新しい鋼床版構造
New Type of Steel Orthotropic Deck System

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Keywords: 疲労，補修，鋼床版， fatigue, retrofit, repair, improvement,orthotropic steel deck

1. Introduction

Many cases of fatigue damage in orthotropic steel bridge decks have been reported. Because the bridge deck directly supports the traffic loads, severe stress conditions have occurred in the almost every connection of orthotropic steel bridge decks. Moreover, the lengths of the influence lines of these stresses are very short, stresses in connections change abruptly with each passing vehicle or set of axles or wheels. This stress condition contributes to the serious fatigue damage. One more characteristic of fatigue damage in this deck system is that the same structural details are widely used in one bridge. This means the possibility exists that the same types of fatigue cracks will arise everywhere simultaneously.

Fig. 1 shows the Maihama Bridge in the Metropolitan Expressway. This bridge consists of the orthotropic deck with two box girders and three continuous spans, and is a typical type of bridge that uses trough ribs for its longitudinal member. This Bridge was put into service in 1978. The current traffic volume per day, for the eastbound and westbound of 3 lanes routes combined, is about 80,000 vehicles. The interfusion ratio of large size trucks is about 15%. Various types of fatigue cracks have been found as the result of an inspection of the inside of the box girder as shown in Figure 2.

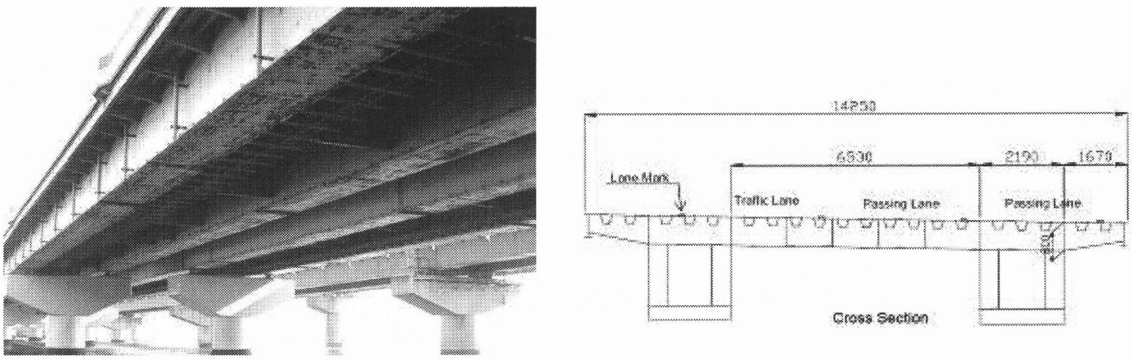

Fig. 1 The Maihama Bridge

Fig. 2 shows typical fatigue cracks observed in orthotropic bridge decks. In order to identify the causes of the fatigue cracks and consider retrofit method, field measurements, finite element analyses and fatigue tests by using a wheel running loading system on full-scale models were carried out.

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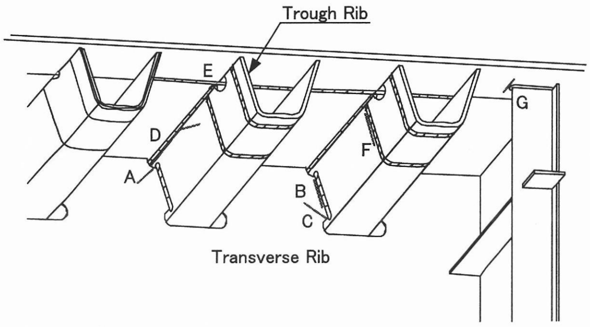
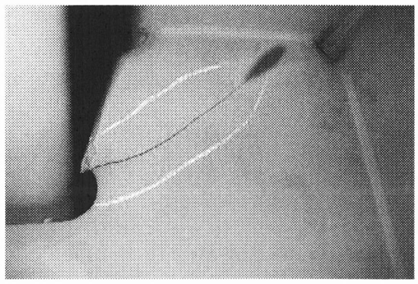
Fatigue cracks in the welds between longitudinal trough rib and transverse rib are the major target of this study. D type fatigue cracks on the longitudinal weld of the trough rib with the deck plate initiated from the weld root. There is a possibility of type D crack penetrating deck plate and causing subsidence of road surface as shown in. This type of crack is hard to detect by visual inspection but might give serious damage on traffic route.

Type C

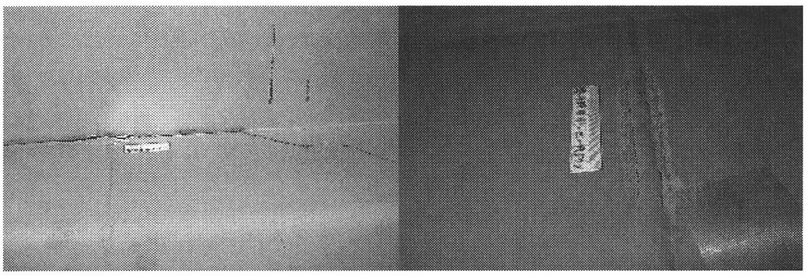




Type D

Type F

Type G



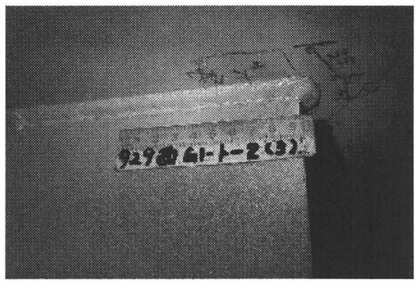
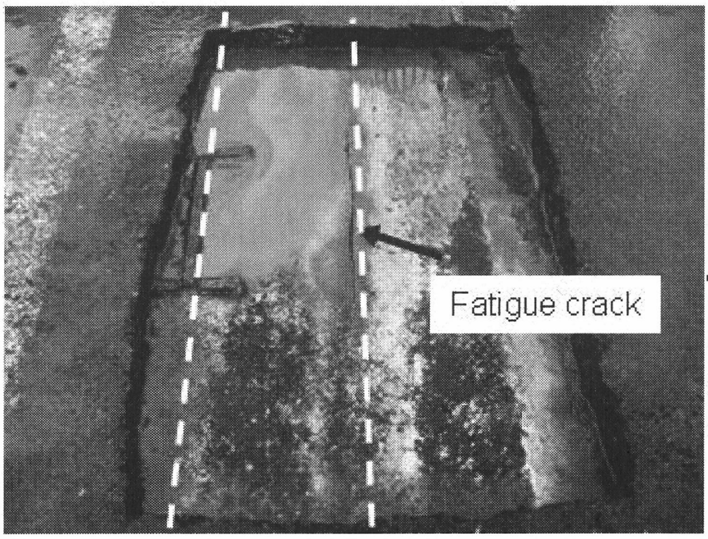


Fig. 2 Typical Fatigue Crack in Orthotropic Steel Deck



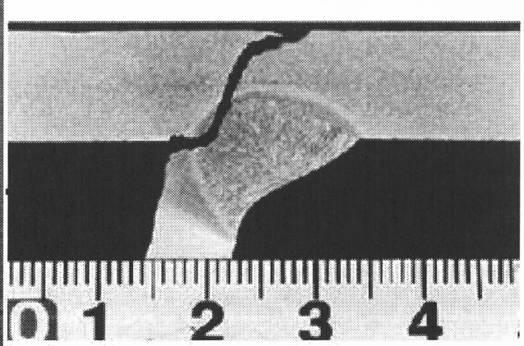


Fig. 3 Deck trough Type Crack

2. Fatigue Crack of Weld between Trough Rib and Deck

2.1 FEM model

Fig. 4 shows the models of FEM analyses which are composed in three step models. The model in the 1st step is the whole bridge model for determining the behavior of the whole structure. The model in the 2nd step is a detailed model for evaluating the stress condition and deformation of the object area, and the model in the 3rd step is a detailed model for estimating and scrutinizing the stresses around the welding zone. The truck with axle loads of 57.5+95.4+ 92.7 KN are modelled as pressure load for tire loadings. Stresses on the object area are investigated by moving the truck load in both longitudinal and transverse directions.

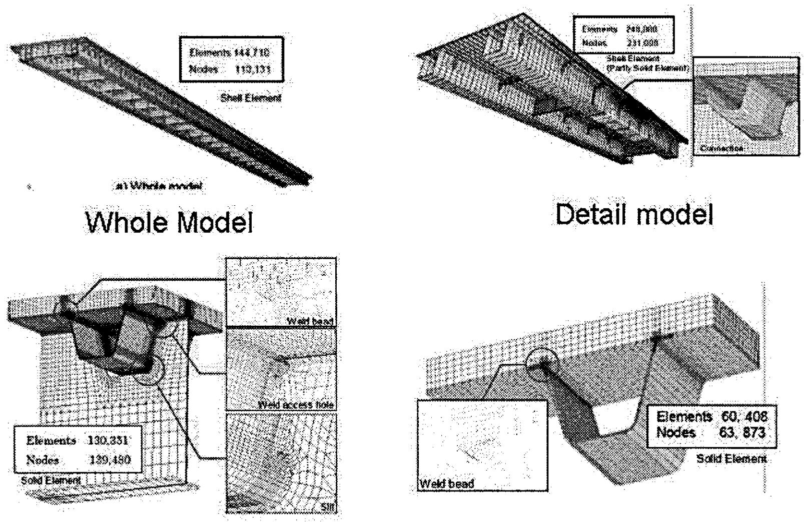


Fig. 4 FEM models

2.2 Local Stress and Deformation around upper scallops in transverse rib (Maihama Br.)

The loading position and stress calculation points (targets) are indicated in **Fig. 5**. The stress distribution and its variation were investigated while the truck moved in the longitudinal and transverse directions. **Fig. 6** shows the stress influence lines of the target points with the load moving in the longitudinal direction. Upper scallops had been used until recently at the connection of the transverse rib and trough rib. **Fig. 7** indicates that stresses of target points at the junction of transverse rib are much higher than those at center of trough rib span.

