Specification for Design and Fabrication of Aluminum Alloy Structures in Civil Engineering

(Load and Resistance Factor Design)

Draft

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FOREWORD

Specification for Design and Fabrication of Aluminum Alloy Structures in Civil Engineering was published by the Light Metal Association in 1977, and a revised version was published by the Japan Aluminum Association in 1998, but the basics of the revised version were almost the same as the first edition. Therefore, a new specification incorporating the latest research results and findings was published by the Steel Structure Committee, the Japan Society of Civil Engineers in March 2015. The main feature of this specification is that there are provisions regarding the design method of aluminum structures using friction stir welding. The aluminum structures section in AASHTO and Eurocode 9 do not yet have provisions for friction stir welding.

However, in the above-mentioned specification published in March 2015, making the provisions for the allowable axial compressive stress and allowable bending compressive stress of the members fabricated by welding and friction stir welding was shelved, since sufficient data had not been provided. Therefore, in order to make up for this deficiency, those allowable stresses were given in the ALST Research Reports below. In addition, the allowable compressive stress of longitudinally stiffened A6061-T6 plates restrained along two edges and the design of A6061-T6 girders with a longitudinally stiffened web were also specified. It has become possible to fabricate members by connecting extrusions of A6061-T6 alloy by friction stir welding.

Revised Draft 1: ALST Research Report 55, May 2019
Revised Draft 2: ALST Research Report 59, February 2020
Revised Draft 3: ALST Research Report 60, January 2021

The above is the history of Specification for Design and Fabrication of Aluminum Alloy Structures in Civil Engineering, but the Specification are described by the allowable stress design (ASD) method.

Japanese Specification for Highway Bridges was changed from the ASD method to the limit state design (LSD) method in 2017. The aluminum structures section in AASHTO is described by the load and resistance factor design (LRFD) method, and Eurocode 9 is described by the LSD method. Under these circumstances, in this ALST research report, the specification is written by the LRFD method. The form of the verification formula for the limit state is slightly different between the LRFD and LSD methods, but the basics are the same. The commentary for the specification is given in ALST Research Report 61, February 2021, though in Japanese.

I hope that this specification will be used as a design standard for those who are considering the introduction of aluminum alloy civil engineering structures.

Finally, I hope that this specification will continue to be revised based on the latest research results and findings.

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* http://www.aluminum.or.jp/doboku/index.html

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Definition of Symbols

Symbol	Definition	Section
A	= entire cross-sectional area of a member	3.4
A_f	= cross-sectional area of a compressive flange	4.2, 4.3, 4.4
A_i	= cross-sectional area of the plate element i that constitutes a compression member	4.1
A_r	= cross-sectional area of a longitudinal stiffener	4.4
A_w	= cross-sectional area of the heat-affected range due to welding or friction stir welding	3.4
	= cross-sectional area of a web	4.2, 4.3, 4.4
A_{wr}	= value given by A_r and A_w	4.4
B_f	= overall width of a compressive flange	4.2, 4.4
D	= diameter of bolt holes	7.2.8, A.2
	= cumulative fatigue damage ratio	8.4.2
F	= coefficient for considering effects of flanges on the shearing load-carrying capacity of girders	4.3
I	= geometrical moment of inertia of a member	5.7, 7.2.5, 7.2.6, 7.3.3
	= geometrical moment of inertia for the gross cross section of connection plates in bolted joints around the neutral axis of a member	7.2.7
I_a	= geometrical moment of inertia for the cross section of the theoretical throat thickness on the joining surface	5.7
I_v	= geometrical moment of inertia of an intermediate transverse stiffener	4.7.2
K	= factor for effective buckling length	4.1
	= coefficient given by A_w/A_f or A_{wr}/A_f	4.2, 4.4
L	= length between the supporting points of compression members or the length for cantilever members	4.1
	= distance between the positions where the bending moments of M_1 and M_2 act	4.5
M	= acting bending moment	5.7, 7.2.6, 7.2.7, 7.3.3
M_1, M_2	= larger and smaller acting bending moments, respectively	4.5
N_T	= total number of all repetitions during a design period	8.4.2
N_i	= fatigue life for $\Delta\sigma_i$ or $\Delta\tau_i$	8.4.2
N_0	= initially introduced bolt axial force	A.4
P, P_i	= acting force	7.2.5, 7.2.6, 7.3.3
	= slip load	A.4
Q	= coefficient given by η_i and A_i	4.1
	= acting shearing force	5.6, 7.2.5, 7.2.6, 7.3.3
R	= variable	3.5, 3.6, 3.7, 4.3, 4.4
	= radius of a bending fitting	9.2.3, 9.3.3

