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Numerical Analysis for Iron-making Equipments Management

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Abstract

Many of iron-making equipments are used under severe conditions of heavy load and high temperature, and they are used over long period. In order to improve management of important equipments, we have to set inspection interval and repair cycle with considering of possibilities of crack initiation and propagation up to final destruction. Also castings with initial defects must be set inspection criteria in consideration of crack propagation possibility. The application of numerical analysis is valid for crack growth assessment of actual equipments with complicated shapes and use conditions. In this report, we introduce studies on accuracy improvements of numerical analysis, and cases of equipments management based on numerical analysis.

1. Introduction

Iron-making equipment usually handles materials of heavy load sometimes under severe conditions of high temperature and characteristically the service lives of the equipment are long. Therefore, equipment management is sought for on the premise that damages such as cracks will be developed in the mechanical equipment due to degradation over time. As to the inspection and estimation of remaining life based on fracture mechanism, shown in ASME is the method [1)] for pressure vessels in the nuclear power field that takes into account fatigue designing in the manufacturing of the equipment and crack propagation in the equipment after the start of operation.

The problem that emerges when application of a similar method is intended to crucial equipment in iron-making equipment other than the piping and pressure vessel is the lack of data that verifies the relationship between the predicted extent of development of damage and the actual extent of development of the damage. In order to correlate the state of stress at the location for estimation of the development of damage, although actual measurement is desired for stress, since it is difficult to measure in a direct manner, estimation of stress by means of numerical analysis is conducted. Furthermore, even concerning the development of damage of the latter issue, the amount of information is insufficient as it has to rely on information when damage becomes apparent by inspection.

When it is suspected whether or not the stress estimated by numerical analysis is equivalent to stress actually generated, it has to be admitted that confirmation of the appropriateness of external force and thermal stress as the premise of development of stress has to be made in an indirect manner. In case parts are not jointed together within an equipment in a completely secured manner, a contacting condition affects propagation of force greatly. Furthermore, when generation of high thermal stress reaching the plasticity region is unavoidable as an external factor, the physical properties of material at high temperature or heat transfer condition at the contact area greatly influence the correctness of the results. As for the information about the development of damage in a large equipment, since acquisition of the information either by exchanging the equipment or by a detailed investigation by disassembling the equipment is impossible, it is necessary to find the development process by numerical analysis in such a manner that the final result of the analysis conforms to the actual result.

This report introduces an attempt of in-house standardization of the concept of maintenance management and optimum structure designing with due attention paid to the risk of crack propagation based on an example of designing and managing a molten iron ladle by using numerical analysis. Furthermore, although it is difficult to make cast-metal objects used in iron-making equipment completely free of internal defects, an attempt is introduced wherein the dimension of a harmful defect that will generate cracks is calculated at each section based on the numerical analysis and the result is incorporated to the inspection standard of nondestructive inspection (as allowable defect dimension).

2. Molten Iron Ladle Equipment Management Taking into Account Crack Development Risk

2.1 Load of molten iron ladle

A molten iron ladle is a container that transports molten iron of

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maximum about 400 tons. In conventional mechanical designing, optimization of form or the like is conducted in such a way as not to generate stress exceeding the elasticity region; however, the thermal stress generated when a ladle receives a high-temperature material can never be relieved even when rigidity is enhanced. For this reason, for a certain equipment, designing and equipment management based on the premise of time degradation under the condition of high stress reaching the plasticity region have to be conducted.

Figure 1 shows the structure and the operation cycle of a molten iron ladle. A ladle consists of a shell and internally lined refractory, and in this structure, high stress is generated during operation in the neighborhood of the joint section of the side shell plate and the base shell plate (hereafter called the ladle corner section). **Figure 2** shows the result of numerical analysis of stress variation. There are two kinds of variation of stress: the variation of stress with a long interval of cycle that takes place while preheating at the time of ladle repair and the variation of stress with a short cycle having a small amplitude that takes place while receiving molten iron. The major factors of development of such are classified as thermal and mechanical factors. The thermal factors consist of a pressure from inside the ladle due to thermal expansion of the refractory and the thermal stress due to temperature deviation in the shell. Furthermore, mechanical factors consist of the weight of the refractory and molten iron, the tare weight of the ladle when lifted, and the effect of tilting of the ladle when discharging molten iron.

