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FATIGUE STRENGTHS OF LARGE-SIZE GUSSET JOINTS OF 800 MPa CLASS STEELS

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Fatigue strengths and fracture characteristics of large-size gusset joints are described in this paper. High strength steels of 30 and 45 mm thickness are used for specimens. The specimens are fabricated using a similar procedure to that for the actual bridges. In the three types of in-plane and three types of out-of-plane gusset joints, the fatigue strength decreases as stress concentration increases. The results from this study have been used as basis for the revision of the fatigue design code for the Honshu-Shikoku Brideges.

1. INTRODUCTION

At the end of a gusset plate, stress concentration due to sudden changes of configuration tends to develop and causes a decrease in fatigue strength. In the fatigue design code for Honshu-Shikoku Bridges before the 1982 revision[1], the end of a gusset plate attached to a flange by a groove weld (Fig. 1, A) was classified category B on the condition that the curvature of the tip had a radius larger than 20 mm. The end

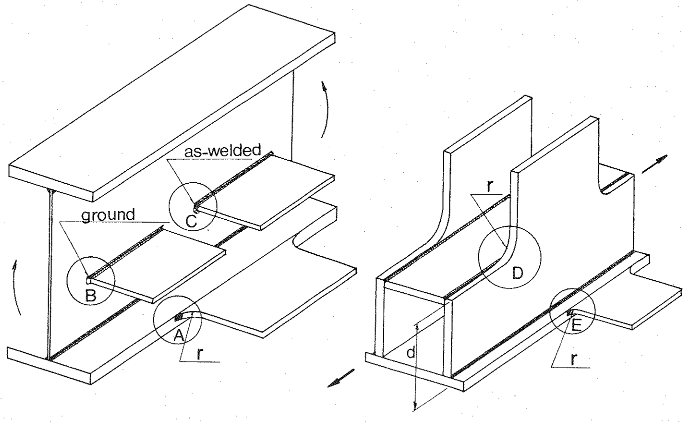

Fig. 1 Types of gusset joints.

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of a gusset plate attached onto a web by a fillet weld was classified category C when the end was finished by a grinder (**Fig. 1, B**), and category D when the end was "as-welded" (**Fig. 1, C**). This fatigue design code had essentially the same specifications as those for the design of steel railway bridges in 1972[2]. However, with regard to the gusset in the truss chord of the main structure (**Fig. 1, D**), based on the evaluation of the static strength, a code denotes that the fillet radius (r) must not be smaller than one-fifth of the depth (d) of the truss chord member ($r/d>1/5$)[3].

The transition radius of fillets, length of gusset plates, width, thickness and many other factors are known to affect the fatigue strength of gusset joints[4]. However, much of the past research on the fatigue strength of gusset joints has used mild steels and small joints[2),5], resulting in insufficient evidence of the influence of these factors. In the Honshu-Shikoku Bridge project, many long, large bridges were constructed using up to 75 mm thick, high-strength steels of 600–800 MPa. Additional fatigue tests were needed to confirm the adequacy of the design allowable stresses for these joints. Research was conducted using high strength steels of similar thickness to those of the actual bridges, and all specimens were fabricated using a similar procedure to that of the actual bridges. Their fatigue strengths and fracture characteristics were then studied. The results of this research have been used as the basis for the revision of the fatigue design code for the Honshu-Shikoku Bridges in 1982[6].

2. FABRICATION OF SPECIMEN

Fig. 2 shows the configurations and sizes of the specimens. Three types of specimens were used to study two different designs : in one group, two gusset plates were groove welded to a main plate on the same plane (GC, GD, GF), and in the other group, two gusset plates were fillet welded perpendicular to the main plate (GA, GB, GE). **Table 1** shows the mechanical properties and chemical compositions of the steels. In **Fig. 3**, welding details for each specimen are shown ; the welding method, finishing method of the surface and its level were adopted from the fabrication code of the Honshu-Shikoku Bridges[7].