R_1, R_2	= constant	3.5, 3.6, 4.3
S	= geometrical moment of area of a member	7.2.5, 7.2.6, 7.3.3
T	= axial force acting in the direction perpendicular to the welding line	5.6
V	= axial compressive force to act on the transverse stiffeners at the supporting points	4.7.1
W	= width of a test piece	A.2
Y_{c1}	= coefficient for corrosion effects on S-N curves	8.4.2, 8.5.4
Y_{c2}	= coefficient for corrosion effects on fatigue limits	8.4.1, 8.4.2, 8.5.4
Y_t	= coefficient for thickness effects	8.4.1, 8.4.2, 8.5.5
a	= distance between adjacent intermediate transverse stiffeners	4.3, 4.7.2
	= theoretical throat thickness of welded joints or friction stir welded joints	5.4, 5.6, 6.3
	= cross-sectional dimension of extrusions of angle section	7.2.8
a_L	= distance between end stiffeners	4.3, 4.4
a_0, a_1, a_2, a_3, a_4	= constant	4.1, 4.2, 4.3
b	= plate width	3.5, 3.6, 3.7
	= cross-sectional dimension of extrusions of angle section	7.2.8
	= flange width	9.5
b_f	= width of a compressive flange on one side	4.2, 4.4
b_r	= width of a longitudinal stiffener	3.7, 4.4
b_s	= width on one side of transverse stiffeners at the supporting points	4.7.1
b_v	= width of an intermediate transverse stiffener on one side of a web	4.7.2
b_w	= web width	4.2, 4.3, 4.4, 4.5, 4.7.1, 4.7.2
b'	= web spacing	9.5
c	= constant	3.5, 3.6, 4.1, 4.2, 4.3
	= reinforcement of lateral butt welded joints	8.5.2
c_a	= allowable fatigue resistance	8.4.2, 8.5.1, 8.5.2, 8.5.3
d	= diameter of bolts	7.2.3, 7.2.4, 7.3.2, A.2
e	= eccentricity between pieces or the gap between a backing strip and a piece	8.5.2, 9.2.4
	= distance from the center of a bolt hole to the end of a connection plate	A.2
g	= gauge of bolts	7.2.8, 7.2.9
g_w	= coefficient that gives the ultimate bending moment of a girder when neither local buckling nor lateral buckling occurs in a compressive flange	4.2, 4.4, 4.6
h	= web height	9.5
j	= coefficient that takes 1 for one friction-surface and 2 for	7.2.4, 7.3.2

	two friction-surfaces or the one that takes 1 for one shearing-plane and 2 for two shearing-planes	
k	= total number of nominal loads	2.1.1
	= shearing buckling coefficient of rectangular plates simply supported at four edges	4.3
	= total number of divisions in a frequency distribution of stress range	8.4.2
k_0, k_1	= constant	4.2
l	= effective buckling length of a compression member	4.1
	= distance between the supporting points of a compressive flange	4.2, 4.4
	= effective length of a weld	5.6
	= gusset length	8.5.2
	= member length	9.5
m	= value representing the slope of S-N curves	8.4.2
n	= total number of bolts on one side with respect to the joining line or the number of bolts in the direction perpendicular to the joining line in bolted joints that horizontally connect plates, subjected to shearing force due to bending	7.2.5, 7.2.6, 7.3.3, A.4
n_i	= total number of bolts on one side with respect to the joining line in the i-th row in high-strength bolted friction-type joints under normal stress that is not uniformly distributed	7.2.5
		8.4.2
	= frequency of a certain stress range component $\Delta\sigma_i$ or $\Delta\tau_i$	
p	= constant	3.5, 3.6, 4.2, 4.3
	= pitch of bolts	7.2.5, 7.2.6, 7.2.8, 7.2.9, 7.3.3, A.2
q_σ	= cumulative fatigue damage for normal stress	8.4.2
q_τ	= cumulative fatigue damage for shearing stress	8.4.2
r	= radius of gyration of a compression member	4.1
	= curvature radius of joints with an in-plane gusset welded to a plate edge and to a flange edge of a girder	8.5.2
r_i	= load factor for the nominal load i	2.1.1
s	= size in fillet welding	5.4
t	= plate thickness	3.1, 3.2, 3.5, 3.6, 3.7, 4.1, 4.2, 4.3, 4.7.1, 5.2, 5.6, 7.2.4, 7.2.8, 7.2.9, 8.5.2, 8.5.5, 9.2.3, 9.2.4, 9.2.7, 9.3.3
t_f	= thickness of a compressive flange	4.2, 4.4
t_j	= increased plate thickness	5.2
t_r	= thickness of a longitudinal stiffener	3.7, 4.4

t_s	= thickness of transverse stiffeners at the supporting points	4.7.1
t_v	= thickness of a intermediate transverse stiffener	4.7.2
t_w	= web thickness	4.2, 4.3, 4.4, 4.5, 4.7.1, 4.7.2
t_1	= thickness of a base material	7.2.3, 7.2.4, 7.3.2, 8.5.3, A.2
t_2	= thickness of a connection plate	7.2.3, 8.5.3, A.2
t_{22}	= total thickness of connection plates	7.2.4, 7.3.2
w	= bolt hole diameter to be considered in calculating the net width of staggered bolted plates	7.2.8
	= plate width	8.5.2
	= web or rib spacing	9.5
y	= distance from the neutral axis of a member to the position where the stress is calculated	5.7, 7.2.7
y_a	= distance from the neutral axis for the cross section of the theoretical throat thickness on the joining surface to the position where the stress is calculated	5.7
y_i	= distance from the neutral axis to bolts	7.2.6, 7.3.3
y_n	= distance from the neutral axis to the bolts at the outermost location	7.2.6 7.3.3
$\Delta\sigma$	= range of normal stress	8.3
$\Delta\sigma_a$	= allowable stress range for normal stress	8.4.2
$\Delta\sigma_b$	= range of plate bending stress	8.3
$\Delta\sigma_{caf}$	= cut-off limit of the stress range for constant amplitude stress, for normal stress	8.4.1, 8.5.1, 8.5.2, 8.5.3
$\Delta\sigma_e$	= equivalent stress range for normal stress	8.4.2
$\Delta\sigma_i$	= one component of the stress range for normal stress	8.4.2
$\Delta\sigma_m$	= range of membrane stress	8.3
$\Delta\sigma_{\max}$	= maximum of the normal stress range predicted during a design period	8.4.1
$\Delta\sigma_{vaf}$	= cut-off limit of the stress range for variable amplitude stress, for normal stress	8.4.2, 8.5.1, 8.5.2, 8.5.3
$\Delta\sigma_{20}$	= fatigue strength at 200,000 cycles for normal stress	8.5.1
$\Delta\sigma_{200}$	= fatigue strength at 2 million cycles for normal stress	8.5.2, 8.5.3
$\Delta\tau_a$	= allowable stress range for shearing stress	8.4.2
$\Delta\tau_{caf}$	= cut-off limit of the stress range for constant amplitude stress, for shearing stress	8.4.1, 8.5.2
$\Delta\tau_e$	= equivalent stress range for shearing stress	8.4.2
$\Delta\tau_i$	= one component of the stress range for shearing stress	8.4.2
$\Delta\tau_{\max}$	= maximum of the shearing stress range predicted during a design period	8.4.1
$\Delta\tau_{vaf}$	= cut-off limit of the stress range for variable amplitude stress, for shearing stress	8.4.2, 8.5.2