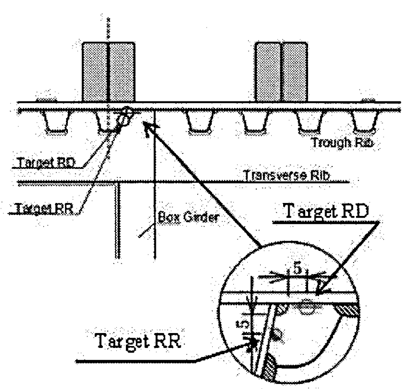


Fig. 5 Loading position of tire relative to the target trough rib

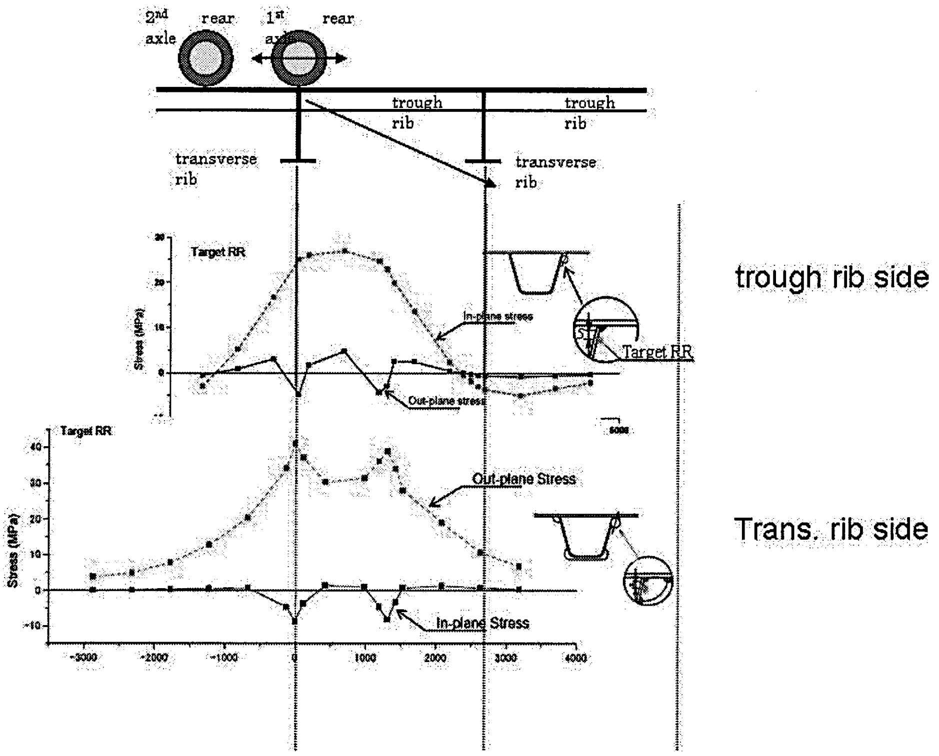


Fig. 6 Stress influence line of trough rib at the upper scallop

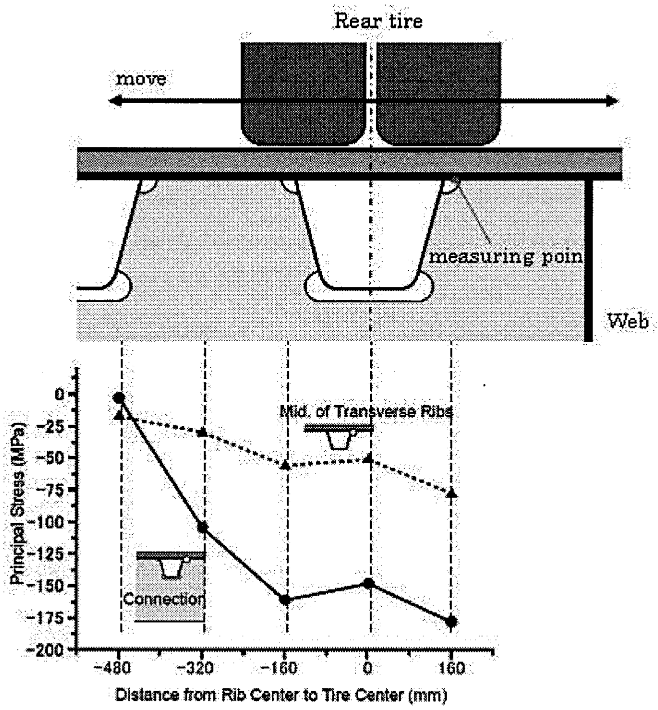


Fig. 7 Comparison of Stress influence line at trans. rib and at the span center

2.3 Fatigue strength of weld connection between trough rib and deck (without upper scallops)

Upper scallop was eliminated in recent spec. but type D crack in Fig. 1 still be found in weld bead. In order to study the fatigue initiation behavior at the root of welds, the Effective Notch Stress (ENS, here after) concept is introduced. ENS is the stress at the notch which assumes linear elastic body (Hobbacher 2003). Hence, ENS is taking into consideration the local nonlinear peak stress that is not considered in hot spot approach. In this approach, local stress is directly evaluated by applying imaginary notch to the root and toe of weld. 0.5mm notch was introduced to our evaluation.

In order to examine detail stress distributions at the root of welds between the deck plate and trough rib, two models were prepared,75% penetration model and shallow penetration model. The leg of the fillet weld was modelled as 8 mm for the deck plate and trough ribs, and 10 mm for the connection. **Fig. 8** shows FEM models for ENS. Mises stresses were used to express the ENS.

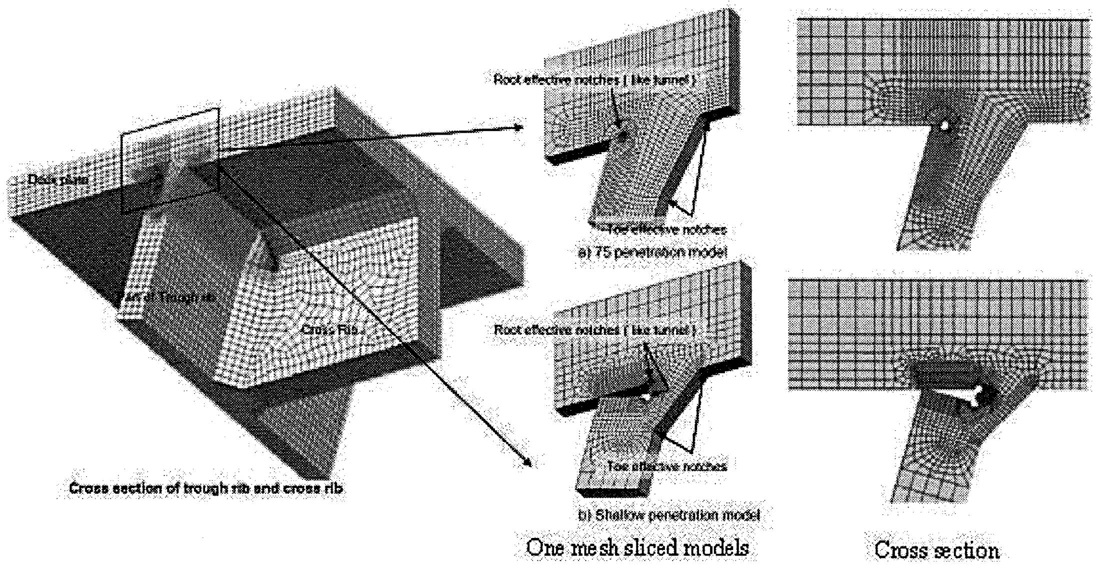


Fig. 8 Detail Model

4 points of effective notch, A, B, C and D, are investigated in one model as shown in **Fig. 8**. The effective notch was modelled so that radii might be divided into 24 meshes, and the mesh of three layers from notch was modelled so that an aspect ratio might be near 1.0.

Effective notches are introduced to these two models. Three loading patterns in transverse direction were applied as shown in **Fig. 9**. First pattern is that center of double tire locates on the target weld. Second pattern is that an edge of single-tire locates on 20mm inside from target crack. Last pattern is that an edge of single-tire locates on 20mm outside of target crack. Each pattern is called as double, single-inside, and single-outside respectively. **Fig. 10** shows that the ENS at the root of the general section (center of trough rib span) and the cross section (at the junction of transverse rib and trough rib). ENS in root at the cross section are higher than those in general section. This means that there are high possibility of fatigue cracking in the cross section zone than in general section zone. **Fig. 11** shows ENS in the weld bead along the longitudinal direction when single tire load is applied on inside of the trough rib web at the cross section. The ENS shown in this figure are the maximum ENS at each section. The remarkable difference of stress has observed in two models. In 75% penetration model, stress concentration occurred only at upper side root notch, which may penetrate deck plate. On the other hand in shallow penetration, stress concentration occurred at both upper side and lower side root notch. Possibility of fatigue cracking is higher in shallow penetration and cracks may appear not only in deck side but also in weld bead. The peaks of stress distribution of " shallow penetration weld model " are generally higher than the stress from " 75% penetration weld model ". Thus the possibility of crack initiation from the target weld will decrease by applying 75% weld penetration.

