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Review of the influential weld details on fatigue failure of OSD in RD joints

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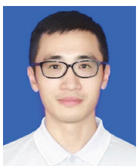

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Research Paper - Subject review

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Review of the influential weld details on fatigue failure of OSD in RD joints

Orthotropic steel bridge decks (OSDs) are commonly used in long-span steel bridges because of their light weight, high load-carrying ability, and ease of construction. The fatigue performance of rib-to-deck (RD) welded joints in OSDs was reported as a key issue in the design of this type of structure. Furthermore, the failure mode at the rib-to-deck welded joint is a key factor affecting fatigue life. This study systematically summarises some of the geometric factors affecting weld-fatigue failure. Some fatigue assessment approaches for rib-to-deck welded-joint details in OSDs are briefly introduced for a deeper understanding and accurate evaluation of their fatigue performance. Several factors have been introduced for fatigue failure modes, among which welding penetration is well-documented to enhance the fatigue strength at the weld root.

Key words:
fatigue failure modes, rib-to-deck joints weld details, weld root failure, fatigue life analysis method

Pregledni rad

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Pregled detalja zavara koji utječu na lom uslijed zamora čeličnih ortotropnih ploča u spojevima rebara i ploče

Čelične ortotropne ploče u mostovima (OSD) često se upotrebljavaju u čeličnim mostovima velikih raspona zbog njihove male težine, velike nosivosti i jednostavnosti gradnje. Ponašanje pri zamoru materijala zavarenih spojeva između rebara i ploče u čeličnim ortotropnim pločama naveden je kao ključni problem u projektiranju te vrste konstrukcije. Također, način otkazivanja na zavarenome priključku rebra i ploče ključni je čimbenik koji utječe na vijek trajanja uslijed zamora. Ovo istraživanje sustavno sažima neke od geometrijskih čimbenika koji utječu na lom zavarenih spojeva uslijed zamora. Predstavljene su i neke metode za procjenu zamora zavarenog spoja rebra i ploče mosta kod čeličnih ortotropnih ploča kako bi se omogućilo dublje razumijevanje i točnija procjena njihova životnog vijeka uslijed zamora. Među brojnim čimbenicima koji utječu na mehanizme loma uslijed zamora, penetracija zavara prepoznata je kao jedan od ključnih parametara koji pridonose povećanju razine čvrstoće uslijed zamora u području korijena zavara.

Ključne riječi:
mehanizmi loma uslijed zamora, priključci zavarenih spojeva između rebra i ploče, lom u području korijena zavara, metoda analize životnog vijeka pri zamoru

1. Introduction

Orthotropic steel decks (OSDs) are advantageous because of their excellent structural characteristics, including high load-carrying capacity, light weight, modular construction, and minimal traffic disturbances. Furthermore, laboratory tests and the in-service performance of OSDs show that, if professionally designed and built, OSDs can provide a 100-year service life with minimal maintenance [1]. Orthotropic bridge decks are primarily composed of bridge-deck plates, ribs, and transverse stiffeners. Occasionally, structural members such as crossbeams are added to ensure the overall stiffness of a bridge [2–5].

Milić et al. [6, 7] counted numerous cases of bridge failures and stated that steel bridge fatigue problems are becoming increasingly problematic as vehicle loads increase. During daily service, steel bridge deck panels are subjected to repeated actions of random live loads, and the first crack typically arises from welding defects. Because fatigue cracks are hidden under the deck, their prompt detection and repair are challenging. Kinuura Bridge, which connects Takahama City to Handa City in Japan, opened to traffic in 1978. However, an inspection conducted in 2003 revealed multiple fatigue cracks along the U-rib direction (Figure 1) [8-10]. These examples show that fatigue-crack initiation occurred at the weld root. It then extends through the deck plate at the rib midspan between the two transverse floor beams. These often occur in OSDs. These cracks propagate from the rib inside the face to the outside, such that they are lengthy after propagating through the deck plate thickness. This fatigue-crack propagation renders them undetectable by visual inspection unless the resulting damage to the asphaltic wearing surface becomes visible.

Compared with primary structural members, OSDs present significant fatigue issues owing to the localised effects induced by wheel loads. Such loads induce significant variations in the local stress, reversals in the stress direction, and an increased number of stress cycles, making it imperative to account for the fatigue design. Fatigue cracking often occurs around rib-to-deck welded joints, starting from the weld toe and weld root and propagating along the bridge deck, rib, or weld throat [3-5] (Figure 2).

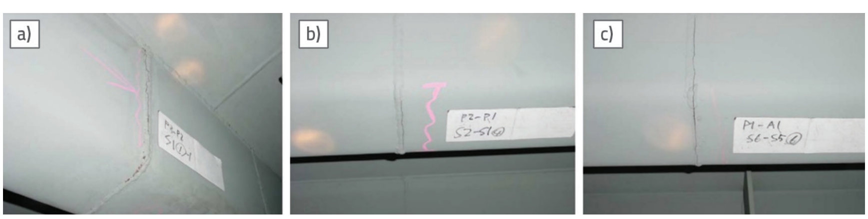

Figure 1. Fatigue cracks in butt welds of longitudinal ribs (cracks are marked with pink lines) [10]