$\Delta\tau_{200}$	= fatigue strength at 2 million cycles for shearing stress	8.5.2
Σ	= symbol that represents the sum of effective lengths	5.6
	= symbol that represents the sum of the bolts on one side with respect to the joining line	7.2.6, 7.3.3
β_0, β_1, β_2, β_3	= constant	4.2
γ_v	= required relative stiffness ratio of an intermediate transverse stiffener	4.7.2
δ	= flatness of a plate, right angle of a flange or deformation of a compression member	9.5
η, η_g, η_i, η_l, η_s	= coefficient that gives the load-carrying capacity	3.5, 3.6, 3.7, 4.1, 4.2, 4.3, 4.4, 4.6
θ	= toe angle of a lateral butt welded joint	8.5.2
κ	$= M_2/M_1$	4.5
λ	= variable	4.1, 4.2, 4.4
λ_1	= constant	4.1, 4.2
μ	= slip coefficient	A.4
ν	= safety factor which adjusts the level of safety in fatigue check	8.2, 8.4.1, 8.4.2
ξ	= 1 for base materials, friction stir welded joints and high strength bolted friction-type joints, and 0.8 for welded joints	8.3
ρ, ρ_H, ρ_P, ρ_{Pi}, ρ_Q, ρ_n	= force acting on one bolt	7.2.5, 7.2.6, 7.3.3
ρ_F	= nominal friction load carrying force per one friction-surface of one steel high-strength bolt for friction-type connection	7.2.4
ρ_{bBBd}	= design bearing fracture load of one bolt for bearing-type connection	7.3.2
$\rho_{bB0.2d}$	= design bearing yield load of one bolt for bearing-type connection	7.3.2
ρ_{bSBd}	= design shearing fracture load of one bolt for bearing-type connection	7.3.2
ρ_{bSYd}	= design shearing yield load of one bolt for bearing-type connection	7.3.2
ρ_{bUd}	= design fracture load carrying force of one bolt for bearing-type connection	7.3.2, 7.3.3
ρ_{bYd}	= design yield load carrying force of one bolt for bearing-type connection	7.3.2, 7.3.3
ρ_{fBBd}	= design bearing fracture load of one steel high-strength bolt for friction-type connection	7.2.4
ρ_{fFd}	= design friction load carrying force of one steel high-strength bolt for friction-type connection	7.2.4, 7.2.5
ρ_{fSBd}	= design shearing fracture load of one steel high-strength bolt for friction-type connection	7.2.4
ρ_{fUd}	= design fracture load carrying force of one steel high-	7.2.4, 7.2.6

	strength bolt for friction-type connection	
σ	= acting normal stress	5.6, 5.7, 7.2.7
σ_B	= tensile strength of base materials	3.1, 3.5, 3.6, 4.1, 4.2, 4.3, 4.6, 7.2.4, 7.3.2
σ_{Fd}	= stress that occurs in a member against the design load	2.1.1
$\sigma_{Fn,i}$	= stress that occurs in a member against the nominal load i	2.1.1
σ_{Rd}	= design strength of a member	2.1.1
σ_{Rn}	= nominal strength of a member	2.1.1
σ_{SB}	= tensile strength of bolts	7.2.4, 7.3.2
σ_{SY}	= yield stress or 0.2% proof stress of bolts	7.3.2
σ_{cud}	= design compressive strength for the load-carrying capacity of plates, the design axial compressive strength for the load-carrying capacity of members or the design bending compressive strength for the load-carrying capacity of girders	3.5, 3.6, 3.7, 4.1, 4.2, 4.4, 4.5, 4.6, 7.2.7
σ_d	= design tensile strength or the design compressive strength	7.2.7
σ_{fB}	= tensile strength of welding materials	3.2
σ_{fBd}	= design tensile strength for the tensile strength of welding materials	3.2
σ_{fgu}	= lateral load-carrying capacity of a compressive flange without considering effects of the local buckling of the compressive flange	4.2
σ_{flu}	= load-carrying capacity for the local buckling of a compressive flange	4.2
σ_{fu}	= lateral load-carrying capacity of a compressive flange considering effects of the local buckling of the compressive flange	4.2
$\sigma_{f0.2}$	= 0.2% proof stress of welding materials	3.2
$\sigma_{f0.2d}$	= design tensile strength for the 0.2% proof stress of welding materials	3.2
σ_{hB}	= tensile strength of the heat-affected zone due to welding	3.2
σ_{hBd}	= design tensile strength for the tensile strength of the heat-affected zone due to welding	3.2, 3.3
$\sigma_{h0.2}$	= 0.2% proof stress of the heat-affected zone due to welding	3.2
$\sigma_{h0.2d}$	= design tensile strength for the 0.2% proof stress of the heat-affected zone due to welding	3.2, 3.3
σ_{ptBd}	= design tensile strength for the tensile strength of members with joints by welding or friction stir welding	3.4
$\sigma_{pt0.2d}$	= design tensile strength for the 0.2% proof stress of members with joints by welding or friction stir welding	3.4
σ_{tBd}	= design tensile strength for the tensile strength of base materials	3.1, 3.4, 3.5, 3.6, 3.7, 4.1, 4.2, 4.4, 4.5, 7.2.7
$\sigma_{t0.2d}$	= design tensile strength for the 0.2% proof stress of base	3.1, 3.4, 7.2.7

