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Can we optimally design light-weight welded structures with sufficient fatigue resistance?

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1. Abstract

A procedure for optimally designing light-weight and reliable welded structures is proposed and applied to the structural design of an illustrative welded structure used in construction and transportation machinery. To verify the effectiveness of the proposed procedure, the designed structures were experimentally produced and evaluated. According to the proposed procedure, a target welded structure is structurally optimized by constraining structural hot-spot stress so that the structure has sufficient fatigue resistance to weld-toe failure. Regardless of the thicknesses in the target structure, during the structural optimization only one finite-element model that has partially fine meshes at weld toes is used to estimate structural hot-spot stress. This mesh division makes it possible to estimate structural hot-spot stress without re-meshing the model. Weld-root failure by fatigue is then assessed by using local-notch stress, because weld-root failure cannot be evaluated by using structural hot-spot stress. Two kinds of test pieces based on the designed welded structure were experimentally produced by changing the weld type of the joints between a top plate and a side plate, i.e., one- or two sided fillet weld, and the test pieces were fatigue tested to verify their fatigue resistance. The produced structures had the fatigue lives predicted through the design and assessment processes, and as a result, it can be concluded that welded structures can be optimally designed by using the proposed design procedure.

2. Keywords: Welded structures, structural optimization, fatigue assessment, structural hot-spot stress, local-notch stress.

3. Introduction

Mechanical designers have been required to develop light-weight products, such as transportation and construction machinery, because the light-weight products are suitable for a “sustainable society;” namely, one that must save raw material and fuel for operation of machinery. When welded structures in machinery are being designed, attention must be paid to their fatigue resistance, because they are subjected to cyclic loading during operation; hence, a welded part in such a structure could become an initiation site of a fatigue crack. The International Institute of Welding (IIW) therefore publishes a recommendation that provides approaches for evaluating the fatigue life of welded joints [1]. The recommendation gives three approaches, which are based on nominal stress, structural stress, and notch stress. When the nominal stress, which is uniformly distributed at the cross section of the plates composing a welded joint, is known, the nominal stress approach can be easily used to check the fatigue resistance; that is, the allowable value of stress is obtained by selecting a weld detail from the catalogue of weld details, and compared with the known nominal stress. However, it is not easy to use this approach when the welded joint to be designed is not simple enough to allow the nominal stress to be estimated. In this case, instead of the nominal-stress approach, the structural-stress or notch-stress approach can be used. As for these approaches, finite-element analysis is used to estimate stress at the welded joint. The structural-stress approach is particularly suitable for evaluating the fatigue resistance of large welded structures, because structural stress can be analyzed even with a finite-element model composed of shell elements; shell elements are frequently used to model a large structure.

In addition to the availability of fatigue assessment for large welded structures, the structural-stress approach, together with a structural optimization method, can be utilized to design a light-weight and reliable welded structure. As mentioned above, structural stress can be estimated with a finite-element model composed of shell elements. By means of shell elements, the thickness of a modeled structure can be handled easily as design variables during a process of structural optimization. That is possible because the shape of shell elements does not have to be changed to change only the thickness. However, even when only the thickness is optimized, a couple of issues remain to be addressed. For example, since a welded structure includes several welded joints, and a welded joint is a junction of two or three plates, it is necessary to determine where in a target structure structural stress is estimated and compared with its allowable value before starting an optimization process. Furthermore, although two crack-initiation sites, i.e., weld toe and weld root, are possible in welded joints, fatigue failure of the weld root cannot be assessed by using the structural-stress approach; that is, the optimal thickness achieved by handling structural stress is not sufficient to avoid fatigue failure of weld roots.

In this study, a procedure for designing light-weight and reliable welded structures is proposed. The proposed procedure is composed of two processes: one is a structural optimization process, where the mass of a target structure is minimized by constraining structural stress, which has previously been proposed by one of authors [2][3]; and the other one is the fatigue assessment process where the fatigue failure of weld roots is assessed on the basis of local-notch stress. To verify the effectiveness of the proposed procedure, an illustrative structure was optimally designed under structural-stress constraints. After this structural optimization, fatigue failure of weld roots at the welded joints having a root face was checked. Furthermore, the designed optimal structures were produced experimentally and fatigue-tested to verify that they have sufficient fatigue strength.