The GC-type specimens simulate a gusset with a transition radius (r) of 60 mm for the attachment of a

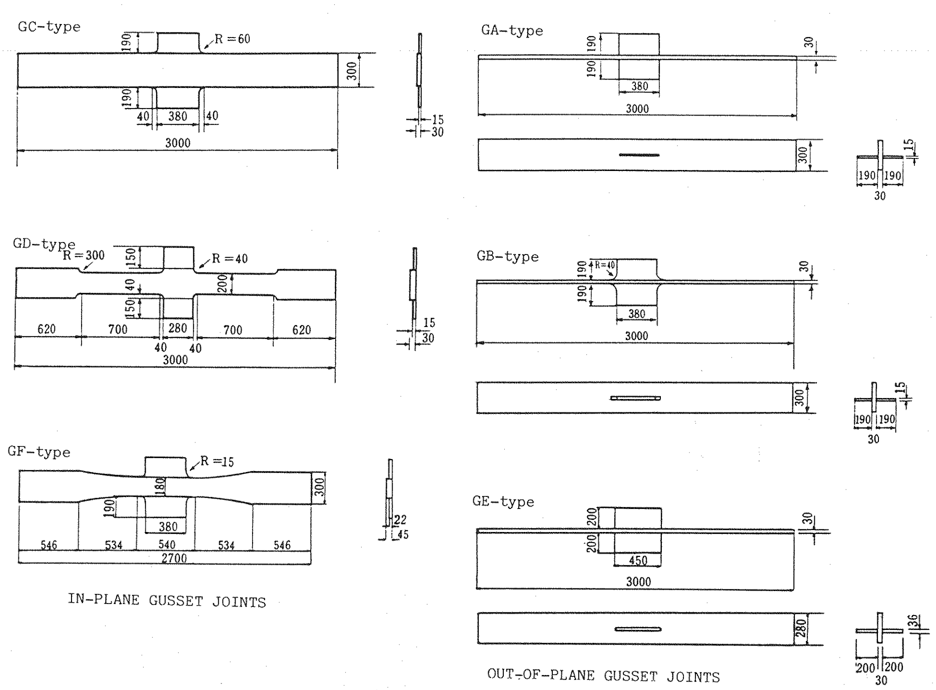

Fig. 2 Configurations and sizes of specimens.

Table 1 Mechanical properties and chemical compositions (mill sheet value)

Steel	Mechanical Properties					Chemical compositions %												Remarks
	t	Y.P.	T.S.	Eℓ	VE	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	B	V	Ceq	
	mm	MPa	MPa	%	N.m	×100			×1000			×100			×1000		×100	
HT80	30	833	882	22	80	11	25	97	18	8	250	83	51	38	10	44	50	Main Pl. GA~GE
HT80	22	764	823	24	201	10	27	97	15	5	—	104	59	33	2	—	50	Main Pl. GF
SM58Q	15	568	657	36	186	14	34	133	17	6	—	1	2	3	—	37	39	Gusset Pl. GA~GD