2.2 Development of highly accurate refractory behavior model

As **Fig. 3** shows, among the kinds of stress generated in the neighborhood of the ladle corner section, stress generated by the expansion pressure of the refractory in preheating stage is greatest. In this study, in order to improve the accuracy of physical properties of the refractory to be incorporated to numerical analysis, expansion ratio of the refractory and the reactional force to expansion were measured by using an apparatus as shown in **Fig. 4** for measuring reactional force of brick thermal expansion and the measured values were used as physical properties for the analysis. As for refractory, when the whole of not only bricks solely but also joint material inclusive is overviewed, the joint material becomes hard to be deformed when shrinking exceeds a certain value. Then, in the analysis, behavior of the joint material is expressed by a model of nonlinear spring and improvement in analysis accuracy was attempted.

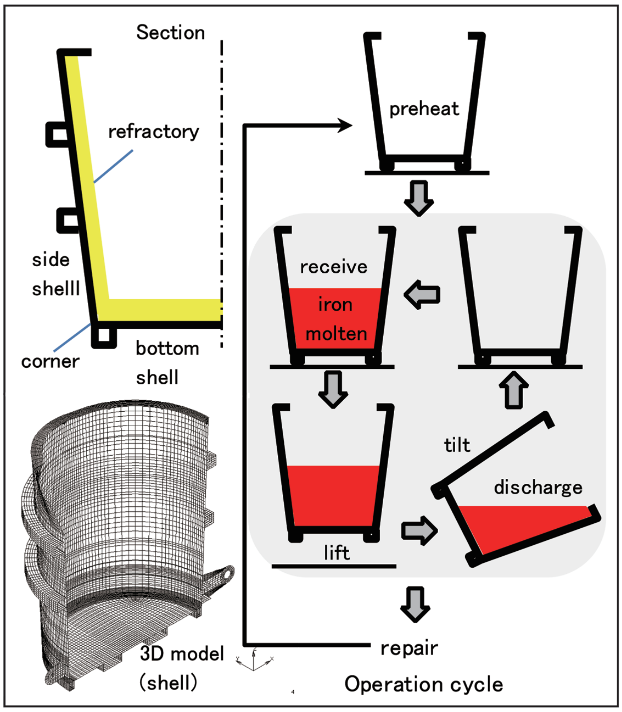

Fig. 1 Structure and operation cycle of molten iron ladle

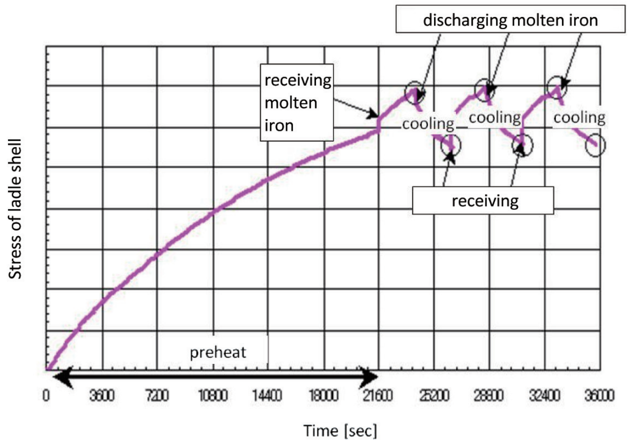

Fig. 2 Stress variation of molten iron ladle shell

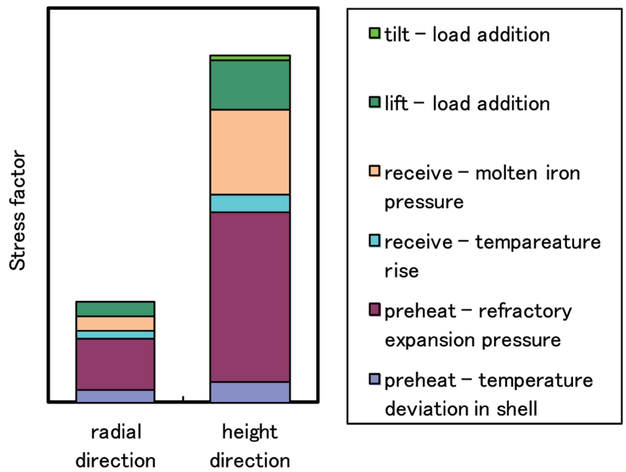

Fig. 3 Stress factor of molten iron ladle shell

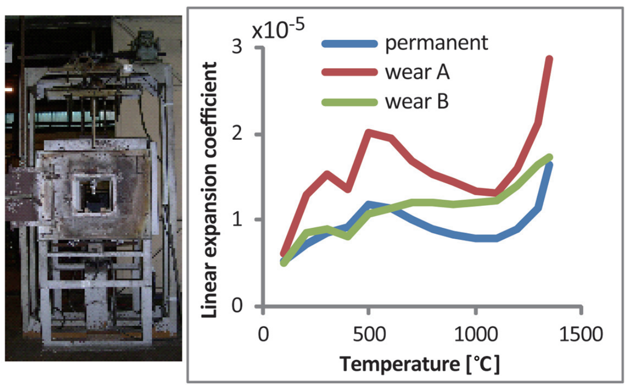

Fig. 4 Measurement of refractory linear expansion coefficient

Yet in the analysis, since lade shell and only the pressure exerted to the ladle shell by heat expansion is sufficient as major items of study, therefore concerning bricks, bricks of common physical properties were treated as a continuum. On the other hand, for a certain subject of study on brick work structure, often the problem of damage mechanism such as gap openings, cracks in the joint material and fracture of brick works become included and needs for analysis of such damage mechanism including heat transfer in the structure of a discontinuous corpus become high. To meet such needs, in Nippon Steel & Sumitomo Metal Corporation, NS-Brick was developed[2] based on the Rigid Bodies-Spring Model (RBSM)[3,4] developed by Kawai et al. Since the element of RBSM is a rigid body, states of strain and stress within an element can't be grasped and therefore handling of deformation of a structure and propagation of a crack is limited. Then, based on the principle of virtual work of mixed type with addition of strain method to deformation method, new brick work structure body analysis program NS-Brick II was developed, employing Hybrid-type Penalty Method (HPM)[5] developed by Takeuchi et al. The program is applied to coke oven furnace body analysis and the like currently.

2.3 Estimation of crack propagation at stress-concentrated section