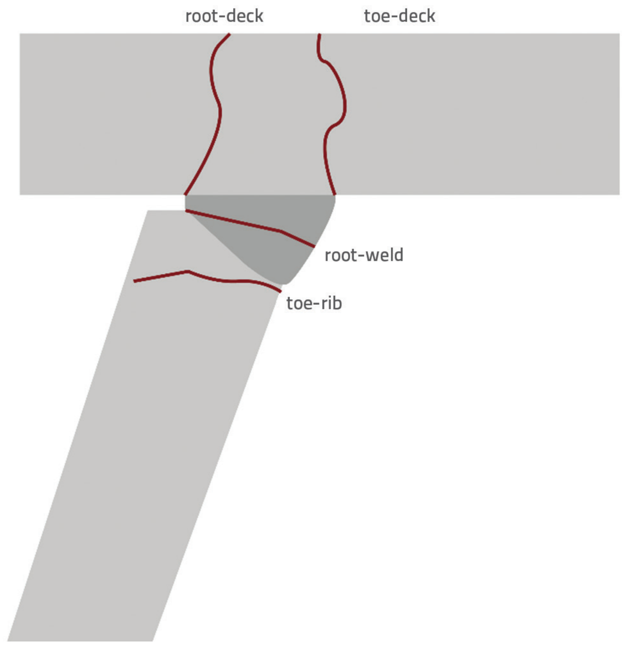

Figure 2. Typical fatigue failure modes in rib-to-deck welded joints

The primary reason for these fatigue cracks is the low stiffness of the deck plate, which is insufficient for handling heavy traffic-wheel loads. Moreover, the increase in heavy traffic causes this fatigue phenomenon to become an even greater concern. Currently, most steel bridge specifications use nominal forces or local approaches to address fatigue failure issues, as seen in standards such as the Chinese Specifications for Design of Highway Steel Bridges and AASHTO LRFD Bridge Design Specifications. The current AASHTO S-N approach uses a single S-N line to predict fatigue life. However, this approach has limitations in solving the problem of fatigue at the position of welded joints, such as incomplete consideration of the size and notch effects. Fatigue failure of welded joints often occurs because of geometric factors and initial flaws. In addition, when the distributions of the initial flaw depth and aspect ratio are the same, root failure is slightly more prevalent than toe failure [7, 16]. Moreover, owing to the influence of welding technology and the environment, the probability of fatigue failure at the weld root cannot be ignored. However, compared to the weld toe, research on weld roots has historically been underdeveloped. Existing studies have shown that the fatigue strengths of various parts of the welding area between the bridge deck and longitudinal rib differ. This study focused on the local geometry of the weld details and the impact of welding post-processing on different failure modes. Thereafter, we summarise the current fatigue-life analysis methods for various parts. Finally, we offer measures to improve the fatigue performance of weld details [12, 13].

2. Common influencing factors of weld detail fatigue

2.1. Weld penetration

Welding penetration is a key factor when assessing root cracks; a higher penetration rate can reduce the possibility of weld-root failure and improve fatigue resistance [14]. Yanbo et al. [15] conducted 80 %- and full-penetration welding experiments on rib-to-deck welded joints. The results of the experiment revealed that the stress level near the weld root of the 80 % penetration weld was much higher than that at the weld toe and that the stress at the weld root was similar to that at the weld toe in the case of full penetration. This reduced the possibility of damage to the root deck. Wei et al. [16] experimentally demonstrated that although the penetration rate has different effects on the fatigue life of welds under different failure modes, a higher penetration rate generally enhances the fatigue performance of welds and reduces the stress levels of the weld roots and toes.

2.2. Weld size

Because the geometric characteristics of the steel bridge rib-to-deck welded joints were similar to those of the T-joints, the geometric characteristics of both joints were considered identical. The failure modes of fillet weld joints are significantly related to the geometry of the welds themselves and the usual failure modes, including those of the root weld and toe deck [17, 18]. Fricke et al. [19] proposed that weld root and weld-toe failures depend on the relationship among the weld-throat thickness, plate thickness, and length of the weld leg, which can be explained by the ratio of the length of the weld leg to the plate thickness (s/t) or the ratio of the weld-throat thickness to the plate thickness (h/t). Similarly, in double-sided welds, the failure mode and fatigue performance are affected by the weld depth, weld leg length, and plate thickness. Moreover, the longer the leg length, the better the fatigue performance. When the lengths of the two weld legs were equal, the control variable method was adopted, considering the influence of the penetration rate on the transformation of the fatigue failure mode. When the penetration depth to thickness ratio (p/t) was 0.2, the critical size (s/t) was 0.85. When (p/t) was 0, the critical size (s/t) was 1.16. When the ratio of the leg length to plate thickness is greater than the critical size, damage generally occurs from the weld toe. However, when this ratio is less than the critical size, an initial crack generally occurs from the weld root, as indicated by Xing et al [20, 21]. Simultaneously, the root-weld failure generally propagated along the 70° throat path. When the penetration rate increased, the damage angle of the weld-throat passage gradually approached 90° (Figure 3). Wei et al. [22] proposed a boundary failure function of s/t based on experiments and traction structure stresses (Figure 4).

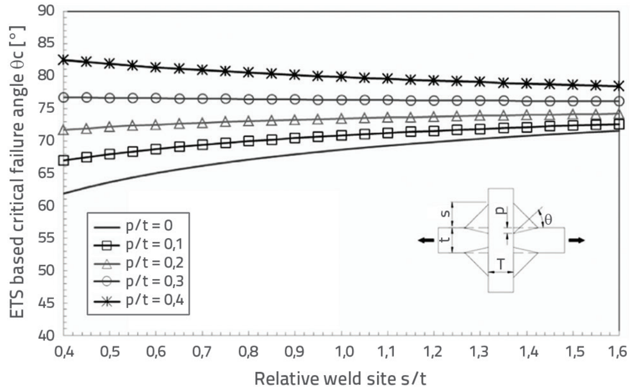

Figure 3. Relationship between penetration rate and failure angle based on effective structural-stress prediction [21]

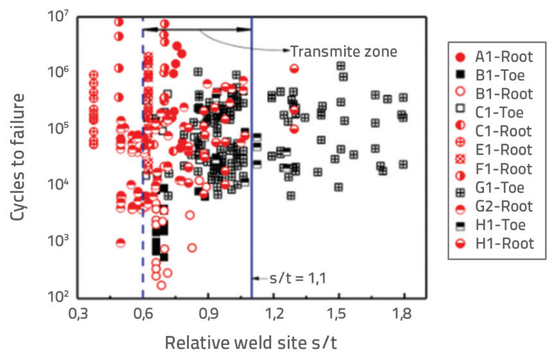

Figure 4. relative weld leg size s / t versus fatigue failure modes [22]

2.3. Root gap

Junlin Heng et al [23]. revealed that three failure modes (root deck, toe deck, and root weld) appeared in their samples, among which the root deck and toe deck were the main failure modes and the probability of toe-deck failure was greater. In addition, wide-ranging mixed failure modes can occasionally occur. The author highlighted that when the penetration rate is greater than 80 % and the root gap is less than 0.5 mm, root-deck damage can be effectively avoided. In addition, Wei et al. [22] determined through finite element simulation that the traction structure stress at the weld-root position increased by 27 % when the root gap increased from 0 to 2 mm. In other words, when the root gap was larger, the weld was more likely to be damaged from the weld-root position; at the same time, the damage channel of the weld throat also changed with the root gap (Figure 5).