	materials	
σ_u	= load-carrying capacity of plates, compression members or girders under bending	3.5, 3.6, 3.7, 4.1, 4.2, 4.4, 7.2.7
σ_{wBd}	= design tensile strength for the tensile strength of the heat-affected range due to welding or friction stir welding	3.2, 3.3, 3.4, 5.6, 5.7
$\sigma_{w0.2d}$	= design tensile strength for the 0.2% proof stress of the heat-affected range due to welding or friction stir welding	3.2, 3.3, 3.4, 5.6, 5.7
$\sigma_{0.2}$	= 0.2% proof stress of base materials	3.1, 3.5, 3.6, 4.1, 4.2, 4.3, 4.6, 7.2.7, 7.3.2
σ_1	= bending compressive stress at the flange edge at the position where the larger bending moment acts	4.5, 4.6
σ_{1B}	= tensile strength of the aluminum alloy for base materials	7.2.4, 7.3.2
σ_{2B}	= tensile strength of the aluminum alloy for connection plates	7.2.4, 7.3.2
σ_{1cud}	= design bending compressive strength at the position where the larger bending moment acts	4.5
$\sigma_{1,0.2}$	= 0.2% proof stress of the aluminum alloy for base materials	7.3.2
$\sigma_{2,0.2}$	= 0.2% proof stress of the aluminum alloy for connection plates	7.3.2
τ	= acting shearing stress	4.5, 4.6, 5.6
τ_{Bd}	= design shearing strength for the tensile strength of base materials	3.1, 4.3, 4.4, 4.7.1
τ_d	= design shearing strength for the case where buckling does not occur in a web	4.7.1
τ_{fBd}	= design shearing strength for the tensile strength of welding materials	3.2
$\tau_{f0.2d}$	= design shearing strength for the 0.2% proof stress of welding materials	3.2
τ_{hBd}	= design shearing strength for the tensile strength of the heat-affected zone due to welding	3.2, 3.3
$\tau_{h0.2d}$	= design shearing strength for the 0.2% proof stress of the heat-affected zone due to welding	3.2, 3.3
τ_u	= shearing load-carrying capacity of girders	4.3, 4.4
τ_{ud}	= design shearing strength for the load-carrying capacity of girders	4.3, 4.4, 4.6
τ_{wBd}	= design shearing strength for the tensile strength of the heat-affected range due to welding or friction stir welding	3.2, 3.3, 3.4, 5.6, 5.7
$\tau_{w0.2d}$	= design shearing strength for the 0.2% proof stress of the heat-affected range due to welding or friction stir welding	3.2, 3.3, 3.4, 5.6, 5.7
$\tau_{\parallel}$	= shearing stress generated in the weld due to a shearing force in the direction parallel to the welding line	5.6

$\tau_{\perp}$	= shearing stress generated in the weld due to an axial force in the direction perpendicular to the welding line	5.6, 5.7
$\tau_{0.2d}$	= design shearing strength for the 0.2% yield strength of base materials	3.1, 4.7.1
ϕ	= resistance factor	2.1.1
ϕ_B	= resistance factor for the tensile strength of base materials, the heat-affected zone due to welding or welding materials	3.1, 3.2, 3.5, 3.6, 3.7, 4.1, 4.2, 4.3, 4.4, 4.6, 7.2.4, 7.3.2
ϕ_F	= resistance factor for the friction load carrying force	7.2.4
ϕ_{SB}	= resistance factor for the tensile strength of bolts	7.2.4, 7.3.2
ϕ_{SY}	= resistance factor for the yield stress of bolts	7.3.2
ϕ_u	= resistance factor for load-carrying capacity of plates, compression members, girders under bending or girders under shearing	3.5, 3.6, 3.7, 4.1, 4.2, 4.3, 4.4, 4.6
$\phi_{0.2}$	= resistance factor for the 0.2% proof stress of base materials, the heat-affected zone due to welding or welding materials	3.1, 3.2, 7.3.2
ψ	= magnification to increase the plate thickness	5.2

1. General Provisions

1.1 Scope of Application

(1) This specification specifies the design and fabrication method for general aluminum alloy structures in civil engineering. When the provisions of this specification are changed and applied, or when the matters not provided in this specification are applied, the parties consult each other to decide whether or not to apply them.

(2) In this specification, the loads specified by the design standard related to civil engineering structures to be designed are used as the design loads.

(3) It must be fully checked that the required performance specified in the design standard related to civil engineering structures to be designed is satisfied.

1.2 Usable Materials

Aluminum alloy materials that can be used for civil engineering structures must comply with the Japanese Industrial Standards (hereinafter referred to as JIS) shown in Table 1.2.1. Aluminum alloy materials with an elongation of 10 % or more shall be used. As for extrusions of A5083-H112 alloy, those with a tensile strength of 275 N/mm^2 or more and a 0.2 % proof stress of 120 N/mm^2 or more shall be used.

Table 1.2.1 Aluminum Alloy Materials

	Aluminum alloys	JIS
Plates	A5083-H112, A5083-O, A6061-T6, A6061-T651	JIS H 4000[1)]
Extrusions	A5083-H112, A5083-O, A6061-T6, A6005C-T5, A6005C-T6	JIS H 4100[2)]
Welding materials	A5183, A5356	JIS Z 3232[3)]

1) JIS H 4000: Aluminum and aluminum alloy sheets, strips and plates, 2014.