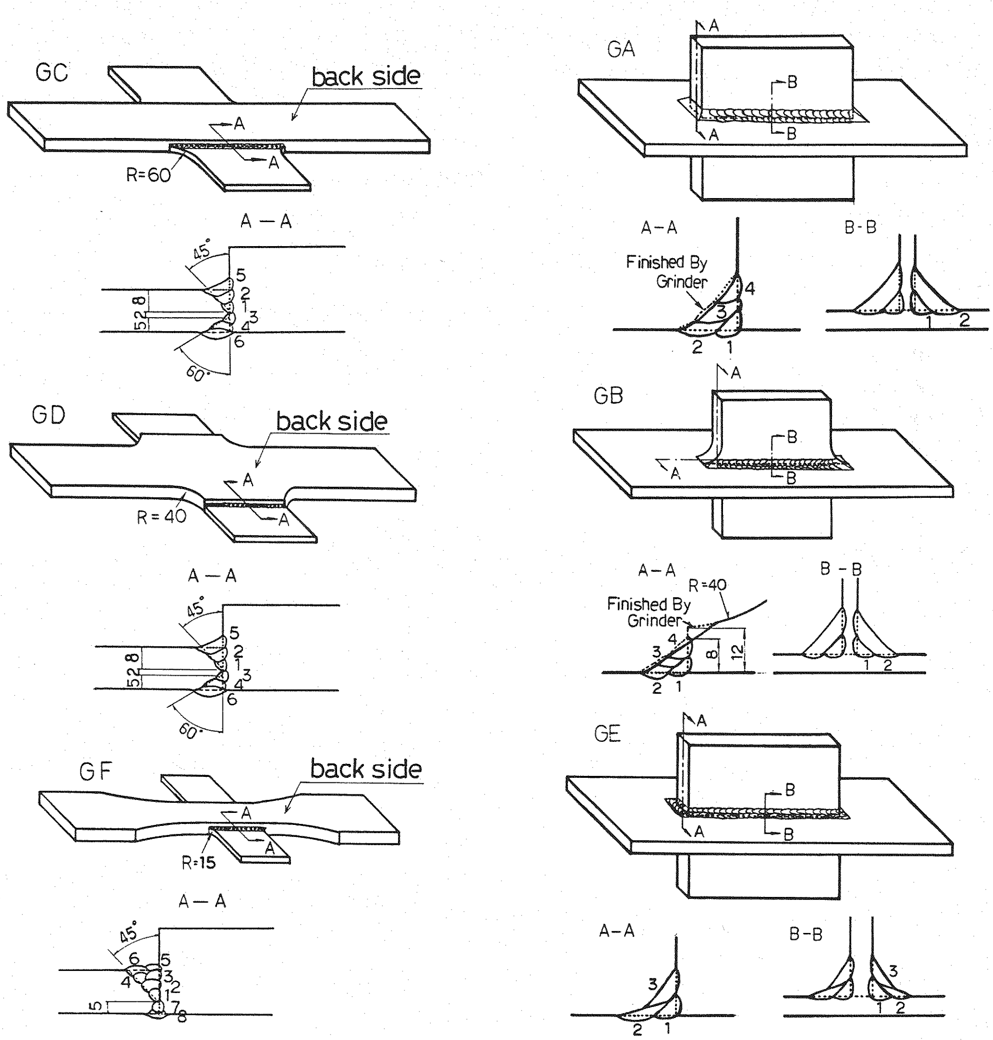

Fig. 3 Welding details.

floor beam to the flange of a plate girder, or for the attachment of a floor truss to the main truss chord in the truss structure (Fig. 1, A, E). A gusset which can be adopted for a main structural truss panel point where a web is incorporated into the gusset (Fig. 1, D) is also considered in the GD-type specimen. It was cut off from the base material with a transition radius of $r=40$ mm and a gusset was welded onto the side surface. The GF-type specimens have the same gusset joints as those of the GC-type and were used for the investigation of the effect of the radius when small (the radius was set at $r=15$ mm). In the GC, GD and GF-type specimens, the thickness of the gusset plates was smaller than that of the main plate. The gusset plate was attached to the main plate by aligning the side and the surface of the gusset to the main plate in the same plane. The weld bead was removed by grinding until the surfaces of the gusset plate and the main plate aligned. (Hereafter, this side will be called the "front" side of a specimen and the other side will be called the "back" side.) The other side of the welding beads were left "as-welded". These details of the specimens are the same as those of the actual bridges. In this paper, GC, GD and GF-type specimens are designated "in-plane" gusset joints.

GA, GB and GE-type specimens simulate a gusset for attachment to a web for connection to a floor beam (Fig. 1, B, C). In the GA-type specimens, the toe of the fillet weld at the gusset end was finished by grinding. This is the most common method for attaching a gusset to a web in steel bridges. In the GB-type specimens, a fillet with a transition radius of 40 mm was attached and the terminal end of the fillet weld was finished by grinding to make a smooth transition to the extension of the fillet of the gusset. In the GE-type specimens, the fillet weld for attaching the gusset plate was kept "as-welded". In Japanese bridges, joints of this type are not used at locations where the possibility of fatigue failure exists. These three types of specimens, GA, GB and GE, are designated "out-of-plane" gusset joints.