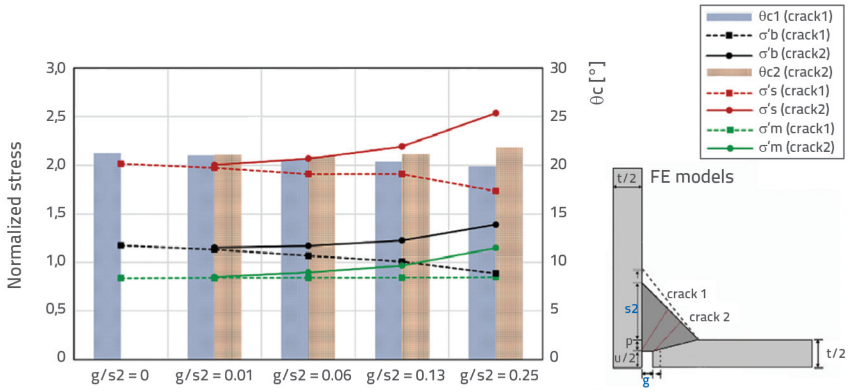

Figure 5. Normalised traction stresses and the relative gap size (g/s2) [22]

2.4. Weld-toe radius and edge preparation

The weld-toe radius, thickness, and edge preparation affect the degree of stress concentration and fatigue life of the weld; however, they generally do not contribute to changes in the failure mode. Ebrahim et al. [24-27] highlighted that a naturally formed untreated toe radius does not reach a clear arc contour shape, whereas a post-processed toe radius reaches a fixed arc shape. When the degrees of stress concentration at the toe before and after grinding were compared, it was found that a larger radius of the weld toe after grinding could effectively alleviate the stress concentration at the weld toe, thereby increasing the fatigue life. Based on this, van Es et al. [28] established a circle at the bottom of each notch of the weld foot and then determined the point closest to the centre of the circle to measure the toe radius uniformly. The authors also found that after the right post-weld treatment, stress concentrations in areas with a larger toe radius were alleviated, and those with a smaller toe radius cracked first. In an orthotropic steel bridge deck, the toe radius may change in two failure modes: toe deck and toe rib. Xiu et al. [29] conducted experiments on T-joints with and without edge preparation and concluded that welds with edge preparation could reduce the influence of dynamic load vibrations, increase the fatigue life at the weld root, and reduce the possibility of fatigue damage at the weld root. Yang et al. [30-32] conducted a test on U-ribs and used the included angle α to represent the edge-preparation angle. Through their experiments, the authors found that when the edge-preparation angle increased from 20° to 60°, the equivalent structural stress at the toe and root decreased with an increase in α. Moreover, the equivalent structural-stress range decreased from 82 to 71 MPa. When α increased from 20° to 45°, the middle of the toe improved more significantly than the edge of the toe did. When α increased from 50° to 60°, the edge position of the welded toe improved more significantly than the middle position of the weld toe. When the edge-preparation angle was between 45° and 50°, the stiffness of the rib-to-deck welded-joint connection increased significantly. Jian et al. [33] conducted similar experiments on T-joints and concluded that increasing the edge-preparation angle can improve the fatigue performance to a certain extent. In addition, increasing the edge-preparation angle led to an increase in the number of welding passes, making the welding complex. Therefore, Xu Jian suggested that the edge-preparation angle should ideally be between 25° and 45° (Figure 6).

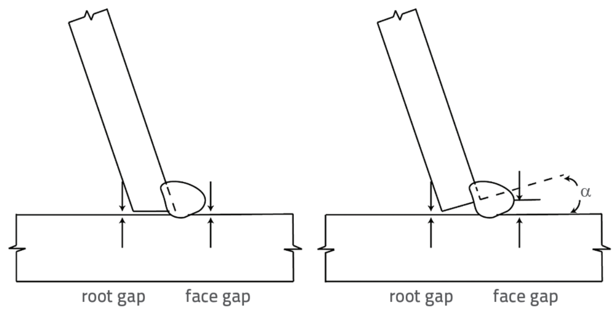

Figure 6. Edge-preparation diagram

2.5. Toe-opening angle

The toe-opening angle 2α (Figure 7) influences the fatigue life of the rib-to-deck welded joints and causes a change in the fatigue failure modes. Luo et al. [34, 35] conducted experiments with several groups of specimens with different penetration rates and toe-opening angles and concluded that an increase in the toe-opening angle changed the failure mode from toe-deck to root-weld or toe-rib modes (Figure 8).

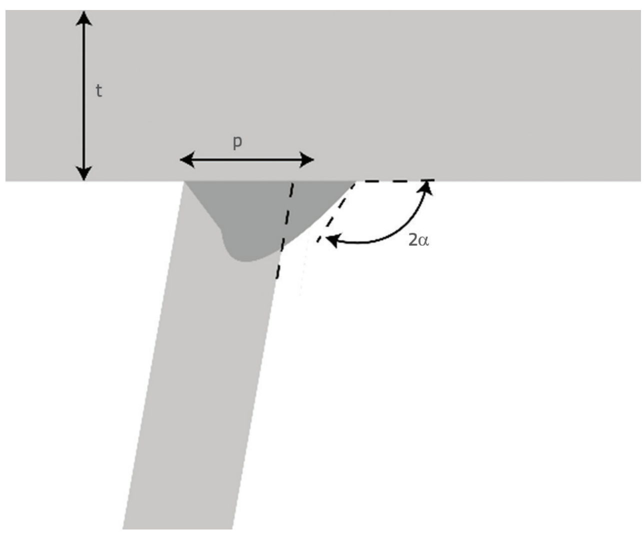

Figure 7. Weld-toe opening angle

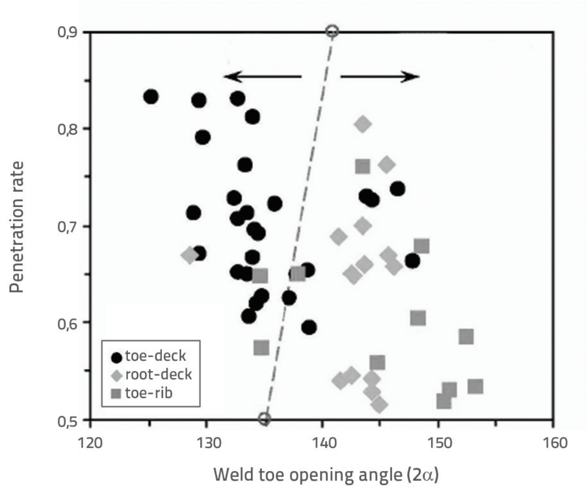

Figure 8. Weld-toe opening angle versus fatigue failure modes [33]