2) JIS H 4100: Aluminum and aluminum alloy extruded profiles, 2015.

3) JIS Z 3232: Aluminum and aluminum alloy welding rods and wires, 2009.

1.3 Values of Material Constants Used for Design Calculations

The values of material constants for aluminum alloys used for design calculations are shown in Table 1.3.1.

Table 1.3.1 Values of Material Constants for Aluminum Alloys

Types of material constants	Values
Density	2.7×10^3 (kg/m^3)
(Unit volume weight)	[26.5 (kN/m^3)]
Young's modulus	7.0×10^4 (N/mm^2)
Shear modulus	2.7×10^4 (N/mm^2)
Poisson's ratio	0.3
Coefficient of linear expansion	24×10^{-6} (1/℃)

1.4 Limit Temperature during Service

The temperature of aluminum alloy structures in civil engineering in service shall not exceed 80℃.

1.5 Anticorrosion

(1) Under normal atmospheric conditions, civil engineering structures made of aluminum alloy materials listed in 1.2 can be used without painting.

(2) When using aluminum alloy materials in combination with dissimilar metals such as steel materials, the contact corrosion with them must be prevented.

(3) The surface of the aluminum alloy materials that come into contact with mortar or concrete must be painted.

(4) Aluminum alloys A5083-H112 and A5083-O and welding materials A5183 and A5356 shall not be used when civil engineering structures placed in a marine environment are in service at temperatures above 66°C.

2. Design Basics

2.0 Definition of Terms

(1) Bolted bearing-type joint

A bolted joint in which forces are carried by the bearing resistance that pushes the bolt and plate against each other, and the shearing force generated in the bolt.

(2) Design load

A combination of loads in which nominal loads are multiplied by load factors.

(3) Design strength

A value obtained by multiplying a nominal strength by a resistance factor.

(4) Fracture load carrying limit

In high-strength bolted friction-type joints and bolted bearing-type joints, the limit at which bolts reach the shearing strength or plates reach the bearing-fracture strength.

(5) Friction load carrying limit

The limit of slippage between plates in high-strength bolted friction-type joints.

(6) High-strength bolted friction-type joint

A bolted joint that applies an axial force to a high-strength bolt to tighten plates and carries forces by the frictional force generated between plates.

(7) Limit state

A state in which a structure or member can no longer meet its intended purpose.

(8) Load and resistance factor design method

A method to determine dimensions of a member so that stresses generated in a member against the design load are less than the design strength of a member.

(9) Load-carrying capacity

Maximum load that a member can withstand before it collapses under compressive force, bending moment or shearing force.

(10) Load factor

A factor for considering the deviation of a nominal load from an actual load, the uncertainty included in the analysis that converts loads into stresses that occur in a member, and the probability that various loads occur simultaneously.

(11) Nominal load

The load specified by the design standard.

(12) Nominal strength

Resistance strength of a member calculated according to this specification.

(13) Resistance factor

A factor for considering the deviation of a nominal strength from an actual strength, the modes of fracture (brittle fracture or ductile fracture), and the seriousness of consequences of fracture.

(14) Serviceability limit state

A critical condition where a structure or member does not collapse but is no longer suitable for normal use.

(15) Ultimate limit state

A critical condition where a structure or member collapses or cannot be used.

(16) Yield load carrying limit

In bolted bearing-type joints, the limit at which bolts reach the shearing yield stress or plates reach the bearing yield stress.

2.1 Check of Limit States

2.1.1 Check of Ultimate Limit State

(1) The ultimate limit state of aluminum alloy structures in civil engineering is checked by the load and resistance factor design method. As shown in the following equations, it is verified that the stress generated in a member against the design load is less than the design strength of a member.

$$\sigma_{Fd} \leq \sigma_{Rd} \tag{2.1.1a}$$

$$\sigma_{Fd} = \sum_{i=1}^{k} \left(r_i \sigma_{Fn,i} \right) \tag{2.1.1b}$$

$$\sigma_{Rd} = \phi \sigma_{Rn} \tag{2.1.1c}$$

where

σ_{Fd} = stress that occurs in a member against the design load

σ_{Rd} = design strength of a member

r_i = load factor for the nominal load i

$\sigma_{Fn,i}$ = stress that occurs in a member against the nominal load i

k = total number of nominal loads

ϕ = resistance factor

σ_{Rn} = nominal strength of a member

(2) For the design loads, the nominal loads, their combination and the load factors specified in the design standard related to civil engineering structures to be designed shall be used.

(3) For tension members, Eqs. (2.1.1) are checked when they reach the 0.2% proof stress and when they reach the tensile strength. For compression members and girder members, Eqs. (2.1.1) are checked when they reach the load-carrying capacity. The design strengths for those members are given in Chapters 3 to 6.

(4) For high-strength bolted friction-type joints, Eqs. (2.1.1) are checked when they reach the friction load carrying limit and when they reach the fracture load carrying limit. For bolted bearing-type joints, Eqs. (2.1.1) are checked when they reach the yield load carrying limit and when they reach the fracture load carrying limit. The design strengths of bolted joints are given in Chapter 7.

(5) The values of the resistance factors are determined according to the level of safety required for civil engineering structures to be designed.

2.1.2 Check of Serviceability Limit State

The check of the serviceability limit state is performed by satisfying the allowable deflection for members, which is specified by the design standard related to civil engineering structures to be designed.