In order to improve the accuracy of analysis, concerning temperature, shell temperature was measured on an actual ladle and the heat transfer between the molten iron and the ladle internal lining wall and the inter-refractory heat transfer boundary conditions were modified. Furthermore, concerning shell stress, by taking into account the state of contact of refractory with shell in addition to precise study on physical properties of refractory, conformity of analysis result to the result of measurement of surface stress of an actual equipment was confirmed. By quantitatively classifying stress-causing factors by thoroughly examining the physical properties of brick including the pressure caused by brick expansion, effective verification using FEM analysis was realized. Stress factors at the ladle corner section are as follows;

- Large amplitude load at every ladle repair is attributed greatly to the effect of brick expansion.
- Small amplitude load at receiving molten iron is mostly attributed to the static pressure of molten iron.
- Both large and small amplitude loads act as a bending force at the root base.

Next, fatigue life and crack propagation characteristics of ladle stress-concentrated joint section of the side shell plate and the base shell plate were estimated. In order to implement crack propagation management during operation, precise study on stress concentration at the section is necessary, and as shown in **Fig. 5**, a method for conducting zooming analysis in elasticity-plasticity analysis based on the result of analysis of the entire ladle was selected. Long-interval cycle fatigue life is estimated with total strain. Possibility of brittle fracture when crack propagates is estimated by judging whether crack propagation form will be stable one or unstable one from the strain generated in the neighborhood of a crack and, by estimating the allowable crack depth for the material used (toughness) in the loading with large amplitude generated at the time of restarting after repair (**Fig. 6**).

With the study as abovementioned, time of generation of a crack and the brittle-crack-generating conditions can be grasped in advance and plans of quantitative crack propagation management including inspection and maintenance planning during service life period has been worked out for each of ladle forms. Since required toughness values of steel materials vary depending on such factors as material of ladle shell (yielding strength and so on), structure of ladle shell (plate thickness inclusive), operating condition (kind of brick used inclusive) and form of weld toe, for ladles using low toughness material, crack propagation estimation (estimation of possibility of propagation to brittle fracture) should be conducted independently by FEM analysis and using material testing data.