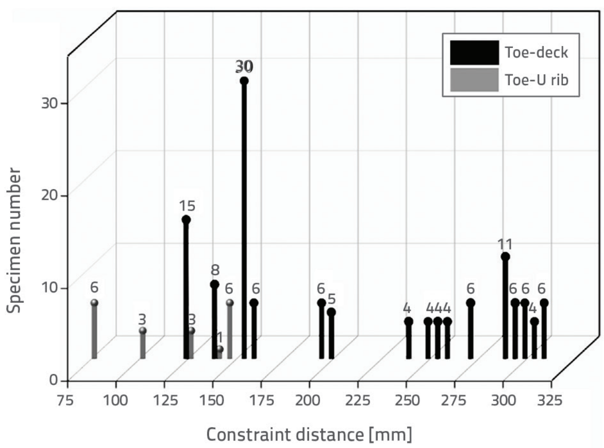

Figure 9. Relationship between constraint distance and failure mode [32]

2.6. Constraint distance

The constraint distance of the U-ribs reflects the distance between them, which also affects the change in failure modes of the rib-to-deck welded-joint positions. Through experiments, Dong et al. [32] demonstrated that when the constraint distance is sufficiently small, toe-rib failure often occurs; meanwhile, when this distance is sufficiently large, toe-deck failure often occurs (Figure 9).

2.7. Others

In addition to the major influencing factors, Gadallah et al. [36] considered residual stress and adopted improvement measures; the fixed mismatch ratio and thickness effect also have an impact on the transformation of the fatigue failure mode and fatigue life. Zhou et al. [17] experimentally considered a fixed mismatch ratio, m, penetration length p/t, and weld length h/t as the three basic parameters of their fatigue failure-mode model. The authors showed that these three parameters play an important role in the failure-mode transformation of cross welds, wherein the fixed mismatch ratio is caused by the uneven force of the weld caused by dislocations. Simultaneously, Yang [30-32] pointed out that the thickness effect can improve the fatigue performance of U-ribs, showing that increasing the thickness of U-ribs or decks can reduce the equivalent structural stress. However, the effect of increasing the deck thickness was more obvious, and the improvement in this effect was more significant at the weld root. Additionally, Liu et al. [37, 38] pointed out through experiments that, compared to increasing the thickness of the U-ribs, increasing the thickness of the deck plays a greater role in improving the fatigue strength. In addition, it was found that the form of the U-rib of an orthotropic steel bridge deck panel has a negligible influence on the transformation of the rib-to-deck failure

Table 1. Factors influencing the fatigue properties of weld details

Type of influencing factors	Influencing factor	Affected site	Effect of influence
Affected by the weld of rib-to-deck welded joints	Penetration rate	Weld root	The lower the penetration rate, the more easily the weld root is damaged
	Weld size	Weld toe, weld root	The larger the s/t, the more easily the weld toe is damaged
	Root gap	Weld root	The larger the root gap is, the more easily the root is damaged
	Weld-toe radius	Weld toe	The smaller the weld-toe radius, the more easily the toe is damaged
	The edge preparation	Weld root	The weld root is easy to damage when there is no edge-preparation setting
	Toe-opening angle	Weld toe, weld root	The toe-opening angle is large, and the toe-deck or root-weld damage can easily occur
Influenced by the orthotropic bridge deck itself	Constraint distance	Weld toe	Toe-deck damage can easily occur when the constraint distance is large

modes. Yang et al. [30-32] also experimentally proved that the fatigue failure modes of orthotropic steel bridge deck panels are not affected by the form of the U-rib. The factors that influence the fatigue properties of the welds are listed in (Table 1).

3. Common local approaches

3.1. Equivalent structural-stress approach

Since the concept of local approaches was first proposed in the 1960s, several approaches have been proposed to avoid non-linear local stresses in welds. This has paved the way for the following three types of techniques that have been roughly developed: the 1 mm stress approach is the state 1 mm away from the local notch in the expected crack growth direction, which represents the early crack growth stage because this is the main part of fatigue life. The hot-spot stress method involves extrapolation of the stress surface at the weld to the hot spot, which is often used to analyse weld toes. Finally, the structural-stress linearisation approach ignores the local peak stress in a specified direction and linearises the stress in the thickness direction. Thereafter, the equivalent structural-stress law regards the non-linear force as a self-balancing force and adopts methods such as the nodal force to solve the structural stress [29], thus achieving the effect of considering the stress concentration phenomenon and local geometry, which is better than global methods, such as the nominal-stress approach, when evaluating local fatigue. Therefore, this method is often applied to the fatigue analysis of weld toes, weld roots, and other positions. However, because this approach ignores part of the stress, it is currently only applied to the analysis of steel and thicker materials [13,18,38-51]. Xiao Wu et al. [52-53] proposed a method which combines the weight function and strength factor based on equivalent structural-stress method to solve this problem.

3.1.1. The 1 mm stress approach

This method suggests that the non-linear stress increases gradually at the weld root or toe, and then gradually decreases to a negligible level at the 1 mm position. This is because, in the finite element mesh division, the mesh size is approximately 1 mm; however, there is no clear definition of the stress composition at this location.

To analyse the weld toes, the stress generated parallel to the direction of the load application should be considered. To analyse root-weld failures, this method does not assume 70° as the throat failure channel but evaluates along a quarter circle with a radius of r = 1 mm in radians, where the direction of the greatest stress is the direction of the assumed throat channel. Despite the development of an effective notch-stress method and the proposed equivalent structural-stress approach, this method has rarely been used (Figure 10).