4. Fatigue-assessment approaches for welded joints

4.1 Structural-stress approach

Structural stress includes the stress-concentrating effects of structural details themselves but not the local non-linear stress peak caused by notch at a weld toe. Structural stress is therefore larger than nominal stress but smaller than local-notch stress near a weld toe, as shown in Figure 1(a). Since a weld toe is one of the so-called "hot spots" where a fatigue crack is nucleated, the structural stress observed at the weld toe is called "structural hot-spot stress." The IIW gives guidelines for modeling welded joints with finite elements and calculating the structural hot-spot stress [4]. According to these guidelines, both solid and shell elements can be used to estimate the structural hot-spot stress. In particular, this availability of shell elements might make the optimal design of welded structures possible in product development settings. That is, the thickness of shell elements can be changed without the time-consuming process of changing the shape of elements, i.e., re-meshing a finite-element model; as a result, optimal thickness can be obtained in practical time. However, even when shell elements are applied, it is not a simple matter to estimate the structural hot-spot stress for various thicknesses without re-meshing. This estimation is difficult because according to the IIW guidelines, a finite-element mesh is generated in such a manner that two nodes are placed at 0.4 t and 1.0 t from a weld toe, as shown in Figure 1(b), where t is the thickness of the plate composing a welded structure. This recommended placement of the two nodes might force the re-meshing of a finite-element model during the optimization of the thickness. A procedure for estimating the structural hot-spot stress for various thicknesses without re-meshing is mentioned in Section 5. In addition to weld toes, weld roots are also fatigue-crack nucleation sites. The structural-stress approach, however, cannot be applied to the fatigue assessment of weld-root failure

4.2 Notch-stress approach

When the notch-stress approach is being applied, local-notch stress is calculated and used to assess the fatigue failure of welded joints. Local-notch stress includes stress concentration caused by geometric discontinuity in a weld profile itself, as shown in Figure 1(a). To analyze the local-notch stress by the finite-element method, the weld profile is therefore modeled with finite elements. For this modeling, the IIW recommends that the notch shape of a weld toe and root is replaced by a small arc with a radius of 1 mm [1], as shown in Figure 2. In this way, to add the weld profiles to the finite-element model of a welded structure, the welded structure has to be modeled with solid elements or two-dimensional elements, i.e., plane strain elements. The notch-stress approach is available for assessing the two modes of fatigue failure, i.e., weld toe and root failures, while the structural-stress approach is only utilized for weld-toe failure. However, it is not easy to use the notch-stress approach for the fatigue assessment of welded joints during a process of structural optimization; that is, a complex process for re-meshing the model of a welded structure is needed even when only the thickness of the welded structure is

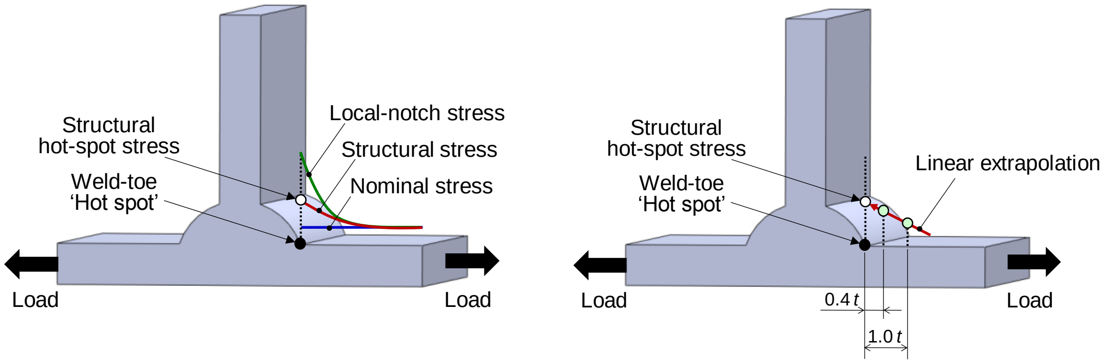


Figure 1: (a) Three kinds of stresses defined at a weld toe and (b) extrapolation to estimate structural hot-spot stress

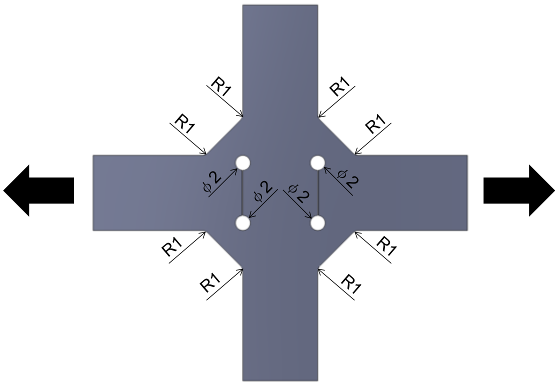


Figure 2: Fictitious rounding of weld toes and roots

optimized. In addition, modeling with solid or two-dimensional elements becomes difficult as the number of welded joints in the structure to be modeled increases. The notch-stress approach is therefore usually used for checking the fatigue resistance of a welded structure that has already been designed [5].

5. Procedure for designing light-weight and reliable welded structures

5.1. Flow chart for designing light-weight welded structures

Light-weight and reliable welded structures can be designed by following the flow chart proposed in this study (see Figure 3). The optimal design is achieved by following two major processes: one is structural optimization, and the other one is fatigue assessment of weld-root failure. The two processes are not repeated but conducted sequentially; accordingly, the whole proposed design procedure is not computational demanding.