2.1.3 Check of Fatigue

Fatigue is classified into the ultimate limit state or the serviceability limit state depending on the location where fatigue cracks occur or on their size when they are found. The brittle fracture of a member that occurs after the propagation of fatigue cracks is an example of the former, and repairable fatigue cracks are an example of the latter. The check of fatigue is given in Chapter 8.

2.2 Cross-Sectional Reduction Due to Corrosion

In designing aluminum alloy structures in civil engineering, it is not necessary to consider the cross-sectional reduction due to corrosion.

2.3 Minimum and Maximum Plate Thickness

The thickness of plate elements that make up a member is 3 mm or more and 40 mm or less. However, it is not necessary to make below 40 mm the thickness of the joint parts where the plate thickness is partially increased (See 5.2 and 6.3).

2.4 Connection of Members

(1) The connection of main members shall be designed for the larger value of the cross-sectional force against the design load and 75% of the strength given by (design strength) × (entire cross-sectional area of a member). However, for the shearing force, the cross-sectional force against the design load may be used.

(2) The connection of secondary members may be designed for the sectional force against the design load.

(3) The connection of members shall be designed so that the following items are satisfied:

1) The stress transmission is clear.
2) The eccentricity with respect to the member axis is reduced as much as possible.
3) The stress concentration is avoided as much as possible.

3. Design Strength

3.1 Design Tensile Strength and Design Shearing Strength of Base Materials

The design tensile strength of base materials is given by the following equations:

For the 0.2% proof stress, $\sigma_{t0.2d} = \phi_{0.2}\sigma_{0.2}$ (3.1.1a)

For the tensile strength, $\sigma_{tBd} = \phi_{B}\sigma_{B}$ (3.1.1b)

where

$\sigma_{t0.2d}$ = design tensile strength for the 0.2% proof stress of base materials

σ_{tBd} = design tensile strength for the tensile strength of base materials

$\sigma_{0.2}$ = 0.2% proof stress of base materials

σ_{B} = tensile strength of base materials

$\phi_{0.2}$, ϕ_{B} = resistance factor for the 0.2% proof stress and the one for the tensile strength of base materials, respectively

Table 3.1.1 shows the tensile strength σ_B and the 0.2% proof stress $\sigma_{0.2}$ of base materials.

Table 3.1.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Base Materials

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125
	A5083-O	$3 \leqq t \leqq 40$	275	125
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120
	A5083-O	$3 \leqq t \leqq 38$	275	120
	A6061-T6	$3 \leqq t \leqq 40$	265	245
	A6005C-T5	$3 \leqq t \leqq 6$	245	205
		$6 < t \leqq 12$	225	175
	A6005C-T6	$3 \leqq t \leqq 6$	265	235

The design shearing strength of base materials is given by the following equations:

For the 0.2% proof stress, $\tau_{0.2d} = \dfrac{\sigma_{t0.2d}}{\sqrt{3}}$ (3.1.2a)

For the tensile strength, $\tau_{Bd} = \dfrac{\sigma_{tBd}}{\sqrt{3}}$ (3.1.2b)

where

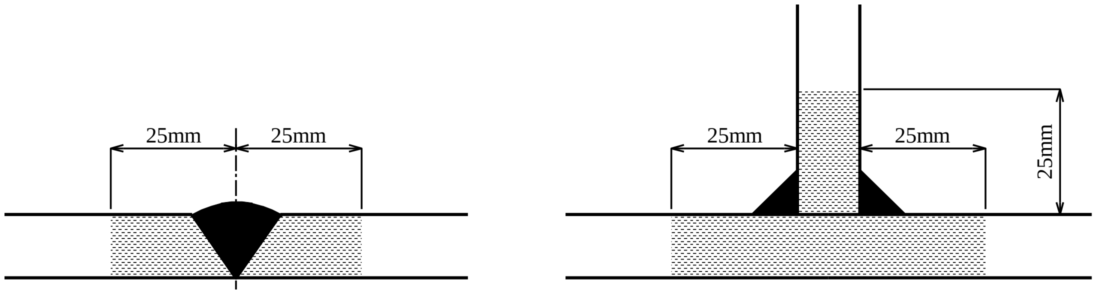
$\tau_{0.2d}$ = design shearing strength for the 0.2% proof stress of base materials

τ_{Bd} = design shearing strength for the tensile strength of base materials

3.2 Design Tensile Strength and Design Shearing Strength of Welds

(1) As shown in Figure 3.2.1, the heat-affected range due to welding, which is the part consisting of the deposited metal and the heat-affected zone of the base material, is 25

mm on each side from the welding center in the case of butt welding, and 25 mm from the welding root in the case of fillet welding.



(a) Butt Welding **(b) Fillet Welding**

Figure 3.2.1 Heat-Affected Range Due to Welding

(2) The design tensile strength of the heat-affected range due to welding shall be the smaller of the design tensile strengths of the heat-affected zone and the welding material, as shown in the following equations:

For the 0.2% proof stress, $\sigma_{w0.2d} = \min\left(\sigma_{h0.2d}, \sigma_{f0.2d}\right)$ (3.2.1a)

For the tensile strength, $\sigma_{wBd} = \min\left(\sigma_{hBd}, \sigma_{fBd}\right)$ (3.2.1b)

where

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected range due to welding

$\sigma_{h0.2d}$, $\sigma_{f0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected zone due to welding and the one for the 0.2% proof stress of the welding material, respectively

σ_{wBd} = design tensile strength for the tensile strength of the heat-affected range due to welding

σ_{hBd}, σ_{fBd} = design tensile strength for the tensile strength of the heat-affected zone due to welding and the one for the tensile strength of the welding material, respectively

The design shearing strength of the heat-affected range due to welding shall be the smaller of the design shearing strengths of the heat-affected zone and the welding material, as shown in the following equations:

