-N curve described in parallel.) for the excess metal weld and grinder versions obtained from the small test pieces, shown in Fig. 7. Results from the full-scale test body are consistent with the S-N curve of the small test piece and a large scattering is not seen. Unlike the small test specimen, the crack initiation site is the edge of the weld or the heat affected zone corresponding to the edge of the weld (the grinder version), as shown in the example of failure in Fig. 8.

In general, a strength decrease caused by a residual stress is likely in a full-scale test body than a small test specimen. However, there was no particular discernible difference between the results from the small-size and full-scale test specimens. This can be explained by the strength advantage of a full-scale test body in a bending test compared with tension-compression conditions because the fatigue strength in a bending test is higher than

(a) Excess metal weld

(b) Grinder version

Fig. 7 Comparison between fatigue design diagram and test results from hollow extrusion welded joints

(a) General view

(b) Cross-section view

Fig. 8 Crack initiation sites on full-scale test bodies for hollow extrusion welded joints

that in a tensile test. In addition, it is also explainable by the disadvantage of the small size specimen due to a curve by welding and the effect of the difference in welded gap sizes, etc. At the point near the corner part of the roof and the side where the fatigue strength is evaluated, this design line chart is considered appropriate from a practicable viewpoint because of the high bending influence, and because there is a close correlation between the two examination results.

5.2 Reinforced welded roof carline and side post joints

Figure 9 shows a situation where a crack has occurred on a full-scale test body for a reinforced welded roof carline joints. Likewise, Fig. 10 shows the crack on the full-scale test body for reinforced welded side post joints. The locations of the cracks were the edge of welds at a point in the reinforced welded roof carline joints and the welded joints at the tip of a side post side in the case of the reinforced welded side post joints. However, the difference was hardly recognizable in the two test results that were derived together from the stress on the smooth base material in the nearby welds.

Figure 11 summarizes the results of the fatigue test

Fig. 9 Crack initiation site on reinforced welded roof carline joint

(a) Surface view

(b) Section view

Fig. 10 Crack initiation sites on full-scale test bodies for reinforced welded side post joints

for the reinforced welded roof carline and the side post joints. The S-N curve and fatigue design line obtained from this in the figure are for the reinforced welded roof

Fig. 11 Fatigue design diagram for reinforced welded roof carline and side post joints

carline joints, the amount of data being comparatively high. From the minor differences between the data for reinforced welded side post joints and this S-N curve it may be concluded that the design line chart is common.

When this line chart is compared with similar fatigue design lines compiled overseas, it is conclusive that ERAAS Standard E7 of ECCS⁵⁾ and Class17 of BS⁴⁾ comparatively proximate that this line is appropriate from this respect. It can be assumed that the equal welding to the reinforced welded joints as intended in this chapter in the weld of the additional point installed in the long direction by the beam.

6. Conclusions

The authors examined fatigue testing with small-size and full-scale test specimens with the intention of preparing a fatigue design diagram for weld joints on aluminum alloy carbody shell. Hollow extrusion welded joints on the boundary part of side-roof constructions of doubled-skinned shells and reinforced welded roof carline and the side post joints on single-skinned shells were selected as typical welded joints.

The present investigation leads to the following conclusions:

- (1) In testing fatigue strength using small-size test specimens to imitate the hollow extrusion welded joints, a minor difference was visible in the presence of excess metal weld and from the differences of the gaps in the weld.
- (2) The results of the fatigue test for the full-scale test bodies imitating hollow extrusion welded joints show a close correlation to the S-N curve of small-size test specimens.
- (3) A minor difference was visible in the examination result of both in the fatigue testing of full-scale test bodies of reinforced welded carline and side post joints.
- (4) We proposed a common fatigue design diagram for both, made from the S-N curves obtained from the test results on small-size and full-scale hollow extrusion welded joints test specimens, and those on full-scale test specimens imitating reinforced welded roof carline and side post joints.

7. In closing

We proposed the fatigue design diagram for typical weld joints of carbody shell made of aluminum alloys. Using the stress range in the base material of the relevant nearby welds, we evaluated the welded joints by this diagram. For the standard welding shape, it is possible to judge easily according to the nominal stress amplitude of the nearby welds, in addition, the strength can be evaluated using the stress generation frequency. It will be necessary to accumulate more cases in the future though it is conclusive that this diagram is appropriate in view of a practical application as the result of the comparative study of the actual working stress data obtained from real car.

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