In the structural-optimization process, the mass of a welded structure is minimized under constraints on structural hot-spot stress. These constraints are necessary to design a welded structure in such a manner that it does not cause the fatigue failure of weld toes. Since this structural hot-spot stress is estimated by finite element analysis, the finite element model of the target welded structure has to be generated. As mentioned in the previous section, shell or solid elements can be applied to estimate the structural hot-spot stress. Regardless of the availability of either of the elements, in this optimization process, the target structure is modeled with shell elements. This choice of shell elements is based on the fact that a finite-element model composed of shell element is compatible with structural optimization, especially when design variables are limited to the thickness of the plates in a welded structure. Although the optimal design having sufficient resistance to the fatigue failure of weld toes is achieved by this optimization process, designers should also pay attention to the fatigue failure of weld roots.

After the optimization process, the fatigue failure of weld roots is assessed. The weld-root failure is checked at welded joints having a root face. The shell model that is used for the structural optimization can be used in this assessment process. That is, by finite-element analysis with the shell model, node forces and moments can be extracted along the weld lines of welded joints having a root face. Local-notch stress at the edge of a root face is then estimated by employing a database that gives the relation between the node forces and moments and local-notch stress. The optimal structure might be modeled with solid elements instead of shell elements for the fatigue assessment. However, modeling a whole welded structure with solid elements is possible only when the welded structure is quite simple.

5.2. Structural optimization

The structural optimization of welded structures addressed in this study is formulated as

$$\begin{array}{lll} \text{(P1)} & \min_{\mathbf{x}} & f(\mathbf{x}) = \rho \mathbf{A}^{\mathrm{T}} \mathbf{x} \\ & \text{subject to} & g_i(\mathbf{x}) = \sigma_i(\mathbf{x}) - \sigma_{allow} \le 0 \qquad i = 1, m \\ & & \mathbf{x}^{\min} \le \mathbf{x} \le \mathbf{x}^{\max}, \end{array} \tag{1}$$

where $\mathbf{x}$ and $\mathbf{A}$ are respectively the vectors of thickness and the area of the plates comprising a target welded structure, ρ is the density of the structural material, $\sigma_i(\mathbf{x})$ and σ_{allow} are the stress generated in the target structure and allowable stress. Here, $\mathbf{x}^{\min}$ and $\mathbf{x}^{\max}$ are the vectors of minimum and maximum thicknesses.

In the process of the structural optimization, a target welded structure can be optimized by the following three steps. In step 1, a finite-element model of baseline design is generated in such a manner that it has almost equally-sized elements (referred to as “uniform mesh model” hereafter), and then a finite-element analysis is conducted with the model. The analytical result indicates where the hot spots of stress will appear in the welded structure to be optimized.

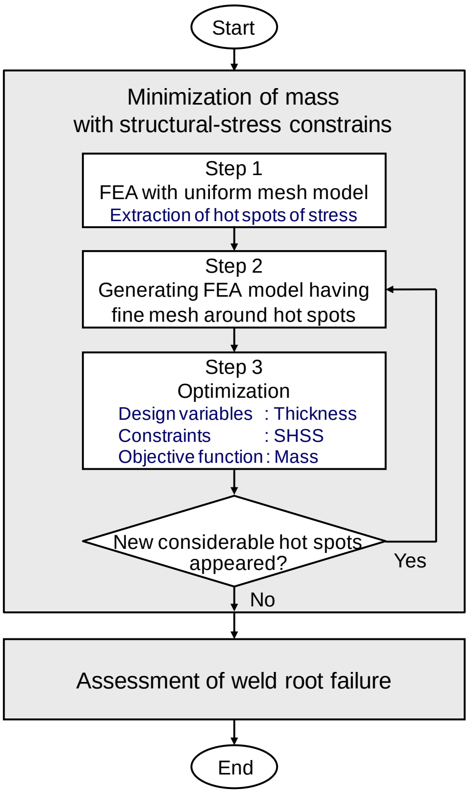
In step 2, the model is re-meshed so that structural hot-spot stress at the hot spots can be estimated; the area around the hot spots is finely meshed, while the element size in the other areas is not changed. To generate fine meshes around the hot spots, lines (referred to as a “stress-extrapolation line,” hereafter) perpendicular to the weld lines are prepared, and nodes are placed on each line at 2-mm intervals. Once the thickness of the plates composing the welded structure is determined, structural hot-spot stress is estimated by selecting the two nodes that belong to a stress-extrapolation line and are placed at 0.4 *t* and 1.0 *t* from the weld toe to be assessed, as shown in Figure 4. By this estimation procedure, structural hot-spot stress can be estimated without changing the fine meshes regardless of the thickness of the modeled welded structure.

In step 3, the thickness of the plates composing the welded structure is optimized under the stress constraints obtained by using the model re-meshed in step 2. Note that re-meshing is not performed in the process of optimization, viz., step 3. Although the structural optimization has already been performed, the hot spots of stress that were not identified in step 1 might be found. In these cases, it is necessary to go back to step 2 and generate fine meshes around the new hot spots that were found.