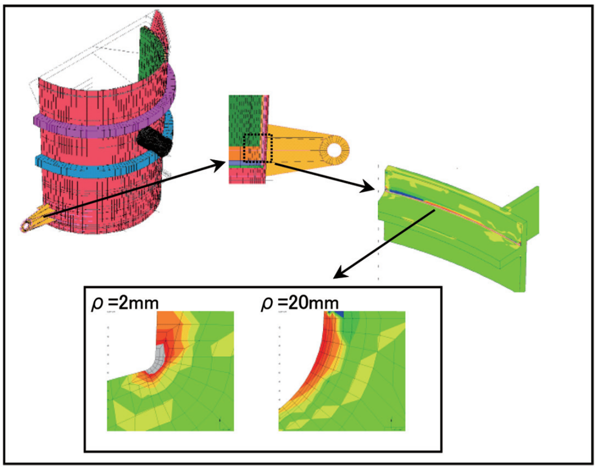

Fig. 5 Zooming analysis of hot spot

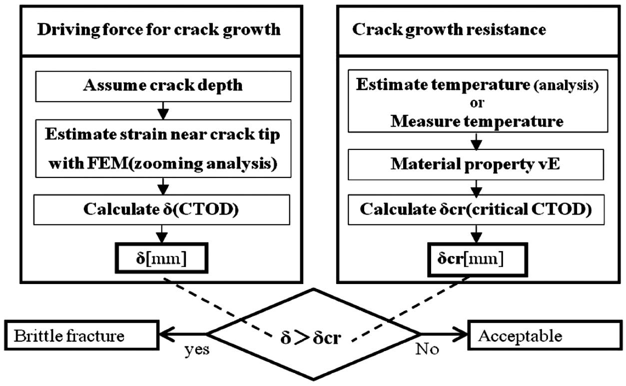

Fig. 6 Criteria of brittle fracture

The abovementioned concerns the maintenance and management of ladles already under operation and, in case of building new ladles, fatigue life at the ladle corner section is estimated, and steel material to be used, form of finished weld toe, refractory to be used (brick) are designed so as to satisfy operating conditions of ladles.

3. Inspection of Casting-metal Object Having Initial Defect

3.1 Estimation of crack propagation initiated at casting defect

There is a number of equipment manufactured by casting among iron-making equipment and some examples show a case where a crack initiated at a casting defect propagates to a damage after a long service of the equipment and the equipment is inevitably shut down.

Figure 7 is the photo showing the hydraulic cylinder of a slab shearing machine having a shearing force of 30MN and is a cast-metal object about three meter in width (material SCW490). The equipment ceased to be operated as a crack was found on the cylinder surface and samples taken at the surface crack by core boring showed the existence of an internal defect where the crack was initi-

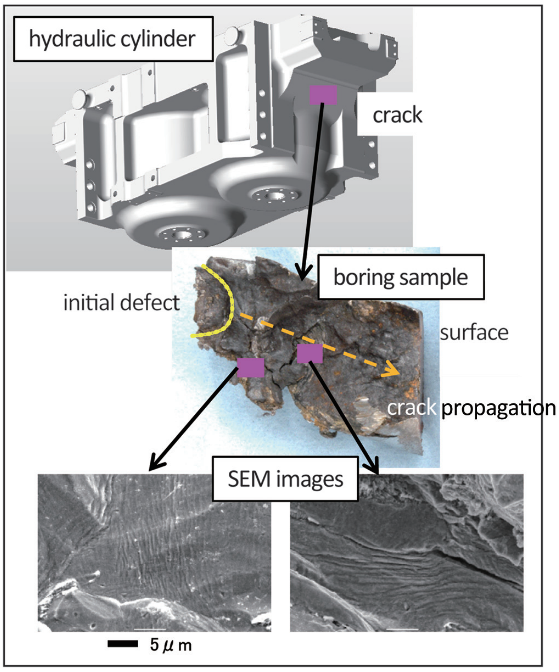

Fig. 7 Crack on hydraulic cylinder

ated. Segregation of phosphorous on the surface of the defect was confirmed by EPMA and the defect was presumed to have been developed during casting.

Here, scope of stress intensity factor is calculated from the stress distribution obtained from numerical simulation and by finding crack propagation rate with modified Paris equation, it was confirmed whether or not the calculated number of frequency of loading during the period of crack propagation from an internal defect to surface agrees with that of actual value (**Fig. 8**).