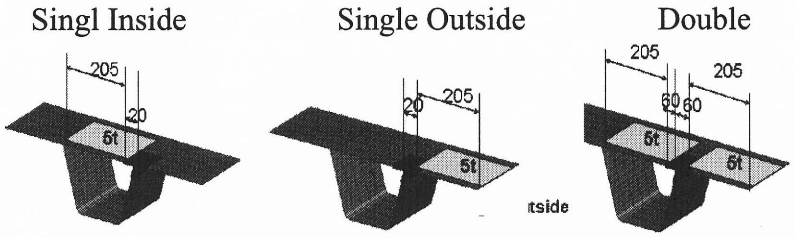


Fig. 9 Loading Pattern

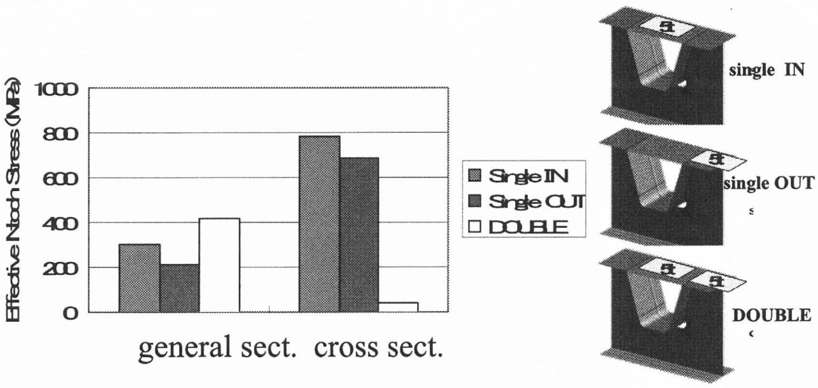
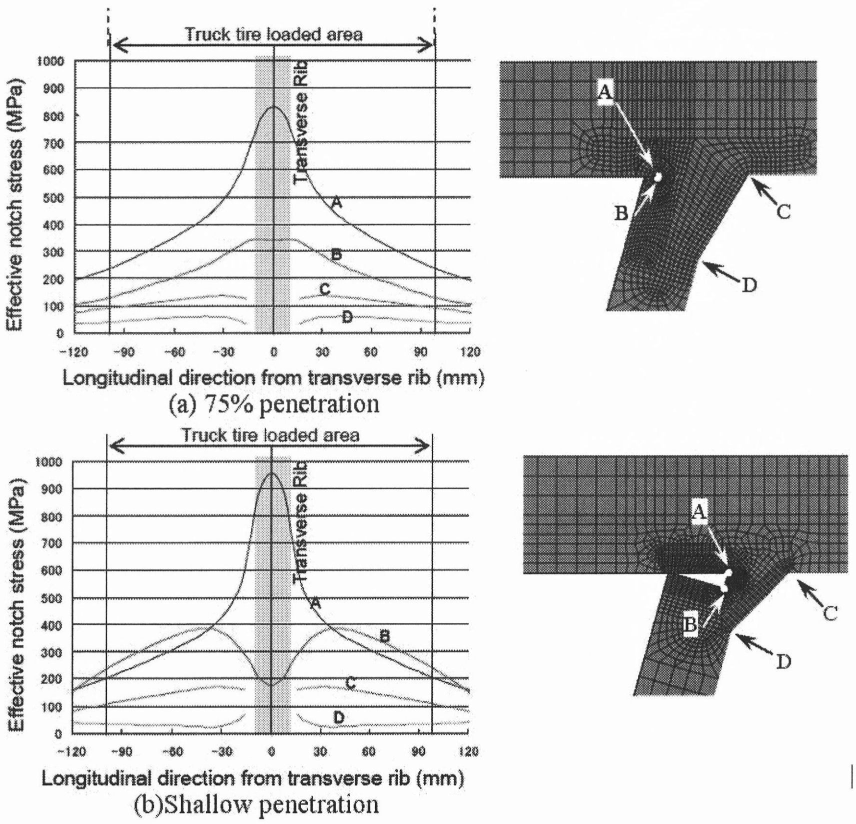


Fig. 10 ENS under 3 loading patterns



(a) 75% penetration

(b)Shallow penetration

Fig. 11 ENS distribution along the weld bead

2.4 Retrofitting Methods

Fig. 12 shows proposed three retrofitting method. In type b, 12mm thick steel plate is spliced on the deck plate. This method was usually applied as a temporary repairing for the cracked deck. In type c, steel fiber reinforced concrete (SFRC) is placed on the deck plate to form composite steel deck system. This method was applied for the preventive strengthening work of Yokohama Bay bridge in Japan in 2004. Type d is the method filling light weight concrete in longitudinal ribs. The performances of these three methods were examined in full scale model tests as shown in **Fig. 13**. **Fig. 14** shows variation of stress with passage of track. Type c, SFRC, showed excellent performance, stresses at all of measuring points significantly decreased. In type b, doubling steel plate with bolt, stresses at measuring point A is not reduced. It is supposed that this is because the doubling plate was not contacted with deck plate. The effectiveness of type d is limited within the trough rib zone and stress of outside zone was increased.