3. DISTRIBUTION OF STRESS IN THE SPECIMENS

The finite element method was used to analyse the stress distribution in the specimens. For the analyses of the GC, GD and GF-type specimens, the two-dimensional plane stress element was used. In the GA, GB and GE-type specimens, firstly, the overall stress distribution was analysed using shell elements, and then the stress distribuion in the main plate was obtained using plane stress elements. The shape of the end of the gusset of the GA-type specimen was made into a diameter of 1.5 mm and a flank angle of 135 degrees. In Fig. 4, results from the measurement of the shape of the toes of fillet welds of the GE-1 specimen are shown. The shape of the end of the gusset of the GE-type specimen for the finite element analysis was determined, based on these results of having a diameter of 0.56 mm and a flank angle of 135 degrees. The

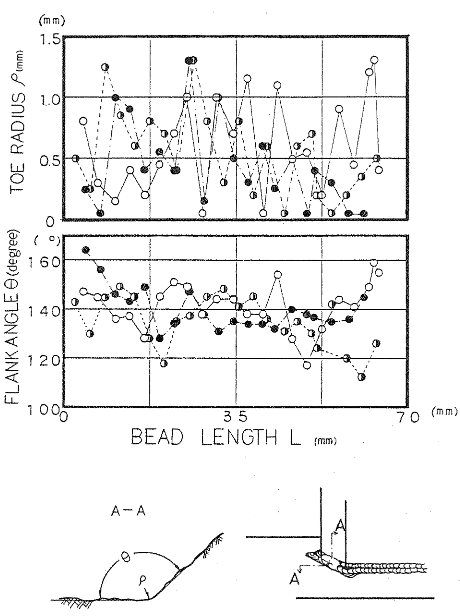

Fig. 4 Measurements of the toe profiles.

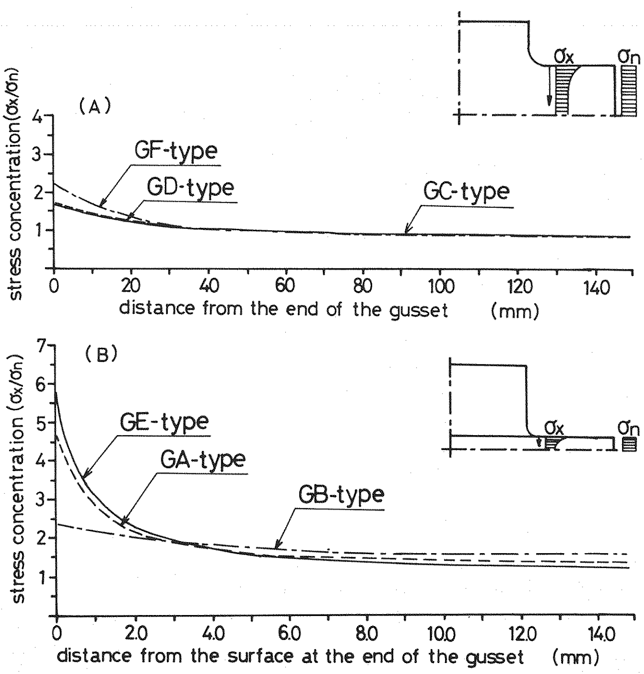

Fig. 5 Stress distributions at the end of the gusset.

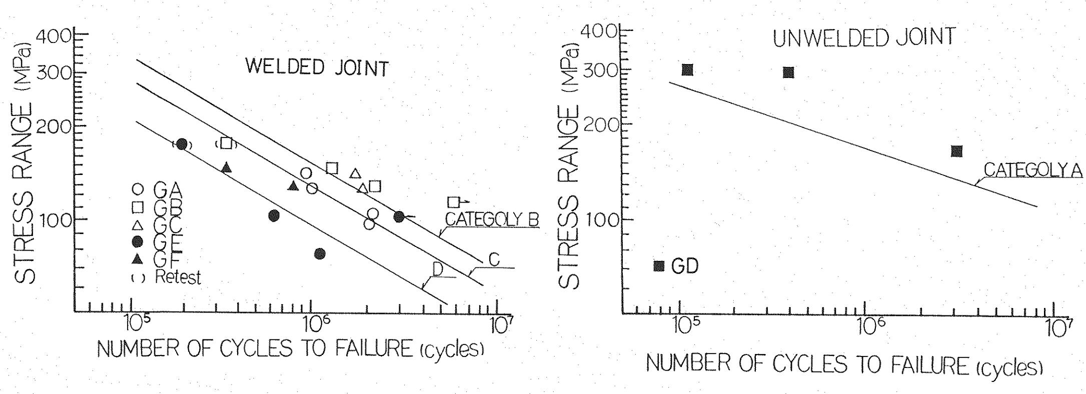

Fig. 6 Comparision of test results and allowable stress ranges.

size of elements in the vicinity of the transition tangency was 0.1×0.1 mm.