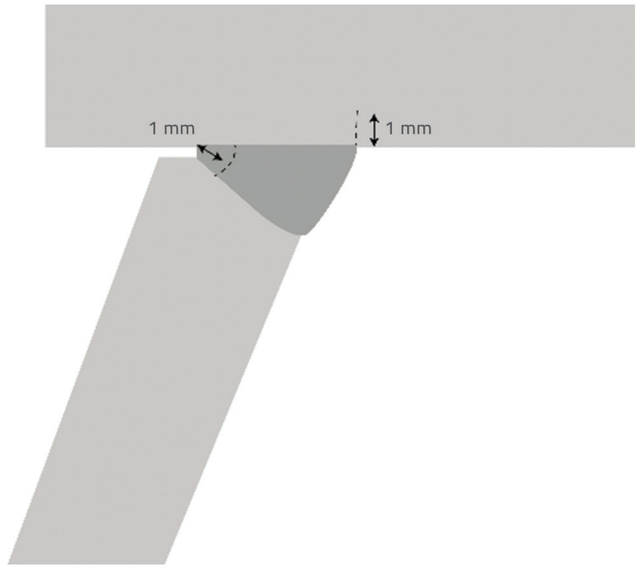

Figure 10. Diagram of 1-mm stress approach

3.1.2. Hot-spot stress method

Hot-spot stress refers to the maximum local stress generated at the weld toe by considering only the effect of the macroscopic geometric stress concentration. The hot-spot stress method refers to the surface extrapolation along the direction of the first principal stress on the surface and generally takes 0.4–1 times the thickness in the direction for consideration. The mainstream extrapolation methods for hot-spot stress are generally two-point linear extrapolation and three-point two-point extrapolation [13], where two and three points refer to the three types of hot spots at the weld toes. Class A was located at the root of the vertical plate and the surface of the mother plate, Class B was located at the surface edge of the vertical plate, and Class C was located on the surface of the vertical or mother plate (Figure 11). Currently, the stress at these hotspots cannot be directly calculated using formulae of material mechanics; the stresses are generally obtained indirectly through finite element or patch methods. Subsequently, the stress of the required extrapolated area was obtained through interpolation, as follows, Eq (1):

$$\sigma_{hs} = \frac{x_2\sigma_{x1} - x_1\sigma_{x2}}{x_2 - x_1} \tag{1}$$

Where x_1 and x_2 represent the distances from the extrapolation points 1 and 2, respectively, to the hot spot, and σ_{x1} and σ_{x2} are the stress values of the extrapolation points 1 and 2, respectively. When using this method, special attention should be paid to the choice of the extrapolation points. The following two conditions should be met: First, the extrapolation points should not be located in an area affected by the toe-notch effect. Second, the distance between the extrapolation point and weld toe should be sufficiently close to show the characteristics of stress concentration. Thus, after obtaining the hot-spot stress, the stress concentration coefficient at the hot spot was obtained from its ratio to the nominal stress. The stress at the hot spot can be measured using both the finite element and strain gauge methods. In most weld joints, the weld root is located inside the weld and cannot be determined through surface extrapolation. Therefore, scholars generally believe that the hot-spot stress method can only perform fatigue analysis at weld toes, that is, fatigue-life prediction of the two failure forms of the toe rib and toe deck [54, 55].

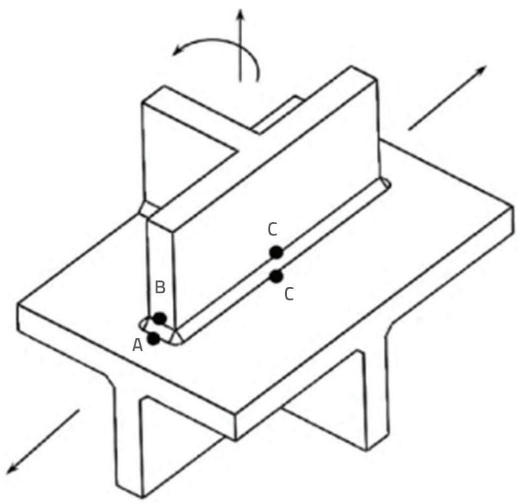

Figure 11. Schematic of weld-toe hot-spot types

3.1.3. Structural-stress linearisation approach

This method is primarily applied to welding positions that are subjected to bending loads. The eccentric loads caused by bending caused the welds to break along the weld legs. The angle of the weld-throat passage was closer to 90° [40]. The idea of structural-stress linearisation is similar to the method of surface extrapolation of structural stress, both of which deal with local non-linear structural stresses using ideal mathematical means, as presented in Equations (2) to (4):

$$\sigma_s = \sigma_m + \sigma_b \tag{2}$$

$$\sigma_m = \frac{1}{l}\int_0^l \sigma_x(y)\,dy \tag{3}$$

$$\sigma_b = \frac{1}{l^2}\int_0^1 \sigma_x\left(\frac{1}{2}-y\right)dy \tag{4}$$

The structural welding stress σ_s can be defined as the sum of the film stress σ_m and bending stress σ_b, which can be derived by linearises the σ_x(y) stress perpendicular to the length of the welding leg (Figure 12). After conducting experiments, Fricke et al. [19] concluded that cracks generally extended along the root plane. The damage angle of the weld throat is generally 70–90°; therefore, the structural-stress linearisation method—which linearly solves the problem along the direction of the weld leg—is different from other methods that assume the angle of the weld throat. Owing to the influence of the root gap and penetration rate, the angle of the weld-throat passage changes. In general, this method can only be applied to structures with small shear stresses and is used at positions where the shear stress is less than 20 % of the nominal stress; otherwise, the fracture path deviates significantly from the predicted path. Consequently, linearised algorithms have significant limitations. In addition, similar to surface extrapolation, the linearisation solution cannot suitably reflect the influence of the size effect on the plate thickness, and only the parameters of the size effect can be used for the following correction [39, 40].