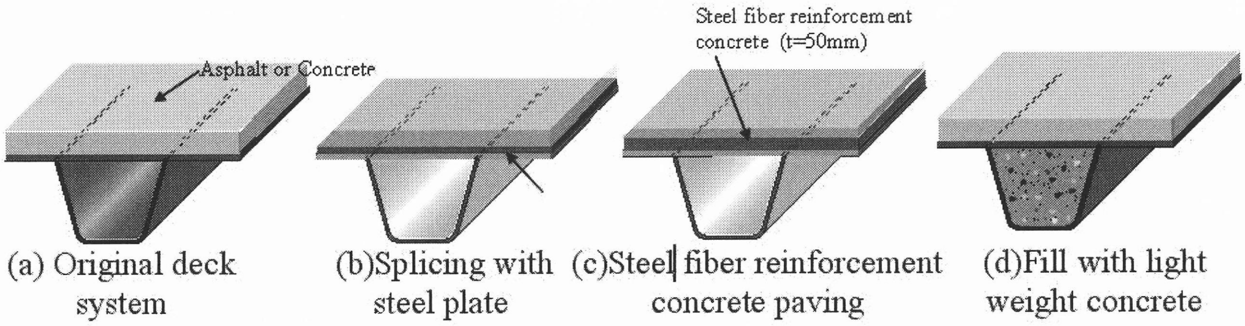


Fig. 12 retrofit methods for upper scallop fatigue crack

Fig. 13 Loading Test of Orthotropic Steel Deck

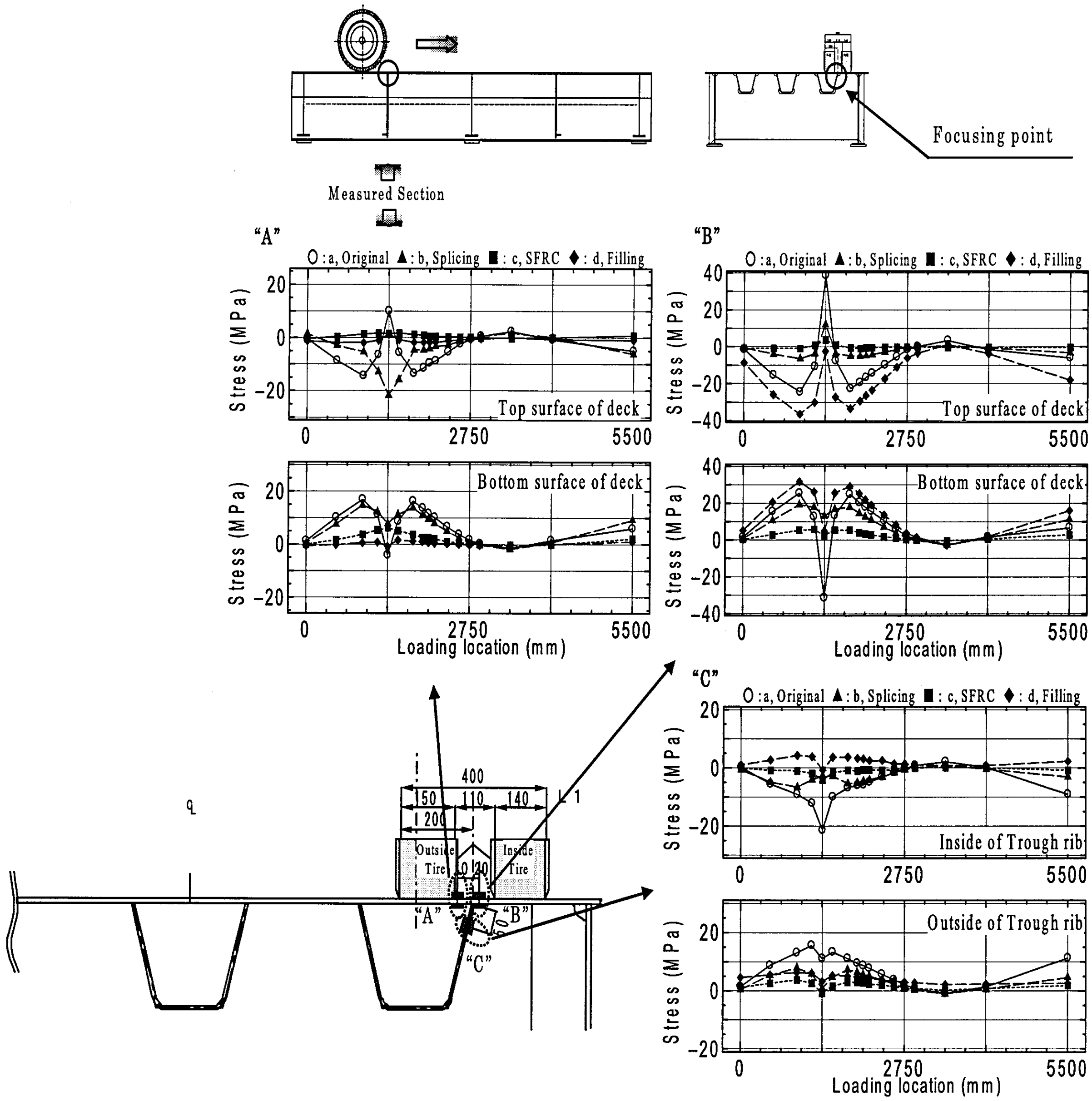


Fig. 14 Stress on deck plate and trough rib close to welded joint (at mid-span of longitudinal rib)

2.5 Wheel Running Fatigue Test for Orthotropic Steel Bridge Decks

Fatigue tests with a full-sized orthotropic steel deck specimen as shown in **Fig. 15**, one is original deck and another is with type c retrofit, were carried out under the similar wheel loading condition of the actual traffic vehicles.

In order to simulate the real wheel load condition, the wheel running fatigue testing machine was used. It has tandem axles with double rubber tires on each axle. The reciprocating wheel loads are applied at prescribed location on the deck. Moving distance is 3m. The vertical load of each double tire was 69kN corresponding to rear axles of 350kN class truck. Wheel base is 1.4m and tire class is normal truck tire, 10.00R20-14PR.

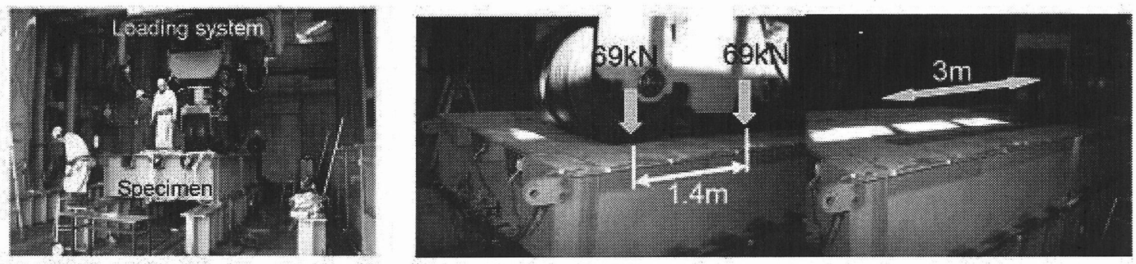


Fig. 15 Fatigue test by Moving wheel Loading Machine

2.5.1 Test results of original deck system

The total number of passing wheel loading was 5.8million by 1.45million cycles of reciprocation. One fatigue crack was found on the upper surface of the deck plate close to the intersection of the transverse rib and trough rib when the number of wheel loading was 5.5million as shown in **Fig. 16**. Existence of the crack had been predicted before it appeared on the surface by stress measurements and ultrasonic testing. Estimated length of fatigue crack is shown in **Fig. 17**. After the fatigue test was finished, several fatigue cracks in the deck plate were detected by ultrasonic testing. The existences of the fatigue cracks were confirmed by exposing crack surfaces. Crack initiation time was estimated by the change of stress at 0.5million cycles. The internal crack face was identified by ultrasonic testing, when the number of passing wheel loading was 1.8million. The crack length was estimated 164mm at that time. Estimated crack length along the weld root was already over 500mm when the crack penetrated through deck plate. When the fatigue test completed, the crack was opened. **Fig. 18** shows the surface of the exposed crack penetrated through the deck plate. The crack length on the deck surface was 130mm and crack length along the weld root was 530mm. It was verified that the crack surface in the deck plate has extremely shallow-wide shape. The etched cross-section at the fatigue crack initiation portion is also shown in **Fig. 18**.

Several fatigue cracks in the deck plate were detected by ultrasonic testing after the fatigue test. The distribution of the detected cracks in the deck plate is shown in **Fig. 19**. It shows that fatigue cracks exist in every longitudinal weld between deck plate and trough rib close to the wheel loading location.