In Fig. 5(A), the stress distribution in the plate at the gusset end is shown for the GC, GD and GF-type specimens. The stress distribution in the thickness direction of the plate at the end of the gusset for GA, GB and GE-type specimens is presented in Fig. 5(B). The stress concentration factors, assumed to be the ratio of maximum to nominal stress at the end of the gusset for GC, GD, GF, GA, GB and GE-type specimens, were 1.6, 1.6, 2.2, 4.7, 2.3 and 5.9, respectively. When the radii at the end of gusset plate are similar each other, the out-of-plane gusset joint has a higher stress concentration than the in-plane gusset joint.

4. FATIGUE TESTING METHOD

Fatigue tests were performed with an electro-hydraulic fatigue testing machine of 4MN dynamic capacity. The stress wave form was sinusoidal and its frequency was 5-6 Hz. The stress ratio was set at approximately 0.1 with pulsating tension. In some tests, the two-step block loading test was performed to produce beach marks on the fatigue failure surface. In this test, the stress range was forced to one-half of each stress range at certain stress repetitions by increasing the minimum stress.

5. TEST RESULTS AND DISCUSSION

Fig. 6 represents the relationship between the stress range (S_r) and failure life (N_f) of each specimen. The GD-type specimen has the highest fatigue strength, and the GC and GB-type specimens have almost same strength. These are followed by GA and GF-type specimens, with the GE-type specimen having the lowest. This order is different from the order of stress concentration factors which were shown previously. However, in the in-plane gusset joint of GC, GD and GF-type specimens and in the out-of-plane gusset joint of GA, GB and GE-type specimens, the orders of the fatigue strengths and the stress concentration factors were the same. Furthermore, if stress concentrations are on the same level, the fatigue strength of the in-plane gusset becomes much lower than that of the out-of-plane gusset.

The oblique lines in Fig. 6 indicate the allowable stress ranges for each joint category in the design code of the Honshu-Shikoku Bridges[6]. In the new design code of the Honshu-Shikoku Bridges, the allowable stress range of each joint varies depending on the welded or unwelded joints, the transition radius (r), the main plate width (d) and employment or non-employment of finishing in the weld toes.

The GC-type specimens are classified category B and the results of those fatigue tests are also shown by the plots to be above the allowable stress range of category B. In Fig. 7, the fatigue failure characteristics for GC-2 specimen are shown. A fatigue crack started at the edge of the back side, slightly toward the gusset plate from the gusset end, namely, in the dip of the ripples of the weld-bead. In other GC-type specimens, fatigue cracks started at almost the same point, which roughly coincides with the point where

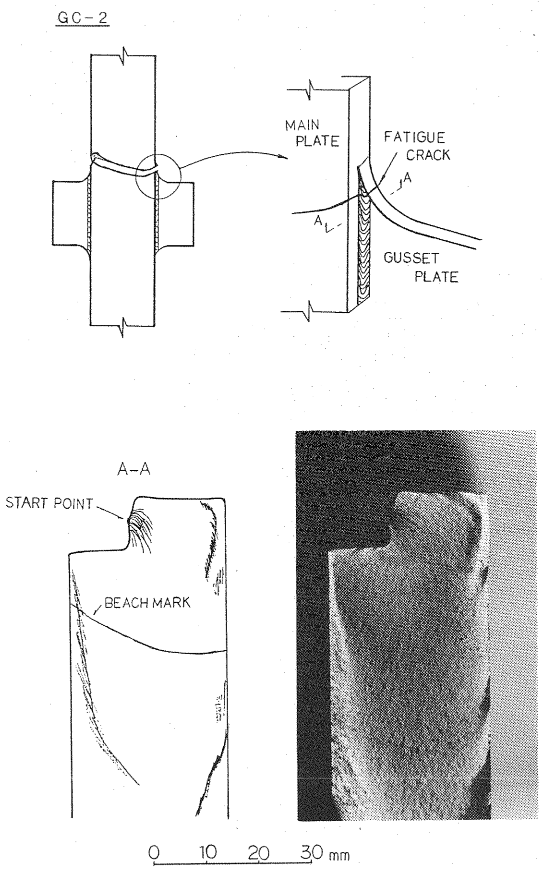

Fig. 7 Failure surface of the GC-2 specimen.