Since the structural-stress approach is applied to the fatigue assessment in this structural-optimization process, structural hot-spot stress is used as stress $\sigma_i(\mathbf{x})$ in (P1). When the vicinity of a hot spot is in a multi-axial stress state, the IIW recommends employing the principal stress of structural hot-spot stress, $\sigma_{\mathrm{HSS-Pl},\,i}(\mathbf{x})$, to confirm the fatigue strength of welded joints there. By handling $\sigma_{\mathrm{HSS-Pl},\,i}(\mathbf{x})$, the optimization problem (P1) is reformulated as

$$\begin{array}{lll} \text{(P2)} \quad \min\limits_{\mathbf{x}} & f(\mathbf{x}) = \rho \mathbf{A}^{\mathrm{T}} \mathbf{x} & \\ \text{subject to} & g_i(\mathbf{x}) = \sigma_{\mathrm{HSS\text{-}Pl},\,i}(\mathbf{x}) - \sigma_{allow,\,i}(\mathbf{x}) \le 0 & i = 1, k \\ & \mathbf{x}^{\min} \le \mathbf{x} \le \mathbf{x}^{\max}, & \end{array} \tag{2}$$

where *k* is the number of stress extrapolation lines.



（FEA: Finite Element Analysis）
（SHSS: Structural Hot-Spot Stress）

Figure 3: Flowchart for designing light-weight and reliable welded structures

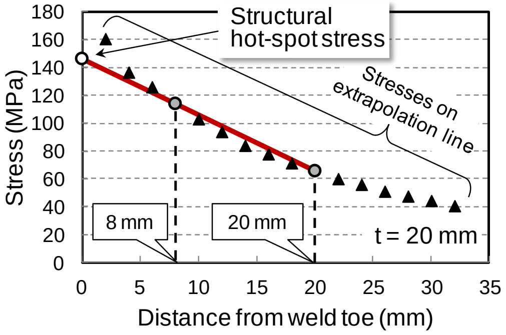


Figure 4: Selection of two nodes for estimating structural hot-spot stress

5.3. Assessment of weld-root failure

The welded structure optimized by following the three steps in Section 5.2 has sufficient resistance to the fatigue failure of weld toes. However, the fatigue failure of weld roots might occur, because only the failure of weld toes is avoided by constraining structural hot-spot stress. The fatigue assessment for weld-root failure is therefore conducted individually after the optimization process. In this assessment process, the same shell model as used in the structural optimization process is applied to this assessment process, nodal forces and moments are extracted along the weld lines of the welded joints having a root face. Local-notch stress at the edge of a root face is then estimated by referring a database (referred to as "notch-stress database," hereafter) that gives the relation between the nodal forces and moments and local-notch stress. The finite element model composed of two-dimensional elements, as shown in Figure 5, can be used for generating the database.

6. Design examples

6.1. Design of L-shape structure

To verify the effectiveness of the flow chart in Figure 3, an illustrative welded structure was designed. The welded structure, which is typically found as a sub-structure of construction machinery such as excavators and dump trucks, is shown in Figure 6. Each gusset plate has a hole with a diameter of 40 mm. It is assumed that one pin is inserted into two parallel holes and load is applied to the welded structure through the pins.

In accordance with step1 of the structural optimization, an automatic mesh generator was used to generate the finite-element mesh of the illustrative structure with almost-uniform element size, i.e., side length of 5 mm. To conduct finite element analysis without modeling the pins, some elements were even generated inside the holes of the gussets. All degrees of freedom of the nodes inside the holes of gusset B were then fixed, and load *F* was applied to the nodes located at the center of the holes of gusset A, as shown in Figure 7. The direction of load *F* was parallel to the line connecting the centers of the holes of gussets A and B. Elastic modulus and Poisson's ratio of the welded structure were respectively set to 210 GPa and 0.3. To take into account the effect of the rigidity of the pins, the nodes at the center of the holes of gusset A were connected with beam elements. The uniform mesh model and the resulting principal stress contour when the thickness of all the plates is 10 mm, namely, the baseline design, and load *F* is 24.5 N are respectively shown in Figures 8 and 9.

In step 2, the local area in the vicinity of the hot spots of stress is finely meshed by referring to the results of finite-element analysis obtained with the uniform mesh model. To generate fine meshes around the hot spots, 48 stress-extrapolation lines were prepared, and points were placed on the lines. The points were utilized by the automatic mesh generator to create nodes at the locations of the points, and the nodes were used to estimate structural hot-spot stress. The fine mesh model is shown in Figure 10.