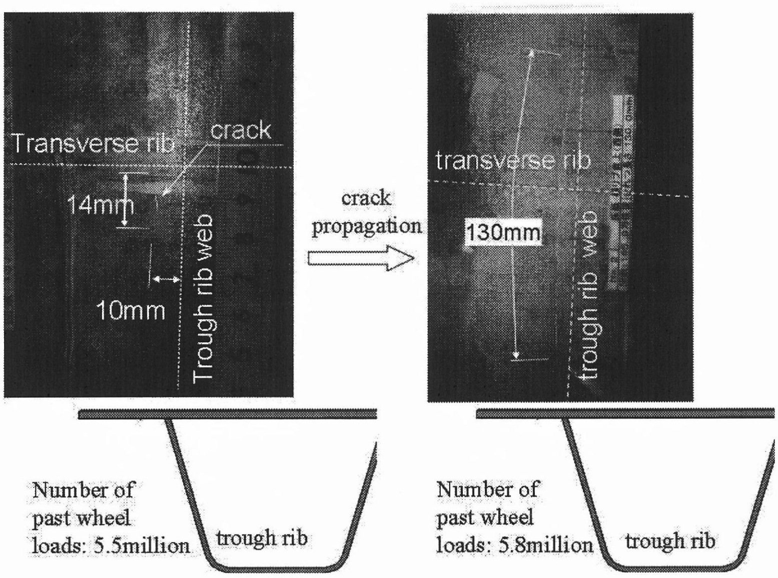


Fig. 16 Fatigue Crack go through the deck

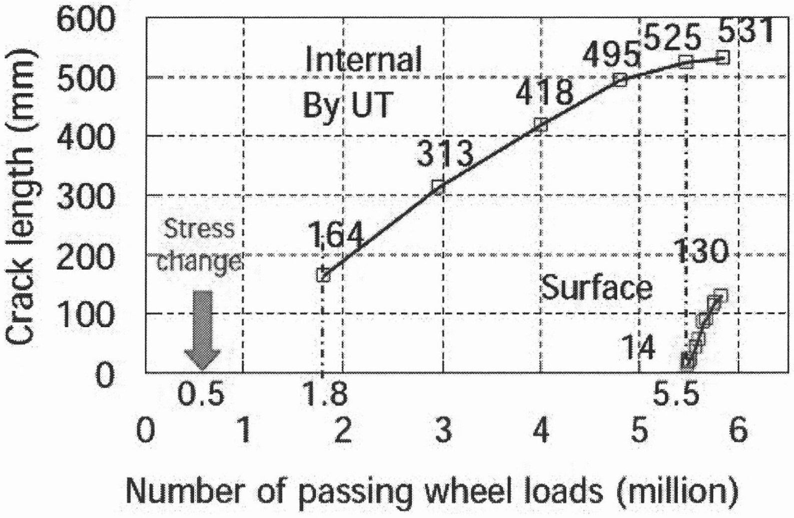


Fig. 17 Propagation of Fatigue Crack

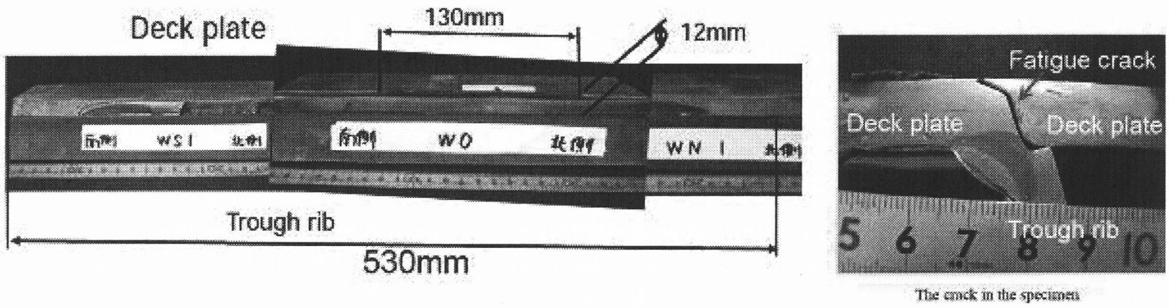


Fig. 18 Exposed fatigue Crack

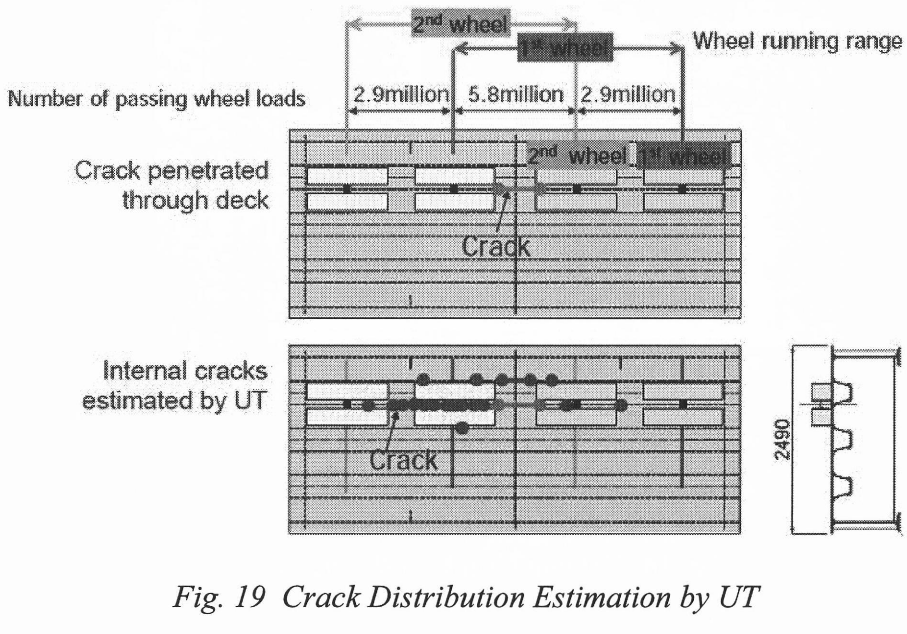


Fig. 19 Crack Distribution Estimation by UT

2.5.2 Test results of deck system with type c retrofit

Fig. 20 shows measured stresses in the original deck and retrofitted deck of type c method. By applying type c method, change to composite deck with SFRC, stresses in deck plate were improved significantly, which reduced almost zero. After 4.4 million cycle loading, no fatigue crack was observed, and condition of SFRC is sound.

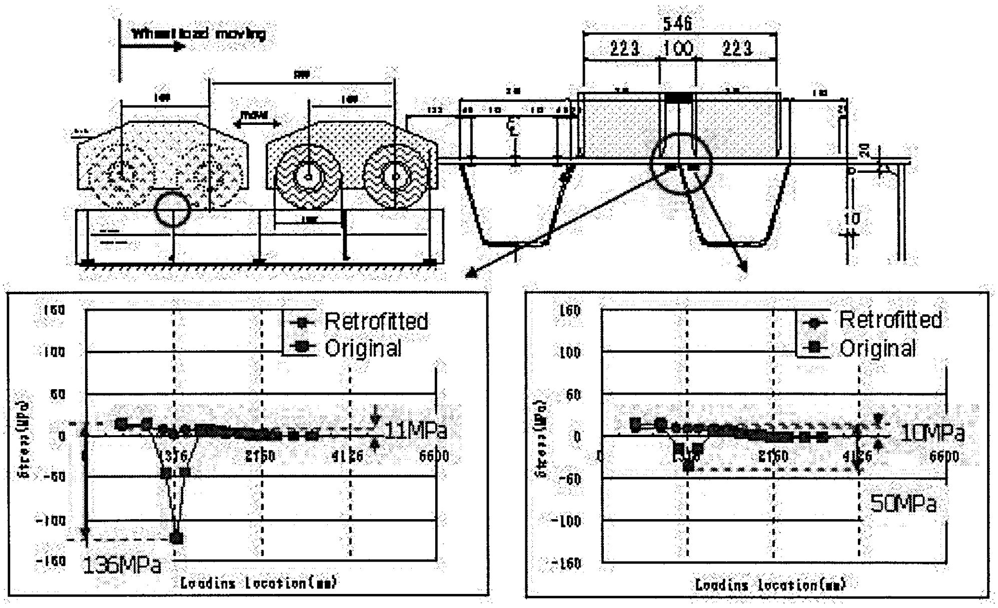


Fig. 20 Stress reduction due to Retrofit (c)

2.6 Conclusions

(1) The cause of fatigue cracks in the longitudinal welds between deck plates and longitudinal trough ribs is local bending stresses in the deck plates and web of trough ribs due to wheel loadings.

(2) In order to decrease the magnitude of these local stresses, the bending stiffness of deck plate have to be made higher

(3) The stress conditions in the longitudinal welds in the intersection zone is more severe than these in the general section zone.

(4) The deeper penetration of longitudinal welds provides lower stresses at the root of welds, which results higher fatigue resistance.

(5) The wheel running fatigue test on a full size structural model reproduced fatigue cracks in longitudinal welds which penetrate through the deck plate.

(6) As the retrofitting measure, the existing steel deck system was changed to the composite deck system by placing steel fibre concrete. The effectiveness of this retrofitting method was confirmed from the result of wheel running fatigue test.

References:

[1] Fujiwara, M., Murakoshi, J. and Tanaka, Y. Fatigue strength around cutout parts of crossbeams in orthotropic steel decks. J. of structural engineering (JSCE), 1991
[2] Hobbacher, A. Recommendations for fatigue design of welded joints and components, International institute of welding, 2003
[3] Iwasaki, M., Nagata, M., Nishikawa, K. and Yamada, K. Field measurement and fatigue assessment of orthotropic steel deck with asphalt pavement. Proc. of JSCE, 1997
[4] Miki, C., Suzuki, K., Kano, T., Sasaki, E., Hosaka, T. and Takamori, H. Preventive works for fatigue damage in orthotropic steel bridge deck by SFRC pavement and long term monitoring of the composite action, Proc. of JSCE,2006 (Under Modification)
[5] Miki, C., Tateishi, K., Okukawa, J. and Fujii, Y. Local stress and fatigue strength of the joint between longitudinal and transverse ribs in orthotropic steel deck plate. Proc. of JSCE, pp127-137, 1995
[6] Tateishi, K., Takenouchi, H. and Miki, C. Mechanism for developing local stress at the connection details in steel bridge structures. Proc. of JSCE, 1995
[7] Wolchuk, R., Ostapenko, A. Secondary stress in closed orthotropic deck ribs at floor beams. J. of structural engineering, ASCE, 1992

3. Fatigue Crack in lower scallops in transverse rib for weld between Trough Rib and Deck

3.1 Introduction

There are a possibilities of the occurrence of two types of fatigue cracks as shown in **Fig. 21**.

(1) Crack from the slit on the transverse rib side

(2) Crack from the slit on the trough rib side

The local deformation of a cross part would be a cause of these cracks. The local deformation would be controlled by contriving geometry of slit form. As a result of parametric analysis; parameters are slit size, slit geometry and so on, with fine meshed FEM, we propose the suitable geometry of slit form.

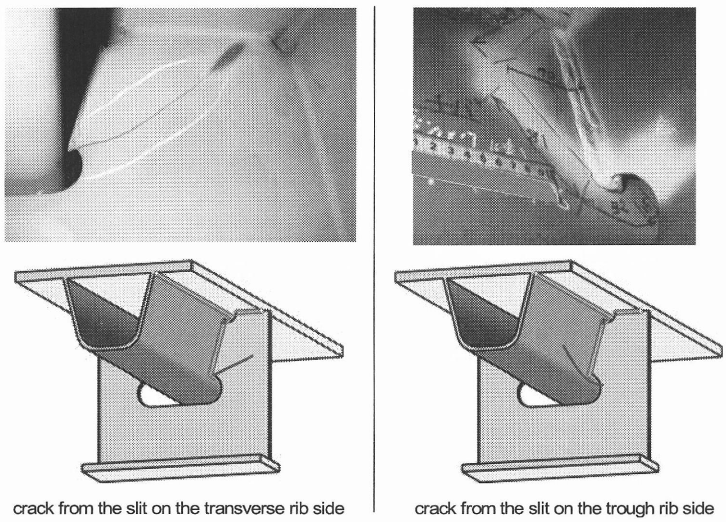


Fig. 21 Typical cracks at the connection of transverse rib and trough rib

3.2 Analysis Models

The deck thickness and the trough width were set as 16mm and 400mm. Span of trough rib is 4000mm in this study, a conventional span is from 2000mm to 2500mm in Japan. The geometry of transverse rib and trough rib in this study is shown in Fig. 22.