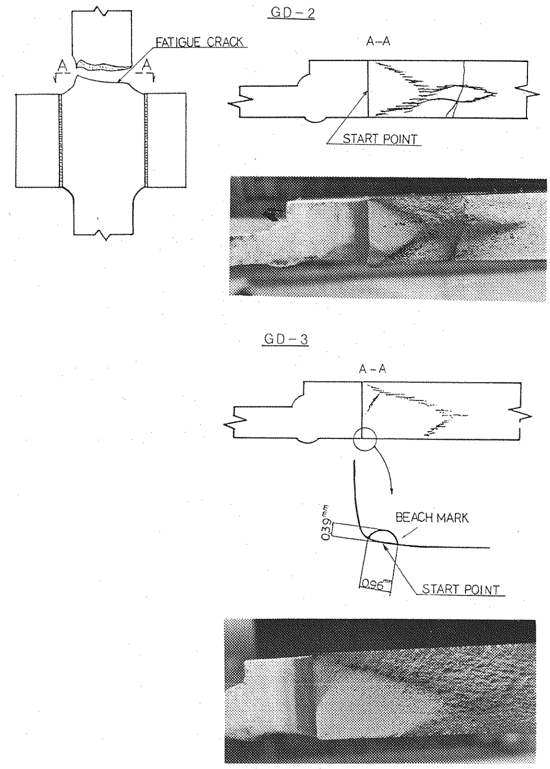

Fig. 8 Failure surfaces of the GD-2 and GD-3 specimens.

the maximum stress occurs. Fatigue cracks advance as one-quarter circle cracks, then penetrate into the main and gusset plates and grow to three-quarter circle cracks. They eventually go through the thickness direction of the main plate.

The GD-type specimens are classified category A of unwelded joints and the results of all three specimens satisfied the allowable stress range for this category. Failure surfaces of GD-2 and GD-3 specimens are shown in Fig. 8. In GD-1 and GD-3 specimens, fatigue cracks initiated at the edge near the fillet toe and expanded as quarter circle fatigue cracks. In the GD-2 specimen, a fatigue crack started from a sharp scratch produced by grinding at the edge of the fillet end. Thus its fatigue resistance was lower than GD-1 and GD-3 specimens. In the gusset of the truss panel points, very high tensile residual stresses develop due to the corner welding and, therefore, fatigue cracks initiate much easier than in the case of the GD-2 specimen. Accordingly, care must be taken when finishing the surface of the fillet end of a truss panel gusset.

The GF-type specimens do not satisfy the transition radius for fillets of gusset plates in the new design code ($r=40$ mm) and, therefore, cannot be used for bridge details. The test results for the specimens of this type are plotted between the allowable stress ranges for categories C and D. In Fig. 9, the failure surface of the GF-2 specimen is shown. In all GF-type specimens, fatigue cracks developed near the center of the thickness of the main plate. The reason that the fatigue cracks start from the inside instead of the edge can be explained by the following:

a) based on the knowledge that fatigue cracks developed at the edge of the two preceding types of specimens (GC, GD), the edge was made round, and