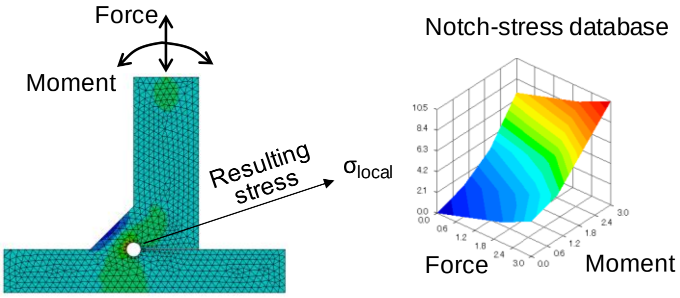


Figure 5: Finite-element model for generating a notch-stress database

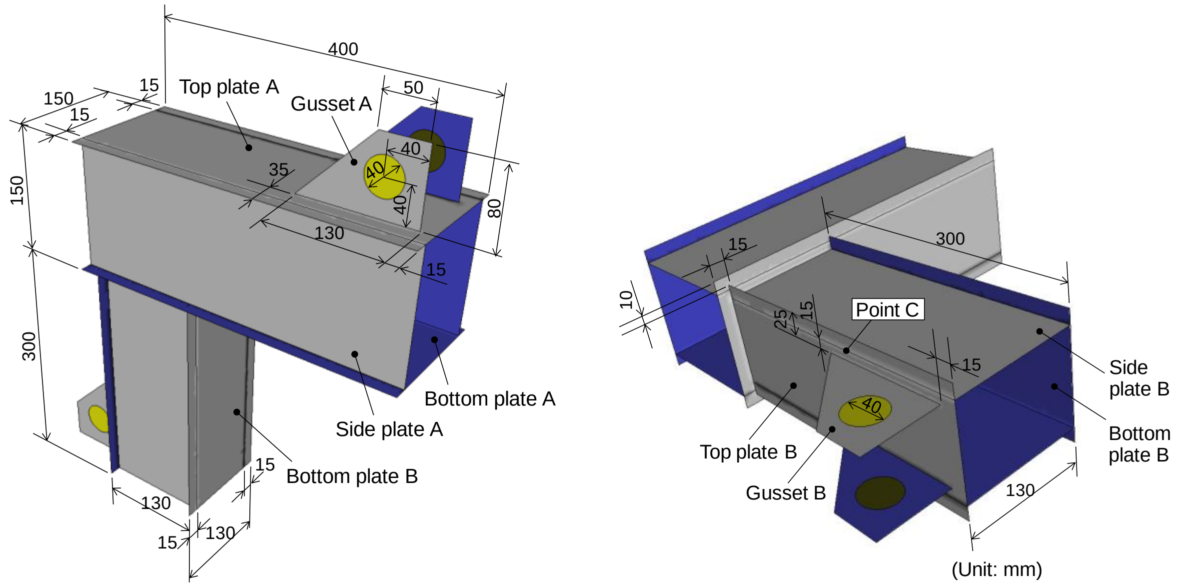


Figure 6: Welded structure typically used as sub-structure of construction machinery