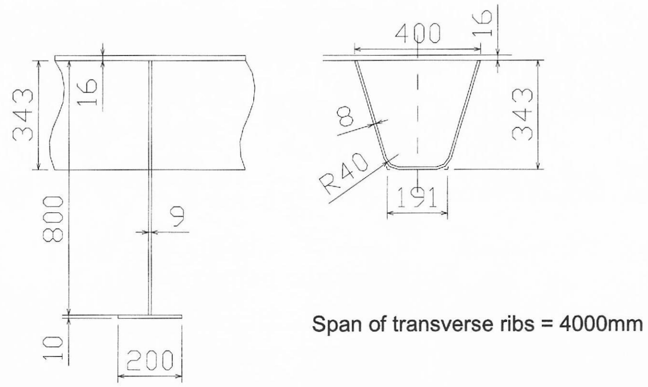


Fig. 22 The geometry of a basic form

The numerical models were consists of bridge model and zoomed-up model as shown in **Fig. 23**. Stress distribution around the slit is analyzed by using the deformation of trough rib and transverse rib around it. Bridge has 120m length and 24m with. Zoomed-up models are prepared for various slit forms. Zooming model has 3 trough ribs and 3 transverse ribs. All the models are created with shell elements. Slit forms are minutely modeled for comparison study. The size of shell element around toe of weld is the same in every model. The shell thickness along the weld toe was modeled as a thick plate as shown in **Fig. 5**. Every model was created with shell elements. Analyses were conducted as linear condition. Elastic module of steel is 200 GPa. Poisson's ratio is 0.03.

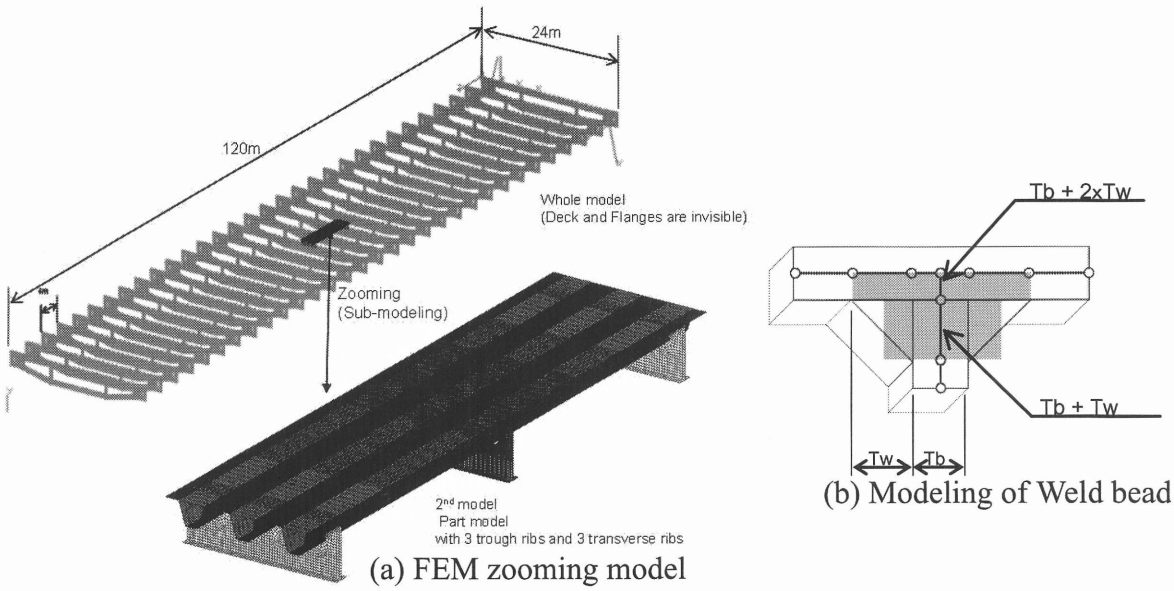
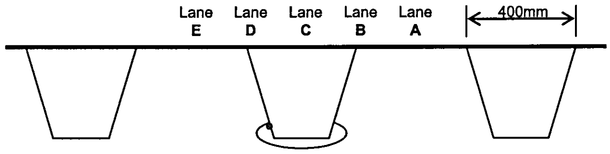


Fig. 23 Numerical model

Loading weight is 120 kN, considering the most heavy truck condition. **Fig. 24** shows the load patterns.



Loading condition (Double tire size)

Fig. 24 Load patterns

3.3 Characteristic behavior of trough rib

Relationship between Loading positions (lanes) and local stress was investigated. Typical type of slit geometry was used for FEM analysis. **Fig. 25** shows the stress change corresponding to the loading on lane A to lane E. The stresses in the figure represent hot spot stress at the lower slit of trough rib side as shown in orange point.

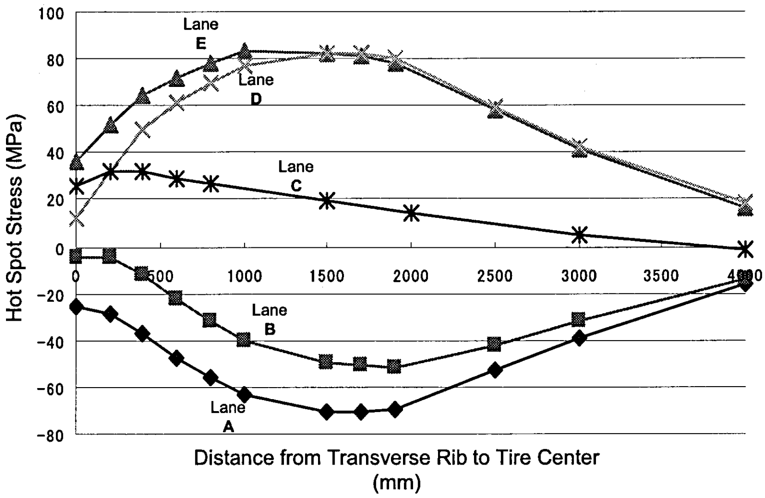
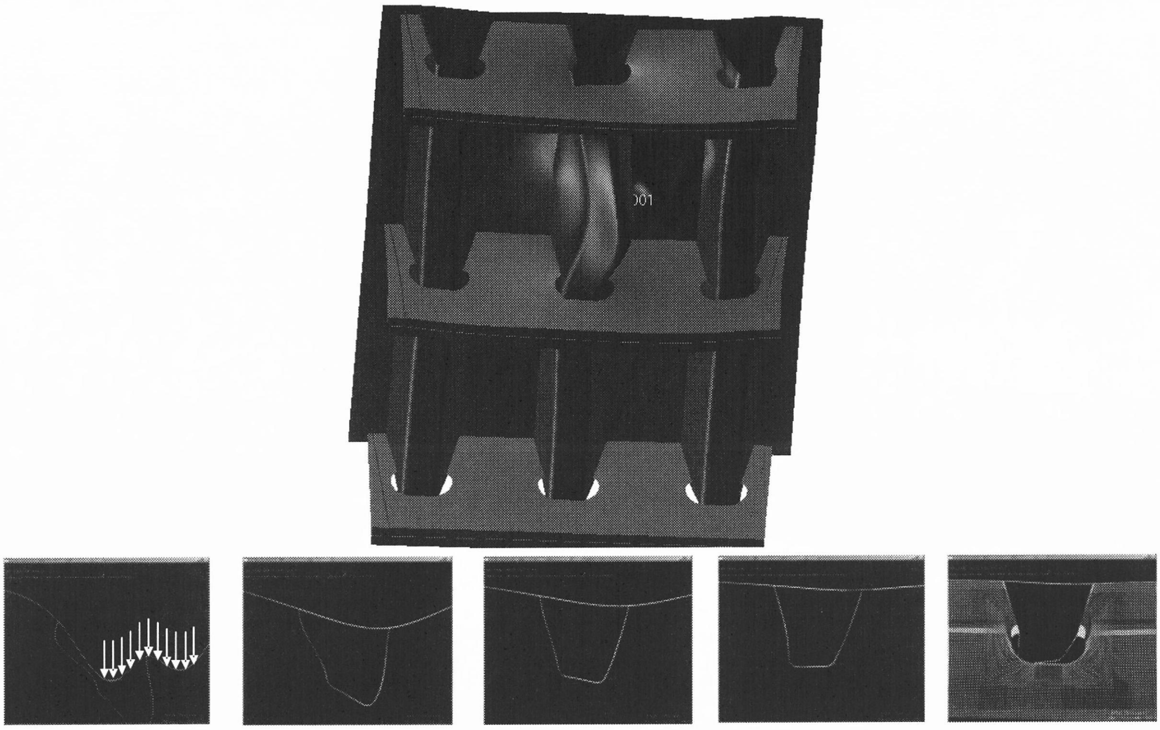


Fig. 25 Difference of stresses relating to the lanes

Stresses are drastically changed according to the changes of loading lanes. There are two special features concerning the stress change. 1) The stress range of lane C is relatively lower than others, although the lane C is center of the target trough rib. 2) Stresses changes from tensile to compression when the load lane is moved from on the measured side (lane D and E) to the opposite side (lane A and B). Deformation of the trough rib may cause this characteristic feature. The deformation of the trough rib when the load is located on lane D, 1500mm from transverse rib is shown in **Fig. 26**. It is clear that the lateral shift of trough rib was restricted by transverse rib and only the bottom flange can shift because slit allows deformation and this causes local bending of trough rib web at the end of slit. Loading on lane C does not induce high stress because the lateral distortion of trough rib is small.



L=1500mm L=800 mm L=400 mm L=100 mm L=0mm (on Trans.Rib)

Fig. 26 Deformation of the trough rib, from loading point to cross part

3.4 Results of parametric study

Geometry of slit form is set as parameters. A shape of slit and a weld length of transverse rib and trough rib are studied. Lane D loading which gives maximum stress is selected as representative loading case here.

3.4.1 Shape of scallop

Two types of scallop shape, perpendicular type and smooth type are prepared as shown in **Fig. 27**. The perpendicular type has an advantage in easy assembly. On the other hand, the smooth type leads smoothly flow of stresses. The welds of the both models are fillet weld.