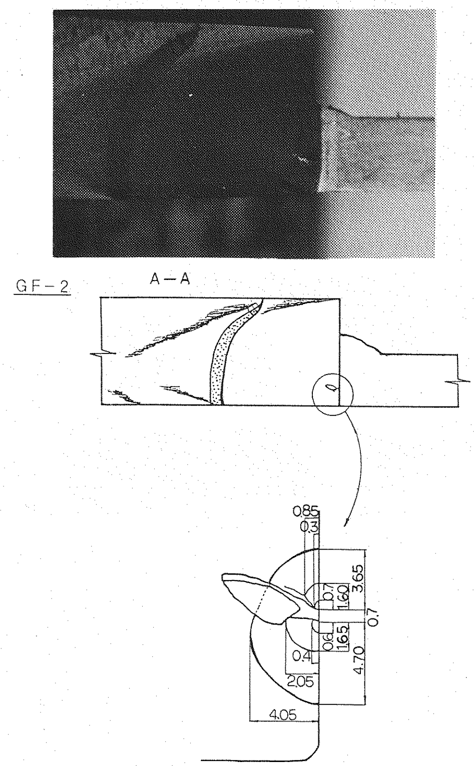

Fig. 9 Failure surface of the GF-2 specimen.

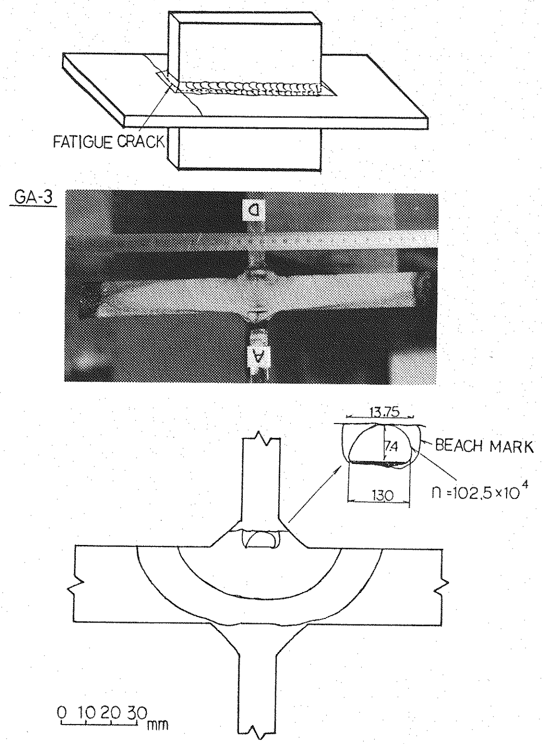

Fig. 10 Failure surface of the GA-3 specimen.

b) since the notch became sharper, the location of the development of the maxilum stress moved inside the plate[8).

The GA-type specimens are classified category C in the old design code, but in the new code they are classified category D. That the experimental values are plotted on the allowable stress range of category C indicates that the classification change to the new code is correct. In Fig. 10, the failure surface of the GA-3 specimen is shown. In two of these specimens, fatigue cracks developed from the root of the fillet welds. In other two cases, fatigue cracks developed at the toe of fillet welds; the crack started from grinding scratches, at the main plate in one specimen and at the gusset plate side in another specimen,

The GB-type specimens are classified category C. The experimental results of these specimens are plotted on the allowable stress range of category B, which, therefore, clearly satisfy the allowable stress range of category C. In Fig. 11, the the fatigue failure surface of the GB-1 specimen is shown. In all of these specimens, fatigue cracks developed from the front edge of the unfused part of the root of the fillet weld. The cracks which developed at the root first advanced in a way that cut the section of the fillet welds to the weld surface (Fig. 11). After the width of the fatigue cracks becomes larger than the width of the unfused part, they advanced into the main plate. These characteristics of the development of fatigue cracks are very similar to the development of cracks in the GA, GB and GE-type specimens. In the flange-cover plate detail, when the toe of the transverse welds was ground, fatigue cracks sometimes initiated at the weld root[9). However, to the best of our knowledge, the development of fatigue cracks from the roots of fillet welds in joints of this type has not previously been reported. The fact that fatigue cracks initiate at the roots indicates that, if the size of fillet welds at the end of the gusset plates is not large enough and if the root is near the surface, the fatigue strength will be reduced greatly. Furthermore, when toes are grind-finished (GA-type) or a fillet is produced (GB-type), these treatments may not necessarily increase the fatigue strength, unless they are not related to the reduction of stresses at the root.