For the 0.2% proof stress, $\tau_{w0.2d} = \min\left(\tau_{h0.2d}, \tau_{f0.2d}\right)$ (3.2.2a)

For the tensile strength, $\tau_{wBd} = \min\left(\tau_{hBd}, \tau_{fBd}\right)$ (3.2.2b)

where

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected range due to welding

$\tau_{h0.2d}$, $\tau_{f0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected zone due to welding and the one for the 0.2% proof stress of the welding material, respectively

τ_{wBd} = design shearing strength for the tensile strength of the heat-affected range due to welding

τ_{hBd}, τ_{fBd} = design shearing strength for the tensile strength of the heat-affected zone due to welding and the one for the tensile strength of the welding material, respectively

(3) The design tensile strength of the heat-affected zone due to welding is given by the following equations:

For the 0.2% proof stress, $$\sigma_{h0.2d} = \phi_{0.2}\sigma_{h0.2} \quad (3.2.3a)$$

For the tensile strength, $$\sigma_{hBd} = \phi_B\sigma_{hB} \quad (3.2.3b)$$

where

$\sigma_{h0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected zone due to welding

σ_{hBd} = design tensile strength for the tensile strength of the heat-affected zone due to welding

$\sigma_{h0.2}$ = 0.2% proof stress of the heat-affected zone due to welding

σ_{hB} = tensile strength of the heat-affected zone due to welding

$\phi_{0.2}$, ϕ_B = resistance factor for the 0.2% proof stress and the one for the tensile strength of the heat-affected zone due to welding, respectively

Table 3.2.1 shows the tensile strength σ_{hB} and the 0.2% proof stress $\sigma_{h0.2}$ of the heat-affected zone due to welding. The values shown in Table 3.2.1 can be applied to MIG welding and TIG welding for one layer.

Table 3.2.1 Tensile Strength σ_{hB} and 0.2% Proof Stress $\sigma_{h0.2}$ of Heat-Affected Zone Due to Welding

Aluminum alloys		Thickness t (mm)	Tensile strength σ_{hB} (N/mm^2)	0.2% proof stress $\sigma_{h0.2}$ (N/mm^2)
Plates	A5083-H112	4≦t≦40	275	125
	A5083-O	3≦t≦40	275	125
	A6061-T6	3≦t≦6.5	165	105
	A6061-T651	6.5≦t≦40	165	105
Extrusions	A5083-H112	3≦t≦40	275	120
	A5083-O	3≦t≦38	275	120
	A6061-T6	3≦t≦40	165	105
	A6005C-T5	3≦t≦12	165	105
	A6005C-T6	3≦t≦6	165	105

The design shearing strength of the heat-affected zone due to welding is given by the following equations:

For the 0.2% proof stress, $$\tau_{h0.2d} = \frac{\sigma_{h0.2d}}{\sqrt{3}} \quad (3.2.4a)$$

For the tensile strength, $$\tau_{hBd} = \frac{\sigma_{hBd}}{\sqrt{3}} \quad (3.2.4b)$$

where

$\tau_{h0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected zone due to welding

τ_{hBd} = design shearing strength for the tensile strength of the heat-affected zone due to welding

(4) The design tensile strength of welding materials is given by the following equations:

For the 0.2% proof stress, $$\sigma_{f0.2d} = \phi_{0.2}\sigma_{f0.2} \quad (3.2.5a)$$

For the tensile strength, $$\sigma_{fBd} = \phi_{B}\sigma_{fB} \quad (3.2.5b)$$

where

$\sigma_{f0.2d}$ = design tensile strength for the 0.2% proof stress of welding materials

σ_{fBd} = design tensile strength for the tensile strength of welding materials

$\sigma_{f0.2}$ = 0.2% proof stress of welding materials

σ_{fB} = tensile strength of welding materials

$\phi_{0.2}$, ϕ_{B} = resistance factor for the 0.2% proof stress and the one for the tensile strength of welding materials, respectively

Table 3.2.2 shows the tensile strength σ_{fB} and the 0.2% proof stress $\sigma_{f0.2}$ of welding materials.

Table 3.2.2 Tensile Strength σ_{fB} and 0.2% Proof Stress $\sigma_{f0.2}$ of Welding Materials

Welding materials	Tensile strength σ_{fB} (N/mm^2)	0.2% proof stress $\sigma_{f0.2}$ (N/mm^2)
A5183	275	125
A5356	265	120

The design shearing strength of welding materials is given by the following equations:

For the 0.2% proof stress, $$\tau_{f0.2d} = \frac{\sigma_{f0.2d}}{\sqrt{3}} \quad (3.2.6a)$$

For the tensile strength, $$\tau_{fBd} = \frac{\sigma_{fBd}}{\sqrt{3}} \quad (3.2.6b)$$

where

$\tau_{f0.2d}$ = design shearing strength for the 0.2% proof stress of welding materials

τ_{fBd} = design shearing strength for the tensile strength of welding materials

3.3 Design Tensile Strength and Design Shearing Strength of Friction Stir Welded Joints

(1) As shown in Figure 3.3.1, the heat-affected range due to friction stir welding, which is the part consisting of the stirring part caused by friction stir welding and the heat-affected zone of the base material, is 25 mm on each side from the welding center.