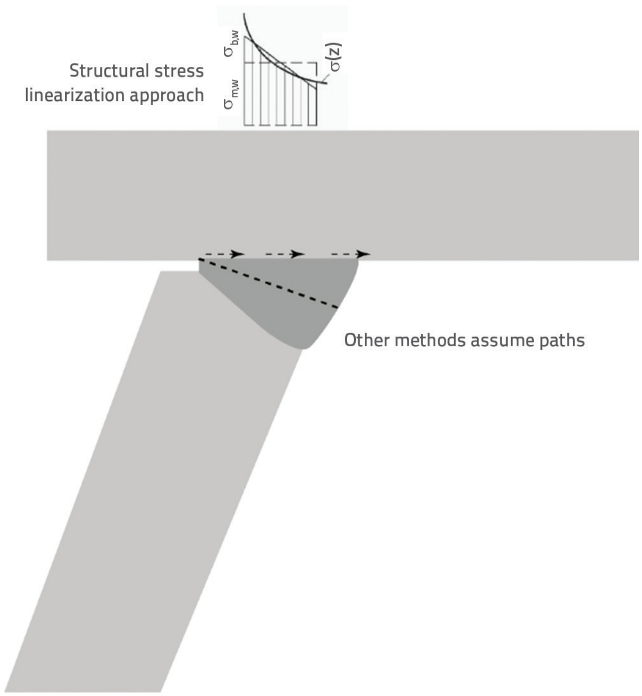

Figure 12. Structural-stress linearisation

3.1.4. Equivalent structural-stress approach

Dong et al. [40] proposed an equivalent structural-stress approach that developed a new concept of structural stress by dividing the stress along the thickness of the weld-toe section under the action of external forces into two parts: structural stress and non-linear self-balancing stress. The structural stress is the stress in balance with external forces and is the sum of membrane stress σ_m and bending stress σ_b, while the nonlinear self-balancing force is caused by a geometric notch, which is always in a self-balancing state. Because the structural stress must be balanced by an external force, the following formula is obtained:

$$\sigma_c = \sigma_m + \sigma_b = f_y/t + 6\, m_x/t^2 \tag{5}$$

where the line force f_y is the force per unit length of the welded wire, m_x is the moment per unit length of the welded wire, and t is the plate thickness. The distance between adjacent nodes was set to l, and the node force of the element was converted into the line force and line moment of the welding line at the weld toe, as defined in Equations (6) and (7). The line force and line moment were then converted into structural stresses using Equation (8).

$$\{f_{y1}, f_{y2}, \ldots, f_{yn}\}^T = L^{-1}\{F_{y1}, F_{y2}, \ldots, F_{yn}\}^T \tag{6}$$

$$\{m_{x1}, m_{x2}, \ldots, m_{xn}\}^T = L^{-1}\{M_{x1}, M_{x2}, \ldots, M_{xn}\}^T \tag{7}$$

$$\sigma_s = L^{-1}\{F_{yn} + 6M_{xn}/t\}/t \tag{8}$$

To use a master S-N curve as the welded structure under different loading modes, Dong et al. derived the equivalent structural-stress parameter ΔS_s using the crack prediction and fracture mechanics theories. The calculation method is shown in Equation (9).

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{(2-m)/2m} I(r)^{1/m}} \tag{9}$$

where: $\Delta\sigma_s$ is the structural-stress range; m is the crack growth index; t is the plate thickness; and $I(r)$ is a dimensionless function, The bending ratio r can be expressed as follows:

$$r = \Delta\sigma_b/\sigma_s \tag{10}$$

Therefore, the equivalent structural-stress approach includes the influence of factors such as the stress concentration effect, thickness effect, geometric shape, and load form. By searching for the master S-N curve, i.e., $\Delta S_s = CN^h$, fatigue analysis in this area can be easily conducted [40-42, 57-61].

Overall, when numerous factors were considered, the accuracy of the equivalent structural-stress approach was significantly better than that of traditional analysis methods. Moreover, because of its mesh-insensitive characteristics, particularly those in 2D, it is more convenient to perform calculations on a computer. However, when a unified master S-N curve is adopted, the tedious comparison of various S-N curves is avoided, and the equivalent structural-stress method provides a relatively accurate theoretical formula. The entire formula was derived from the material and fracture mechanics. Furthermore, adopting Paris' law which considers the plastic state of the crack tip, is sufficient to show that the entire formula has clear physical significance. However, the equivalent structural-stress approach generally ignores some local stresses near the weld, and is not ideal for evaluating the details of small non-smooth tips, that is, the local geometry (Figure 13). Therefore, many researchers have introduced other methods based on the equivalent structural stress to address this [53].

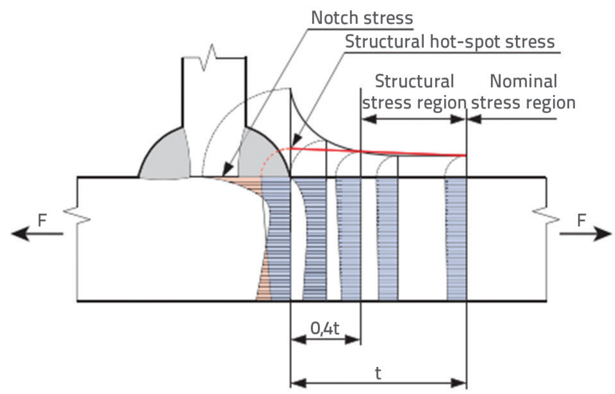

Figure 13. Description of local stresses near weld toes using different analytical approaches

3.2. Effective notch-stress method

The notch-stress method was first proposed in the 1990s. This method considers the notch effect of the weld, that is, the stress concentration caused by structural geometry changes, structural discontinuities, and welding. The largest notch stress at the joint was then considered as a parameter to evaluate fatigue. Therefore, the notch-stress method accurately included the peak stress caused by the notch effect. In theory, when the fatigue strength is expressed using the notch-stress method, it depends only on the difference in the notch shapes at the weld toe and weld root. Under the condition that the welding process has no defects and is highly stable, a relatively general S-N curve suitable for different joints can be obtained at the weld root or toe under real stress. It is unnecessary to choose the S-N curve repeatedly according to the state of the joint, as in the nominal-stress method. After calculating the notch stress, the notch-stress concentration coefficient of this type of welded joint was calculated based on its ratio to the nominal stress. The notch stress of the same type of welded joint can be calculated directly using the coefficient and nominal stress [62-65]. However, owing to the irregular shapes of the weld roots and toes, a virtual radius is generally set for the calculation. It is defined as:

$$\rho_{ref} = \rho + S\rho^* \tag{11}$$

In the most unfavourable state, it is customary to set the virtual radius to 1 mm (Figure 14). However, when the thickness was less than 5 mm, setting the radius in this manner was inconsistent with the stress in the actual weld, thereby affecting the fatigue prediction results. Therefore, in this case, it is necessary to use a small-sized notch-stress method for thin-plate materials, set the virtual radius to 0.05 mm, and then perform fatigue prediction. If the slope index of the predicted S-N fatigue curve m is 3, then the virtual radius should be changed back to 0.1 mm. In addition, the small notch-stress method is commonly used to predict weld throats, and the notch stress at the weld root is combined with the width of the weld-root seam.