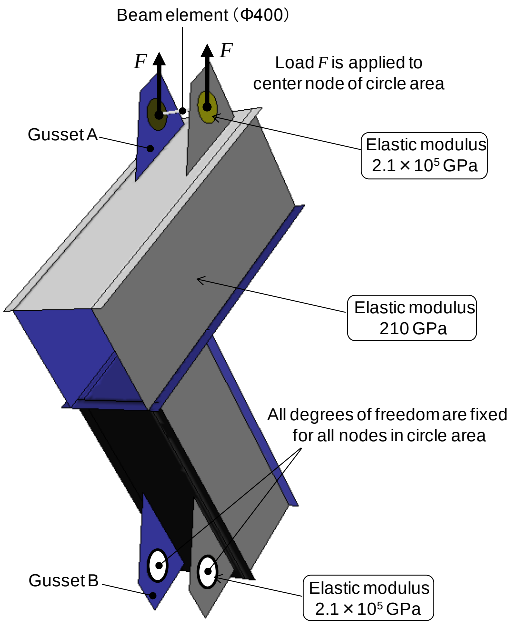


Figure 7: Boundary condition

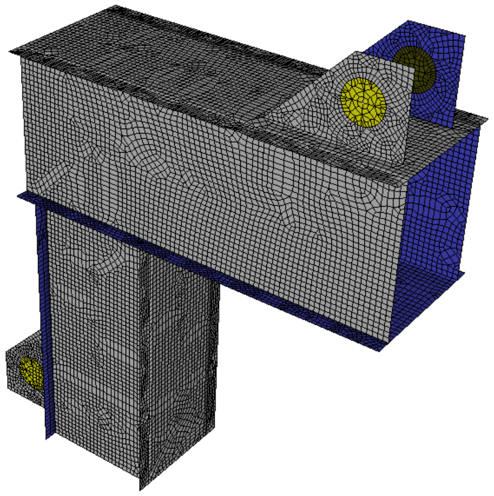


Figure 8: Uniform mesh model of welded structure

In step 3 of the structural optimization, the mass of the welded structure was minimized by changing the thickness of the plates comprising the welded structure. From the aspect of good manufacturability, the thickness should be selected from several standard thicknesses. Nine thickness values were therefore prepared: 6, 9, 12, 16, 19, 22, 25, 28, and 32 mm. Due to this limitation on the thickness values, the optimization problem mentioned in Section 5.2 is a “combinatorial optimization” one, which can be effectively solved by genetic algorithms (GA). In this study, GA was therefore applied to the structural optimization. The design update by the GA is terminated if a solution has survived for 100 generations without a better solution being found. To determine the allowable stress of structural hot-spot stress in (P2), a design curve for structural hot-spot stress should be prepared. According to the IIW guidelines, the FAT class of joints, namely, the stress range that causes fatigue failure at 2.0 million cycles in case of load-carrying fillet welds is 90 MPa if the joints are put into service as welded. The design curve of FAT 90, shown in Figure 11, was used to determine the allowable stress. The structural optimization was performed three times by changing the value of the allowable stress in (P2): 300, 250, and 200 MPa. The applied load was set to 49 kN for all the cases. The mass and thicknesses of the optimized structures are listed in Table 1. Notice that the resulting mass changes in accordance with the value of the allowable stress. The fatigue lives that are expected with the three allowable hot-spot stresses are also listed in Table 1. The fatigue lives listed in the row labeled “Design” are those calculated by using the design curve for structural hot-spot stress, while those listed in the row labeled “Mean” are the lives calculated by using a mean curve for structural hot-spot stress [6]. The design and mean curves express survival probabilities of 97.7 % and 50% for the weld-toe failure.

A one-sided fillet weld is often selected as the weld type that is used for making box structures like the illustrative structure shown in Figure 6. It is a weld type with a root face; therefore, weld-root failure was assessed after the structural optimization. As mentioned in Section 5.3, nodal forces and moments on the weld lines of the structure were extracted, and local-notch stress at the weld lines was calculated by using the notch-stress database. In the case that allowable stress was 300 MPa, the resulting maximum notch stress was 2,642 MPa and observed at point C, which is shown in Figure 6, on the weld line between top plate B and side plate B. The fatigue life of the weld root at point C is determined as 8.6×10^3 from a mean curve for local-notch stress [7], as shown Figure 11. This expected fatigue life is extremely shorter than that for the weld-toe failure. The one-sided fillet weld is therefore not applicable at the weld line between top plate B and side plate B, so a two-sided fillet weld should be utilized there.

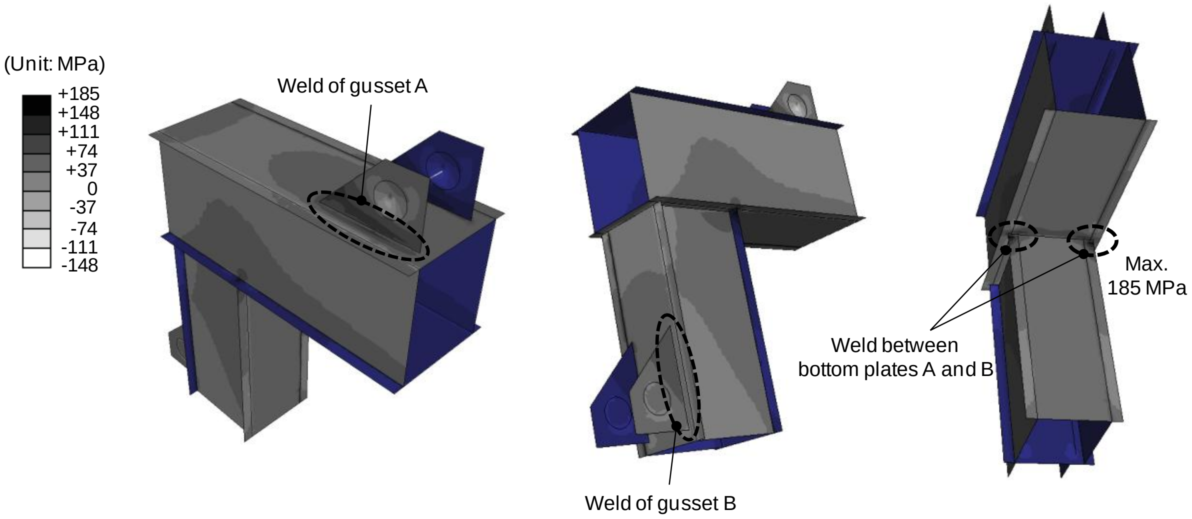
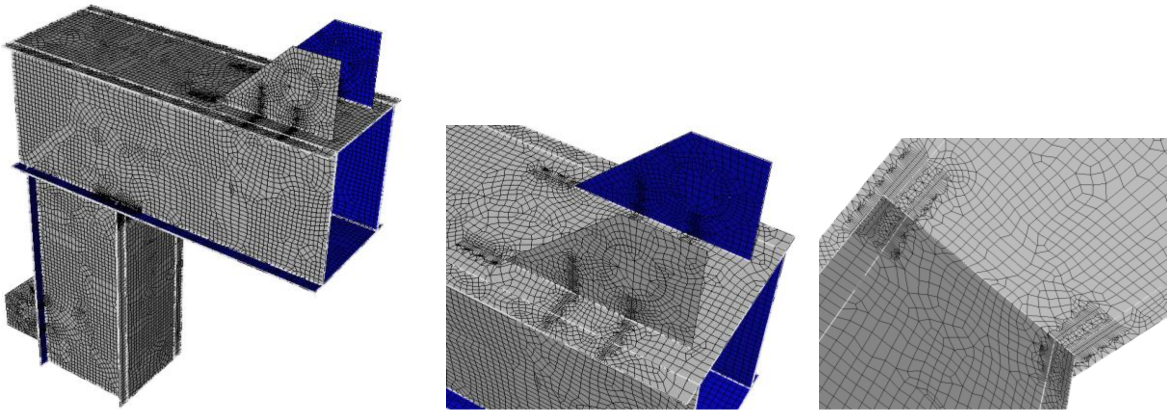