Equation (1) shows the crack propagation rate indicated by modified Paris equation.

$$\frac{da}{dN} = C \times \left(\Delta K^m - \Delta K_{th}{}^m\right) \tag{1}$$

In Japan Welding Engineering Society (WES-2805) and Society of Steel Construction of Japan (JSSC), a parameter is shown to each welded joint of welded structure and the following value is shown to a mean curve.[6, 7)]

$C = 1.45 \times 10^{-11}$, $m = 2.75$, $\Delta K_{th} = 2.45$ MPa $\sqrt{m}$

Although in welded joints, the parameter is based on the premise that residual tensile stress exists, and concerning cast-metal objects, each parameter was decided by assuming that residual stress is not high, and furthermore, by assuming that the stress is pulsating stress (stress ratio = 0) as stress under no load is of the tare weight and sufficiently small as compared to the stress under loaded conditions. The parameter becomes as below.

$C = 5.39 \times 10^{-12}$, $m = 2.75$, $\Delta K_{th} = 8.14$ MPa $\sqrt{m}$

As a result, gradually increasing its propagation rate, the crack had reached both surfaces at the 1 500 000th operation cycle, piercing through the entire thickness. On the other hand, the total actual cycle of operation was 1.4 million. From this, it is found that; for finding the elapse of time of propagation of a crack from a defect to a surface, use of stress analysis based on numerical simulation and fatigue crack propagation analysis conforming to WES was confirmed to be effective in the actual equipment. Furthermore, with this study, it was also confirmed that assumption of the study that residual stress in cast-metal objects is of no problem as it is negligibly small (**Fig. 9**).

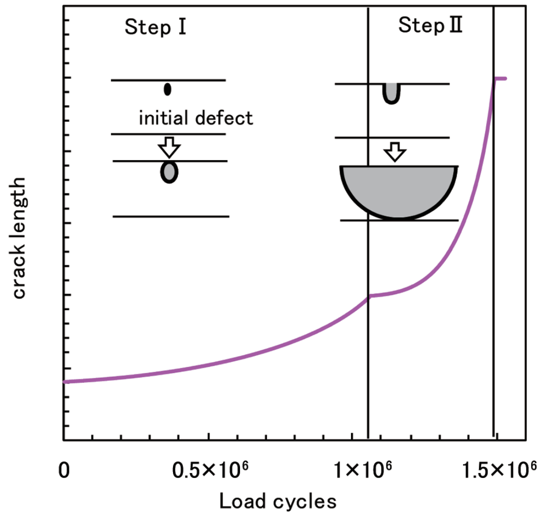

Fig. 8 Analysis of crack propagation

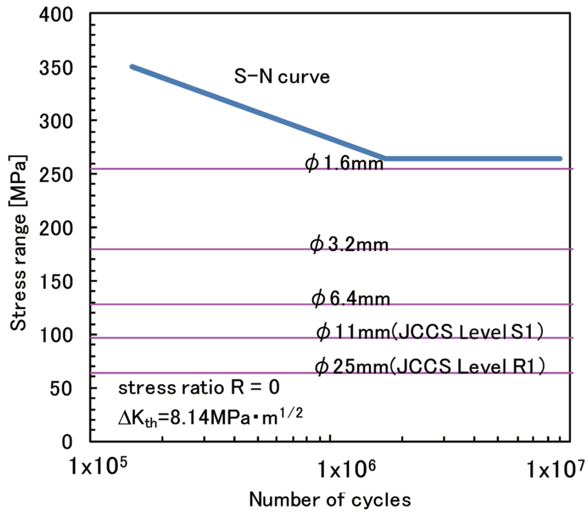

Fig. 9 Relation between defect size and allowable stress range

3.2 Establishment of acceptance criteria in non-destructive testing of cast-metal objects

Although it was known that an initial defect produced in the latter stage of casting triggers initiation of a crack, the defect had passed the UST inspection at the time of manufacturing and the actual dimension of the defect was within inspection standards. However, the stress at the defect position was relatively high of about 70 MPa; scope of stress intensity factor found together with crack dimension exceeded the lower limit of stress intensity scope. Thus, when a crucial equipment is manufactured by casting, appropriateness of acceptance criterion of inspection for a casting defect developed during manufacturing and inspection points become a matter of deep concern.

On the other hand however, applying a high standard inspection level that does not allow minute defects scattered throughout the entire region of a cast-metal object is not economical.