A connection length of trough rib and transverse rib are same in both type. The hot spot stresses on the toe of trough rib side are shown in **Fig. 28**. Almost same stresses are found in both type. Min. principal stress contours are shown in **Fig. 29**, when the load located on the lane D at 1500mm. In the perpendicular type, high stress area is expanded to the weld toe (fictitious line plotted to show the toe). On the other hand in smooth type, stress range decreased at the weld toe.

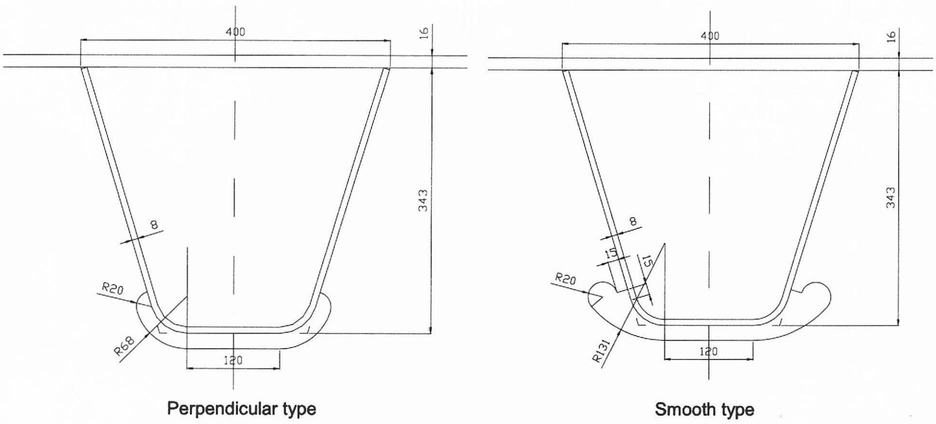


Fig. 27 Models for discussing Connection form of slit

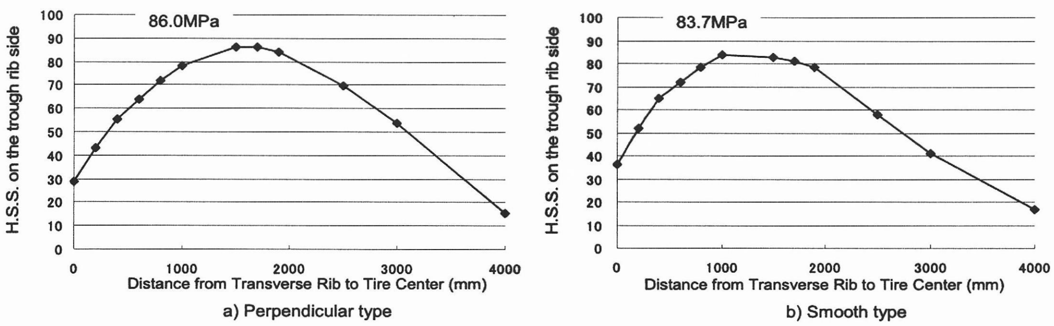


Fig. 28 Stresses on the toe of trough rib side

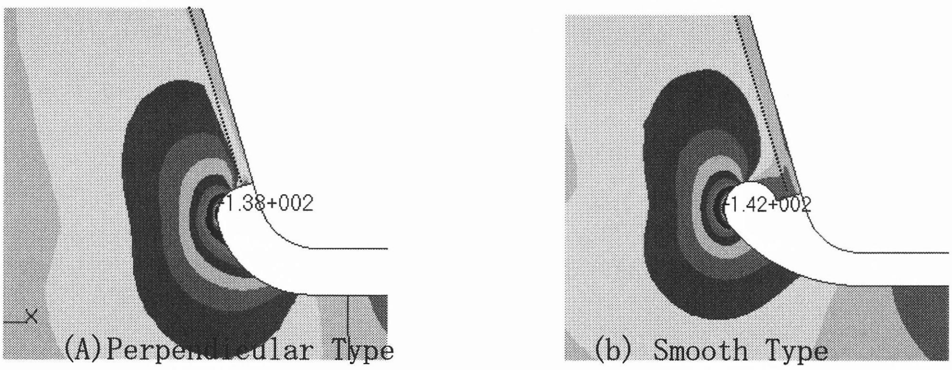


Fig. 29 Min. principal stress contours (Lane D, 1500mm)

3.4.2 Welded length of transverse rib and trough rib

3 types of the models were prepared for comparing the effect of weld length of transverse rib and trough rib. These models are shown in **Fig. 30.** Scallop is smooth type. The weld length of the "long weld length type" is decided based on weldability. The deformation of trough rib at the junction can be restricted in the long welded type. Hot spot stresses on the trough rib side are shown in **Fig. 31**. The small scallop results in the smallest local deformation and stresses in "the long welded length type". Large scallop reduces stress concentration at the boxing weld in case of "the short welded

length type". But the stresses are almost same in all models. In the short welded type, the short welded length lead to the shortage of share capacity at the connection. Stress level in 3 scallop types are not low enough from fatigue point of view.

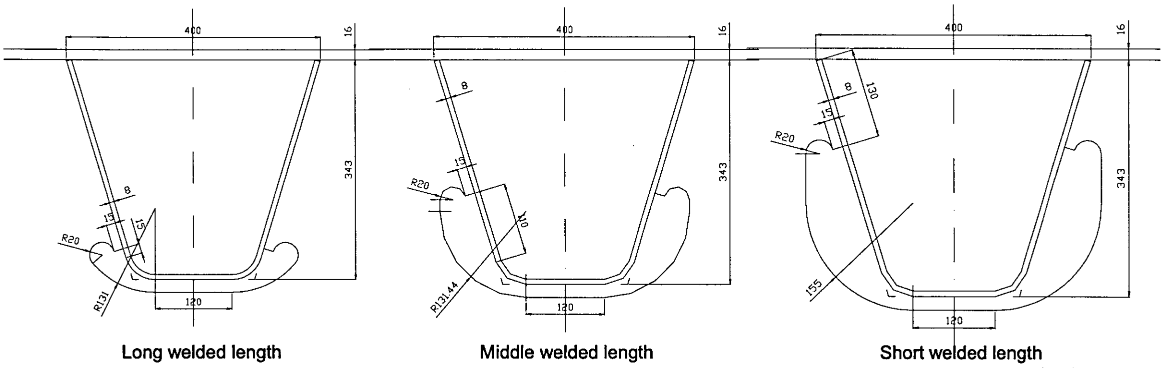


Fig. 30 Models for discussing welded length of transverse rib and trough rib

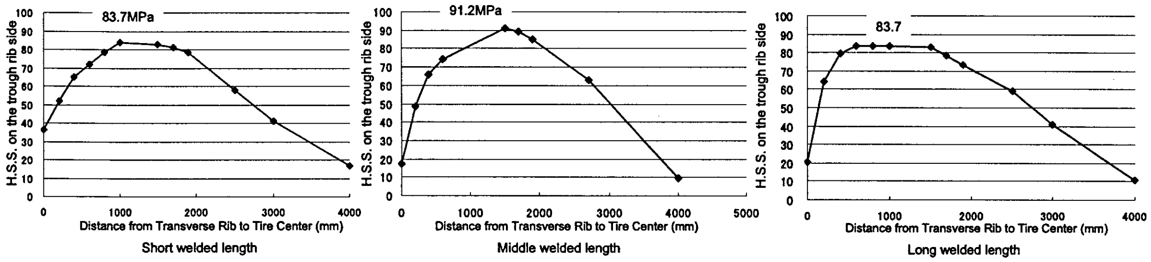


Fig. 31 Stresses on the toe of trough rib side

3.4.3 Tying the lower flange of trough rib

There is a limitation to reduce the stress on the trough rib by changing only the scallop geometry. Further stress reduction methods with installing additional members are investigated.

Lateral movement of the lower flange of trough rib causes the stress as mentioned before. By tying the lower flange to the transverse rib, the stress reduction can be expected. Example of tied model is shown in Fig. 15. This model shows the best performance of all. But it turned out that the connected point will be a new stress concentration point. Hot spot stresses are shown in **Fig. 33**. Stresses on the trough rib web side decrease as expected, but high stress concentration occurred on the lower flange connection.