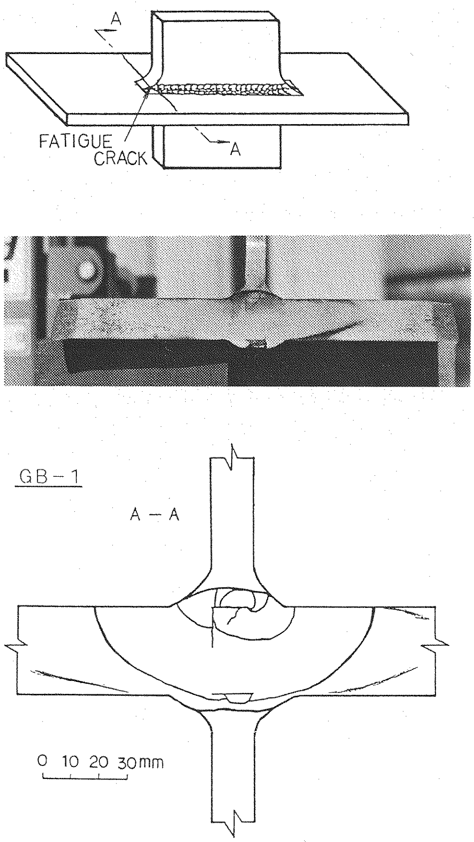

Fig. 11 Failure surface of the GB-1 specimen.

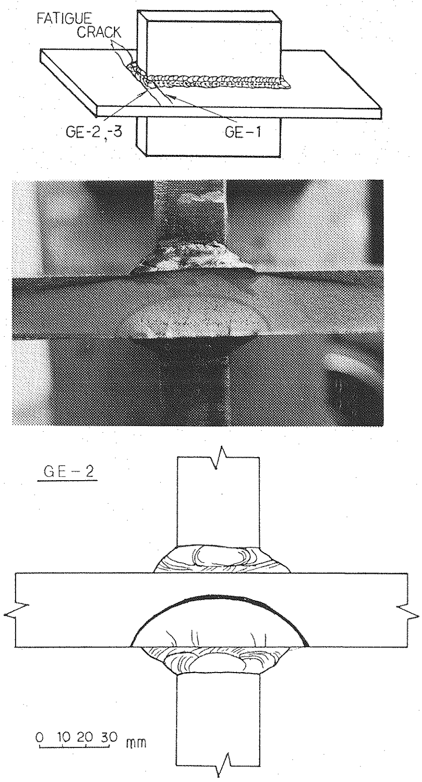

Fig. 12 Failure surface of the GE-2 specimen.

In the Honshu-Shikoku Bridge project, the attachment of a gusset to the GE-type specimens is not considered. The experimental results of all GE-type specimens also do not satisfy the allowable stress of category D joints. Accordingly, if such a design detail as this were adopted, it would be necessary to set a new category for joints whose fatigue strength is lower than D, namely category E. In Fig. 12, a fatigue failure surface is shown for the GE-2 specimen. The fatigue crack initiated from the toe in two of these specimens and from the root in another.

6. CONCLUDING REMARKS

The principal findings obtained from the current investigation are as follows:

(1) In the three types of in-plane and the three types of out-of-plane gusset joints, the fatigue strength decreases as the stress concentration increases. In in-plane and out-of-plane gusset joints with similar stress concentration factors, the fatigue strength for the in-plane gusset joints is much lower than that of the out-of-plane gusset joints.

(2) In the in-plane gusset joints, fatigue cracks often start from the edge on the back side near the end of gusset plate. The fatigue strength, therefore, is influenced by the level of finishing near the gusset plate end and especially the weld edge.

(3) In the out-of-plane gusset joints which were fillet welded, fatigue cracks often developed at the front part of the unfused edge of the root of the fillet welds. These cracks advanced in a way that would cut the throat section in the fillet welds and then penetrate into the main plate. Therefore, it is important to pay attention to the location of the front edge of the unfused portion of the root and its stress conditions, in

addition to the finishing condition at the toe of fillet welds.

(4) Based on these results, the fatigue design code was revised in 1982. In the new code, the allowable stresses for gusset joints are determined based on the gusset types, the transition radius of fillets, the width of the plate and the presence or absence of the toe finish.

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