Figure 9: Principal-stress distribution obtained with uniform mesh model



(a) Overall view (b) Gusset A and Top plate A (c) Bottom plates A and B

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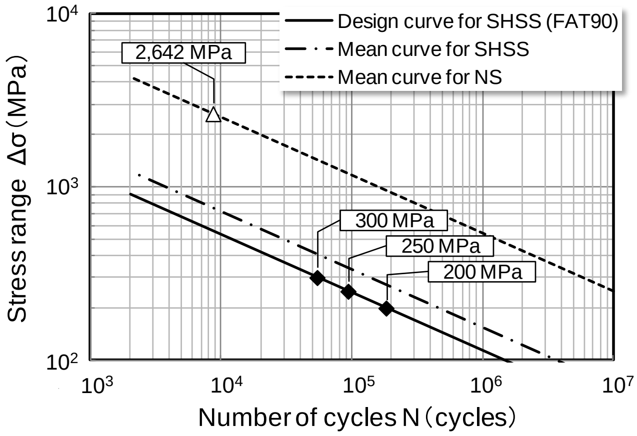
Figure 10: Fine-mesh model of welded structure for evaluating structural hot-spot stress

Table 1: Thickness optimized by constraining structural hot-spot stress

Allowable stress (MPa)		200	250	300
Thickness (mm)	Top plate A	16	16	16
	Side plate A	9	9	6
	Bottom plate A	28	22	19
	Top plate B	9	9	9
	Side plate B	12	12	6
	Bottom plate B	28	25	25
	Gusset A	19	16	12
	Gusset B	16	12	12
Mass (kg)		51.4	44.1	38.7
Expected fatigue life (cycles)	Design	1.8×10^5	9.3×10^4	5.4×10^4
	Mean	4.6×10^5	2.3×10^5	1.4×10^5



(SHSS: Structural Hot-Spot Stress)
(NS: Notch Stress)

Figure 11: Design and mean curves for predicting fatigue life

6.2. Verification of L-shape structure

To investigate whether fatigue strength was well designed using the proposed procedure for thickness optimization, L-shape structures were produced experimentally. The dimensions of the L-shape structures are identical to those in Figure 6. Two kinds of the L-shape structures were produced by changing the weld type of the joint between top plate B and side plate B, i.e., a one- or two-sided fillet weld, as listed in Table 2; that is, top plate B and side plate B were two-sided fillet welded only in the case of design II, which is designated as “Opt. II” in Table 2. All the structures were made of rolled steel for general structure, namely Japanese Industrial Standards (JIS) SS400. The L-shape structures had the thicknesses designed with allowable structural stress of 300 MPa. One of the structures is shown in Figure 12. Furthermore, cross sections of the one- and two-sided fillet welds are shown in Figure 13. Root faces can be observed in the welds; therefore, the observed faces may be at risk of weld-root fatigue. No techniques to improve the weld toes were applied; in other words, the structures were tested under the as-welded condition. To measure structural hot-spot stresses, strain gauges were placed on the plates or at the edge of the plates along the stress-extrapolation lines. The lines on which the strain gauges were placed were selected on the basis of the magnitude of stress calculated by finite-element analysis; as a result, the strain gauges were placed near the weld toes of the gusset plates and the weld toes between bottom plates A and B.

To confirm the fatigue lives of the produced structures, cyclic-load tests on designs I and II were conducted. Two specimens were prepared for each of the designs. Load was applied as a sinusoidal wave having a load range of 100 kN; that is, the maximum and minimum loads were 101 kN and 1 kN, and the frequency of the sinusoidal load was 2 Hz. To record any changes in the range of stress, the strains on various stress-extrapolation lines were continually measured during the fatigue test. The measured fatigue lives for design I and II are compared in Figure 14. The fatigue failure observed in the experiments is herein defined as a 10% change in structural hot-spot stress. As expected, the fatigue life was extended by changing from the one-sided to the two-sided one. In fact, fatigue cracks initiated at the weld root of point C for design I, and at the weld toes of gusset B for design II.