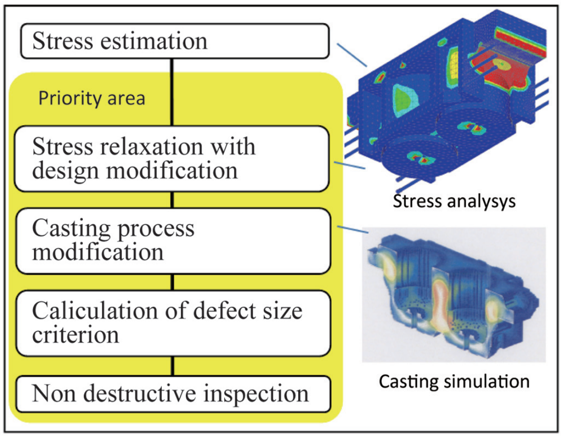

Fig. 10 Procedure of defect minimization and inspection

Then an appropriate way to minimize the effect of the defect is; to apply general inspection acceptability criterion in the first place and, to apply more stringent inspection acceptability criterion to the sections where stress developed is high and a crack will propagate even if the defect size is allowed by such criterion.

Specifically, at first, stress generated is calculated by numerical simulation under an assumed equipment operating condition. Here, areas where stress developed was high were specified as prioritized control areas and stress-alleviating to the extent possible by means of modifying configuration was attempted. Further, the allowable defect size is sought for of which stress intensity factor based on the premise of alleviated stress does not exceed the lower limit of the stress intensity scope. In the areas where stress generated is high, allowable defect size becomes small and this means consequently; stringent acceptability criterion has been applied to prioritized control areas. In this example, the criterion was based on the SI Standard of Steel Castings and Forgings Association of Japan (JCSS).[8] Furthermore, for prioritized control areas, a casting process suppressing the generation of defects becomes necessary and, pouring positions and arrangement of cooling metal were reviewed not to lower the solidification index for the purpose by utilizing casting simulation. In the final inspection after the casting, judgement of acceptability is made based on the predetermined inspection standard and in case a defect exceeds an allowable dimension, the defect is removed or repaired. **Figure 10** shows the summary of the process flow where the following two items are the main points.

- Establishment of areas specified as prioritized control areas and inspection standard corresponding to stress by conducting stress analysis based on assumed equipment operating conditions.
- Study on means for suppressing casting defect generation in prioritized control areas.

As shown in this example, effectiveness of the integrated equipment management from designing stage, manufacturing, inspection after manufacturing and to maintenance thereafter has been confirmed and such integrated equipment control are being applied to such a large casting-metal object such as a rolling mill housing.

4. Conclusion

This report has introduced efforts and application examples of improving accuracy of numerical analysis required for damage development estimation based on fracture mechanics in large ironmaking equipment.

For molten iron ladle, improvement in stress analysis accuracy was worked out by; measuring refractory physical property in entire temperature region, by taking into account non-linearity for joint material compressibility and state of contact of the shell with refractory. Furthermore, by grasping in advance the time of crack generation at the stress-concentrated section and crack initiation condition, quantitative crack propagation management method plan including inspection · maintenance plan during operation was introduced to each kind of ladle forms and is utilized currently for equipment management of molten iron ladles. Possibility of crack propagation estimation by assuming that residual stress in large cast-metal objects is nil was confirmed and a method of establishing economical inspection standard in manufacturing stage was shown.

References

1) ASME: ASME Boiler and Pressure Vessel Code
2) Yamamura, K., Matsuzaki, S., Toh, T., Yamada, Y., Nakagawa J.: Shinnittetsu Giho. (391), 143 (2011)
3) Kawai, T.: J. of the Society of Naval Architects of Japan. 114, 1867-193 (1977)
4) Toi, Y., Kiyosue, T.: Transactions of The Japan Society of Mechanical Engineers. 59 (568), 2858 (1993)
5) Takeuchi, N., Kusabuka, M., Takeda, H., Sato, K., Kawai, T.: Journal of Structural Engineering. 46A, 261-270 (2000)
6) The Japan Welding Engineering Society: Estimation Method of Defects Concerning Generation of Weld Joint Brittle Fracture and Fatigue Crack Propagation. 2007
7) Japanese Society of Steel Construction: Direction and Explanation of Fatigue Design of Steel Structure. Gihodo, 1993
8) Castings and Forgings Association of Japan: Vertical Ultra Sonic Testing Standard for Carbon Steel and Low Alloy Steel Casting Objects. JCSS 14-1984

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