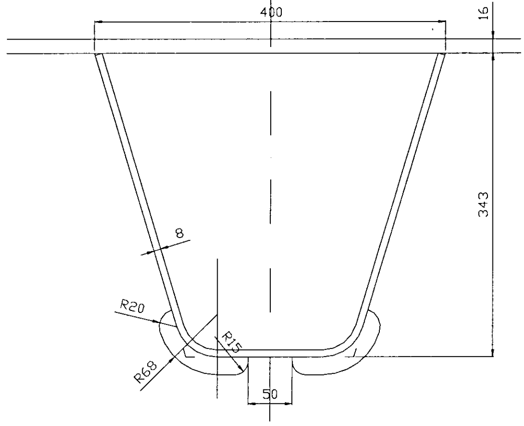


Fig. 32 Example of tied model

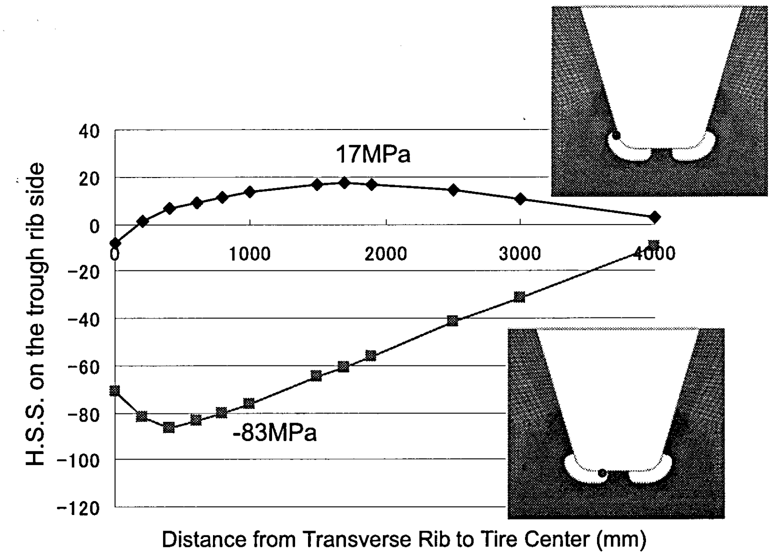


Fig. 33 Stresses on the toe of trough rib side and lower flange side

3.4.4 Inner Rib

The stress distribution was aimed by installing the inner rib. Thus the inner rib was expected to resist the deformation on the end of slit form. Figure 17 shows the discussed models. Parameters are the size of the inner rib. The possibility of crack initiation also joins the point of an inner rib. Analyses were performed in consideration of stress alternating.

The hot spot stresses on two points are shown in Fig. 18. The height of an inner rib differs between Type A and Type B. Thus the stiffness of inner rib is difference. As a result of comparing Type A and Type B, when the stiffness of an inner rib drops, the stress range by the side of an inner rib will decrease. On the other hand, the stress on the slit side goes up. The inner rib was lengthened in order to reduce the stiffness of an inner rib on Type C. Although the stress on the inner rib side decreased further, increase on the slit side is slight. The long inner rib relaxes the bending of a trough rib.

As a result of parametric study, the geometry of an inner rib is effective to raise a slit rear-face part's stiffness, in order to decrease the stress on the slit side. On the other hand, in order to decrease the stress on the inner rib side, it is effective to lower the stiffness near an inner rib head.

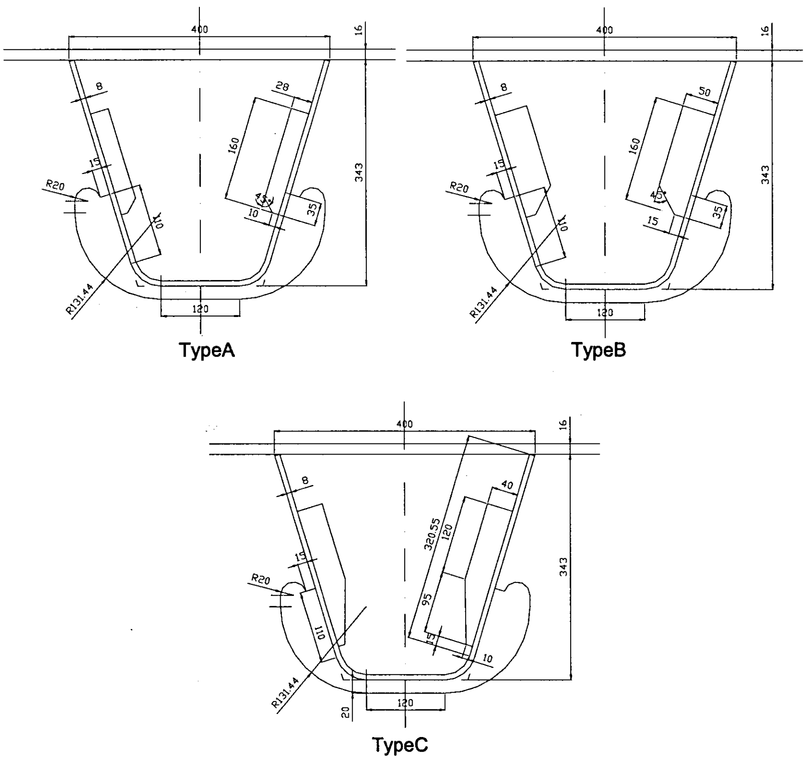


Fig. 17 Models for discussing the size of inner rib

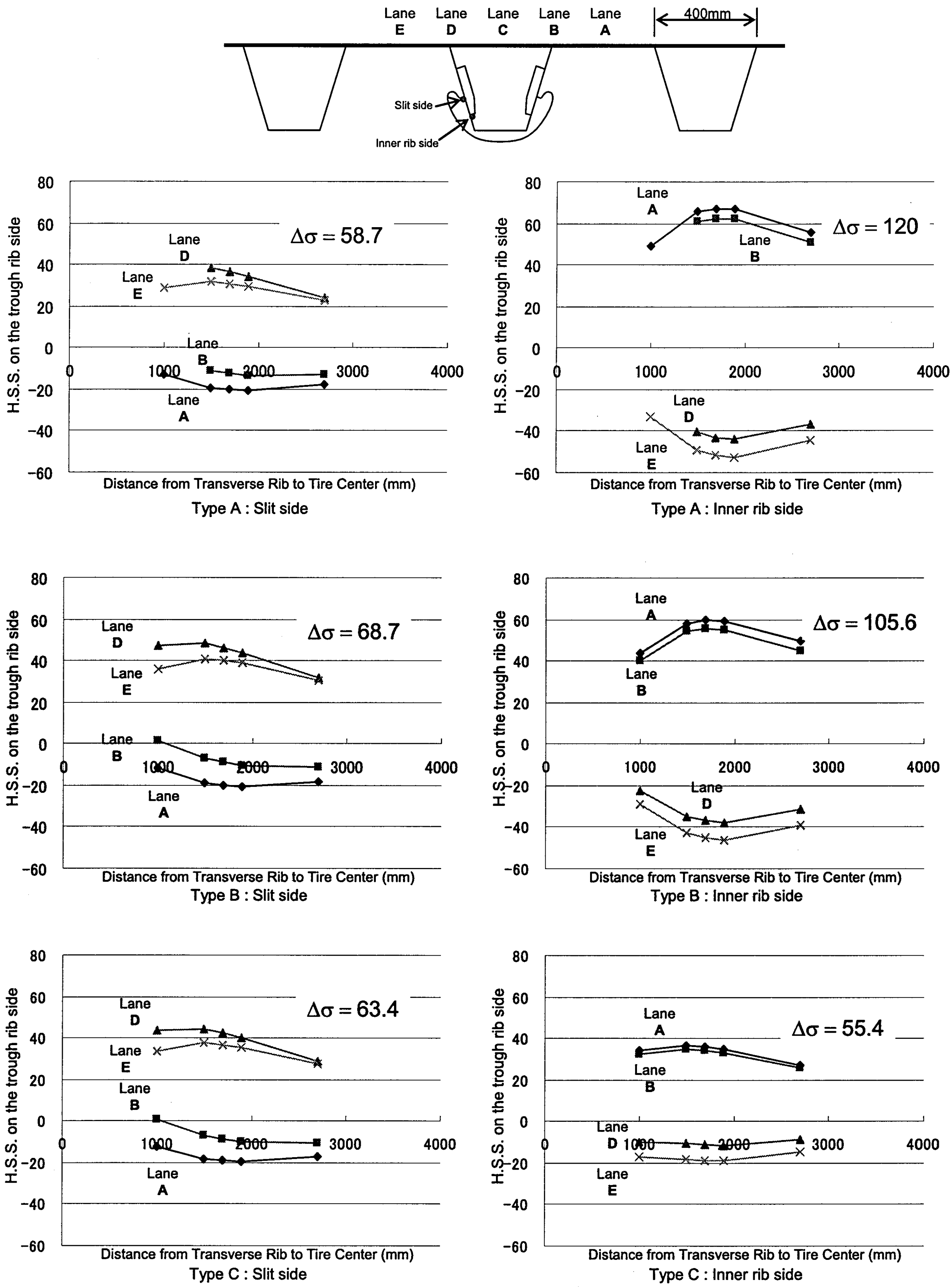


Fig. 18 Stresses on the toe of trough rib side (slit side) and Inner rib side

3.5 Conclusions

In this section, the parametric study with fine meshed FEM was conducted in order to design new orthotropic steel deck structure with high fatigue resistance for slit of trough rib. As a result, the inner rib is the effective way to prevent the crack from the slit on the trough rib side.

(1) Stress alternation is occurred on the trough rib side.

(2) Small slit form is effective to decrease the stress on the trough rib side. It is, however, difficult to reduce the stress sufficiently on the trough rib side only in modification of geometry.

The effective notch analyses which examined the crack from boxing weld of the transverse rib side are under analyses.

References

[8] IIW Joint working Group XIII-XV: "Recommendations for fatigue design of welded joints and components", IIW doc XIII-1965-03 / XV-1127-03

[9] Hisatada SUGANUMA, Chitoshi MIKI, Masayuki TOMIZAWA: " Cause identification of fatigue damage in the orthotropic steel deck structure with box girder " , IIW-XIII-1973-03