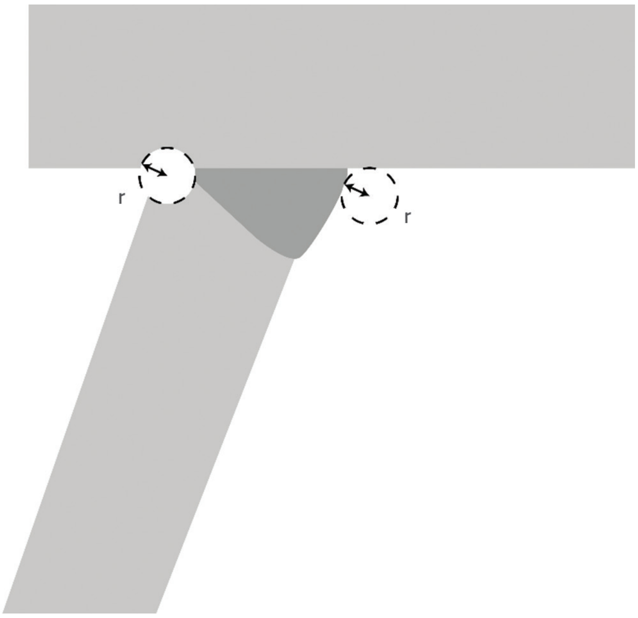

Figure 14. Notch rounding of the weld root of a rib-to-deck welded joint

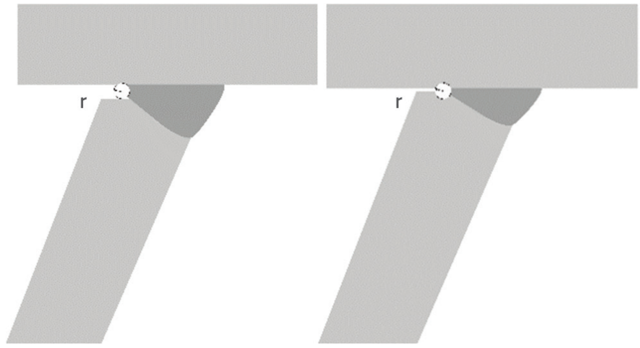

Figure 15. U-shaped and keyhole notch

The penetration rate determines the type of weld-root FE model (Figure 15). Compared with the equivalent structural-stress approach, the greatest advantage of the notch-stress method is that it considers the local geometric size and local stress distribution. However, because of this, the effective notch-stress method is sensitive to the division of the mesh, and different S-N curves must be selected in different states when considering the participating stress. In addition, these two methods adopted diverse methods to solve the problem. The notch-stress method adopts elastic theory, where a circle with a virtual radius is set at the top. The notch stress near the notch was affected by the virtual radius, which was set based on the size effect, stress

Table 2. Local approaches of welding fatigue

Common local approaches		Advantage	Disadvantage
Equivalent structural-stress approach	1 mm stress approach		- 1 mm is the smallest unit commonly used for finite elements and has no clear physical significance. - Multiple S-N curves need to be considered.
	Hot-spot stress method	- Local stress is considered better for weld details	- It can only be used for analysing life at the toe. - Multiple S-N curves need to be considered.
	Structural-stress linearisation approach	- Applied to welding positions subject to bending loads	- Affected by shear stress. - Multiple S-N curves need to be considered.
	Equivalent structural-stress approach	- Insensitive to meshing. - Has a master S-N curve - It has clear physical significance, combined with elastic-plastic mechanics. Fracture mechanics considers the development of cracks	- The consideration of local stress is poor. - The analysis effect is poor for small-sized and thin-plate components
Effective notch-stress method		- Considers the local geometric features and the local stress effect. - The analysis effect is good for small-sized and thin-plate components. - Good simulation of the root gap	- Sensitive to meshing. - It is necessary to select the S-N curve. - Focuses more on the elastic theory

concentration, and other parameters (also known as the notch effect). Dong et al. [66] addressed this shortcoming by using a critical distance approach based on the effective notch-stress method. The equivalent structural-stress approach considers the crack development to a greater extent and introduces Paris' law to consider the plastic stress field at the crack tip.

The hot-spot stress method is often used for the fatigue-life assessment of welded toes; for instance, it is used to determine the failure modes of welded toe-decks and toe-ribs. The notch-stress method is widely used in fatigue-life assessments at various positions, and the equivalent structural-stress approach is often used for steel with a larger thickness. This method is used for aluminium with a thickness less than 5 mm. Therefore, the notch-stress method was used to predict the failure modes of the root welds; however, it was ineffective in predicting the welded throat passage. Therefore, Dong et al. recently proposed the opening throat traction stress and opening stress state of a welded throat based on the equivalent structural stress for the fatigue analysis of a welded throat. However, the effect of the equivalent structural-stress method has yet to be verified in thin-section analyses or when considering the local stress caused by the local geometry. Four common local analysis methods for the fatigue failure modes of the rib-to-deck welded joints of steel bridges are summarised in Table 2.

4. Measures to improve the fatigue performance of weld details

4.1. Double-sided weld

Double-sided welding technology refers to the use of small welding robots inside a U-rib using conventional means for external welding. Liu et al. [37, 38, 67] showed through experimentally demonstrated that under the same penetration rate, double-sided welds transformed the original mode of root failure into the first failure at the weld toe. The author pointed out that, compared to single-sided welds, the fatigue resistance of double-sided welds was greatly improved, and highlighted that the fatigue performance of double-sided welds was improved mainly for the following reasons. First, the centroid of the double-sided weld was aligned with the centroid of the U-rib, such that the eccentricity of the weld changed less. Second, the cross-sectional area of the weld and stiffness of the local weld improved. Third, the unbelted part of the rib-edge preparation formed a closed rigid area, which changed the stress state of the weld root. Based on fracture mechanics and experiments, Yang et al. confirmed that double-sided welds can delay failure at the exterior of weld toes, which improves the fatigue life. Qinghua et al. [3-5, 9] pointed out that two-sided welds were also affected by the penetration rate; however, the effect was not significant when the penetration rate exceeded 75 %. When a double-sided weld was fully penetrated, it was not damaged by the weld root, and there were only four modes (toe deck and toe rib on both sides) (Figure 16) because the fatigue strength at the weld root was low. This effectively increased the fatigue life of the weld.