Table 2: Weld types of experimentally produced structures

Design	Opt. I	Opt. II
Gusset A		
	Two-sided fillet	Two-sided fillet
Top plate A		
	One-sided fillet	One-sided fillet
Side plate A		
	One-sided fillet	One-sided fillet
Bottom plate A		
	One-sided fillet	One-sided fillet
Bottom plate B		
	One-sided fillet	One-sided fillet
Side plate B		
	One-sided fillet	Two-sided fillet
Top plate B		
	Two-sided fillet	Two-sided fillet
Gusset B		

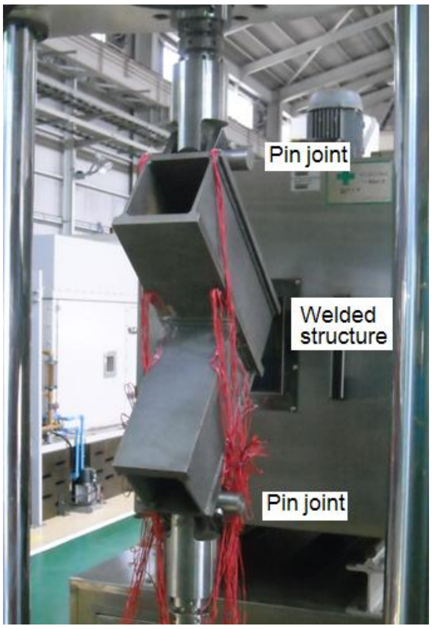
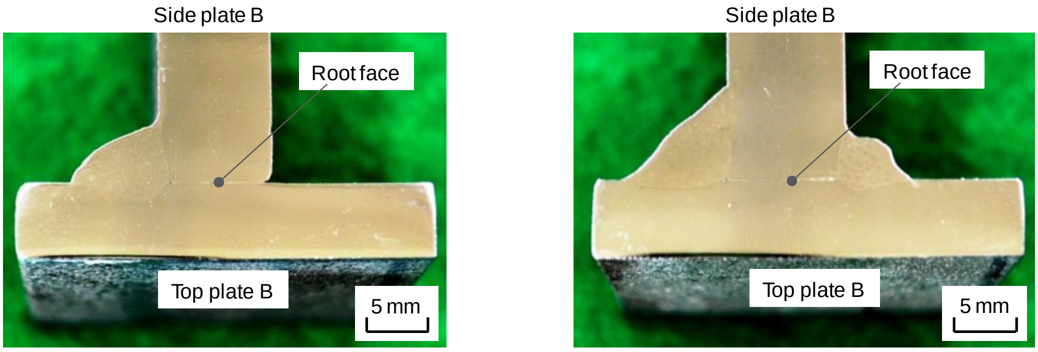


Figure 12: Experimentally produced L-shape structure



(a) One-sided fillet weld

(b) Two-sided fillet weld

Figure 13: Cross sections of fillet welds

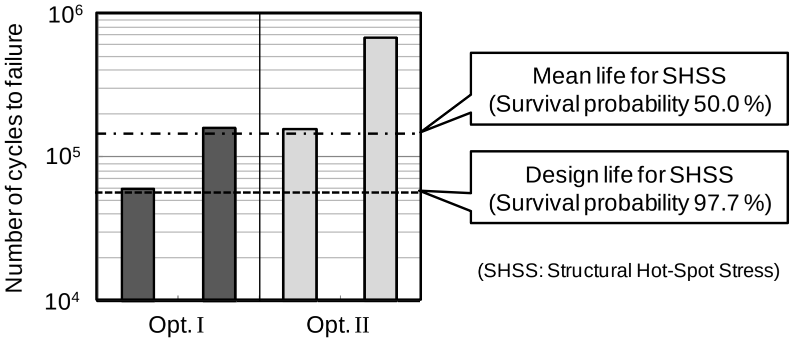


Figure 14: Measured and predicted fatigue lives

7. Concluding remarks

It was confirmed that light-weight and reliable welded structures can be appropriately designed by constraining structural stress, which is one of stresses recommended by the IIW for evaluating the fatigue resistance of welded joints. A design procedure for minimizing the mass of welded structures and maintaining high fatigue resistance was proposed. The procedure was applied to an illustrative example, namely, a welded structure typically used for construction machinery, in which the design variables were the thicknesses of the plates composing the structure. As a result, it was confirmed that the proposed optimization procedure worked well for achieving appropriate optimal solutions under different structural-stress constraints. After the structural optimization, weld-root failure by fatigue was assessed; consequently, the possibility of a weld-root failure was found. The optimal structures were then experimentally produced and fatigue tested to check whether the structures have the expected fatigue resistance. In the case of the structures produced by using only one-sided fillet welds, as evaluated in the fatigue assessment process, fatigue cracks were nucleated from the weld roots. However, as for the structures that have a two-sided fillet weld at the location where the weld-root failure was predicted, fatigue failures occurred at weld toes; accordingly, the fatigue life of the structures was extended to the expected cycle. It can therefore be concluded that lightweight and reliable welded structures can be designed by following the proposed procedure for structural optimization of a welded structure and fatigue assessment for weld-root failure.

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