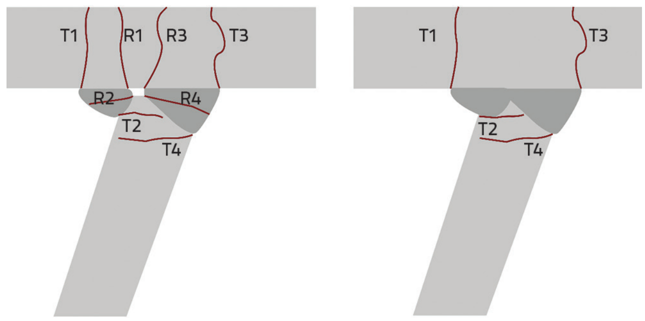

Figure 16. Failure modes of double-side weld

4.2. Post-weld treatment methods

Schneller et al. [42] experimentally concluded that surface-defect welds were more likely to cause fatigue damage. Compared with large internal defects, small surface defects are more likely to lead to crack initiation. Therefore, post-weld treatment methods are mostly adopted to address surface defects and extend fatigue life. Fuštar et al. [75] confirmed that HFMI treatment of welded joints is a simple and cost-effective method for improving the fatigue resistance of fatigue-loaded joints. They also demonstrated that most of these post-weld treatment methods aim to improve the weld toes. Tempering, light grinding, and TIG dressing (Figure 17) are generally adopted to reduce the

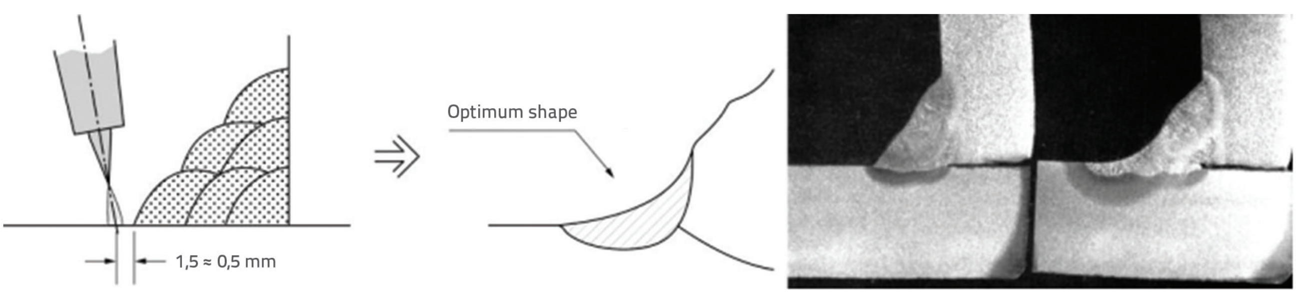

Figure 17. TIG dressing

influence of residual stress, weld-toe radius, and surface defects on fatigue strength. Van Es et al. [28] used the TIG-dressing method for the post-weld treatment of a weld toe. This method effectively alleviated the stress concentration phenomenon while increasing the radius of the weld toe. Simultaneously, certain surface defects were removed to reduce the stress level at the weld toe. In general, depressions with a smaller radius can be effectively alleviated; however, compared with welds with lower weld penetration or a larger root gap, they are more likely to be damaged from the root position. However, most post-processing techniques, such as shot peening, aim to address fatigue failure that starts from the weld toe.

4.3. Reinforcement measures

Currently, three primary methods are used for fatigue-crack reinforcement in China and worldwide. The first method involves changing the distribution of the stress field at the crack tip, such as by using stop-hole technology. The second is to increase the overall stiffness of the structure by using composite deck technology. Finally, the local structural reinforcement at the location of the crack can be changed, such as in double-sided repair welding technology [68-73]. Lu et al. [45] conducted experiments, compared various reinforcement methods, and confirmed that these reinforcement measures can effectively extend the fatigue life of components at locations where cracks appear. Kalstei et al. [74] highlighted that the major reason for these fatigue cracks was the low stiffness of the deck plate. They used a sandwich steel plate system to reduce the global stresses on the bridge deck and extend the fatigue life of welds.

5. Conclusions

Many factors influence the changes in the fatigue failure mode of rib-to-deck welded joints in OSDs. Numerous researchers have performed experiments to examine the fatigue problem at this position and have proposed numerous methods and models. Although numerous results have been obtained, some problems remain unaddressed.

Fatigue analysis methods that address root-weld failure modes have historically been underdeveloped. The hot-spot stress method can only be applied to weld toes, and the notch-stress method cannot effectively predict the throat passage. The linearisation and 1-mm stress approaches rely on many assumptions to predict the fatigue at the weld root. Recently, based on the equivalent structural-stress approach, Dong et al. extended this idea to damage weld roots and throats and achieved meaningful results. However, this study primarily examined fillet welds, which are limited in actual use because of their geometric symmetry. Therefore, further research should be conducted to promote this method for other types of weld.

Most existing failure modes of rib-to-deck welded joints focus on the position of the weld toe and adopt methods, such as improving the penetration rate or adopting double-sided welding technology to avoid weld-root failure. However, the results of Heng et al. showed that many welds still occurred through the failure mode of the root deck. Therefore, it is necessary to determine the functional relationship between the failure-mode transformation of rib-to-deck welded joints and weld-root gap, penetration rate, and weld size.

Most existing literature on weld roots is based on tensile experiments on fillet welds, and most studies that have examined the root position of U-rib welds refer to T-joint welds. However, owing to the different experimental conditions, it is difficult to directly apply the conclusions of cross-joint or T-joint welds to damage U-rib weld roots. Whether the weld is formed using single- or double-sided weld technology, the position failures of the weld roots still need to be determined experimentally.

The equivalent structural-stress approach has been widely promoted and applied. However, owing to the limitations of local stress, the notch-stress method cannot be completely replaced. Further investigation is required to promote this method and determine how the shortcomings of the equivalent structural-stress method can be addressed.

Post-processing was primarily used at the weld toe. When the welding quality cannot be guaranteed, the weld is destroyed from the weld root. Thus, the effect of improvement measures that assess the fatigue properties of weld details is less than expected. Therefore, it is necessary to continue delving into measures to improve the fatigue life of weld roots.

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