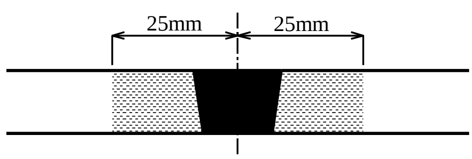


Figure 3.3.1 Heat-Affected Range Due to Friction Stir Welding

(2) The design tensile strength of the heat-affected range due to friction stir welding is given by the following equations, which is the same as the design tensile strength of the heat-affected zone due to welding:

For the 0.2% proof stress, $$\sigma_{w0.2d} = \sigma_{h0.2d} \quad (3.3.1a)$$

For the tensile strength, $$\sigma_{wBd} = \sigma_{hBd} \quad (3.3.1b)$$

where

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected range due to friction stir welding

$\sigma_{h0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected zone due to welding [Eq. (3.2.3a)]

σ_{wBd} = design tensile strength for the tensile strength of the heat-affected range due to friction stir welding

σ_{hBd} = design tensile strength for the tensile strength of the heat-affected zone due to welding [Eq. (3.2.3b)]

The design shearing strength of the heat-affected range due to friction stir welding is given by the following equations, which is the same as the design shearing strength of the heat-affected zone due to welding:

For the 0.2% proof stress, $$\tau_{w0.2d} = \tau_{h0.2d} \quad (3.3.2a)$$

For the tensile strength, $$\tau_{wBd} = \tau_{hBd} \quad (3.3.2b)$$

where

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected range due to friction stir welding

$\tau_{h0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected zone due to welding [Eq. (3.2.4a)]

τ_{wBd} = design shearing strength for the tensile strength of the heat-affected range due to friction stir welding

τ_{hBd} = design shearing strength for the tensile strength of the heat-affected zone due to welding [Eq. (3.2.4b)]

3.4 Design Tensile Strength and Design Shearing Strength of Members with Welded Joints

(1) As shown in Fig. 3.4.1, for a member subjected to tensile force or shearing force, the design strengths when there are joints by welding or friction stir welding on a part of the cross section are given as follows:

1) When a tensile force is applied in the joining-line direction [See Figure 3.4.1(a)],

For the 0.2% proof stress, $$\sigma_{pt0.2d} = \sigma_{t0.2d} - \frac{A_w}{A}(\sigma_{t0.2d} - \sigma_{w0.2d}) \quad (3.4.1a)$$

For the tensile strength, $$\sigma_{ptBd} = \sigma_{tBd} - \frac{A_w}{A}(\sigma_{tBd} - \sigma_{wBd}) \quad (3.4.1b)$$

2) When a tensile force is applied in the direction perpendicular to the joining line [See Figure 3.4.1(b)],

For the 0.2% proof stress, $\sigma_{w0.2d}$

For the tensile strength, σ_{wBd}

3) When subjected to shearing force [See Figure 3.4.1(c)]

For the 0.2% proof stress, $\tau_{w0.2d}$

For the tensile strength, τ_{wBd}

where

$\sigma_{pt0.2d}$ = design tensile strength for the 0.2% proof stress of members with joints by welding or friction stir welding

$\sigma_{t0.2d}$ = design tensile strength for the 0.2% proof stress of base materials

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress of the heat-affected range due to welding or friction stir welding

σ_{ptBd} = design tensile strength for the tensile strength of members with joints by welding or friction stir welding

σ_{tBd} = design tensile strength for the tensile strength of base materials

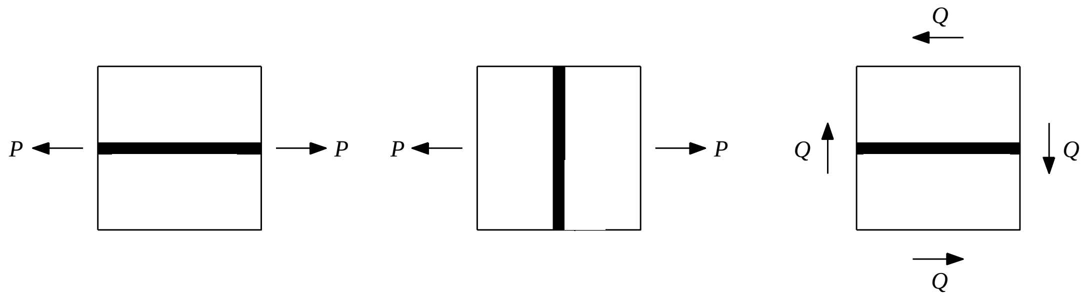
σ_{wBd} = design tensile strength for the tensile strength of the heat-affected range due to welding or friction stir welding

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress of the heat-affected range due to welding or friction stir welding

τ_{wBd} = design shearing strength for the tensile strength of the heat-affected range due to welding or friction stir welding

A = entire cross-sectional area of a member

A_w = cross-sectional area of the heat-affected range



(a) Tensile Force Acting in the Joining-Line Direction

(b) Tensile Force Acting in the Direction Perpendicular to the Joining Line

(c) Shearing Force

Figure 3.4.1 Forces Acting on Members with Welded Joints

(2) When welded joints cause a decrease in strength, the design tensile strength and the design shearing strength of welded joints where the thickness of the welded joint is partially increased according to 5.2 or 6.2 are able to be taken the same as the design tensile strength and the design shearing strength of base materials, respectively. However, in this case, the thickness of the partially thickened joint is assumed to be the same as that of the base material.

3.5 Design Compressive Strength of Plates Restrained along Two Edges

The design compressive strength of plates restrained along two edges that are subjected to uniform compressive stress is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (3.5.1a)

For the tensile strength, $\sigma_{tBd} = \phi_B \sigma_B$ (3.5.1b)

where

σ_{cud} = design compressive strength for the load-carrying capacity of plates restrained along two edges under uniform compressive stress

σ_{tBd} = design tensile strength for the tensile strength of aluminum alloy materials

σ_u = load-carrying capacity of plates restrained along two edges under uniform compressive stress

σ_B = tensile strength of aluminum alloy materials

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of plates restrained along two edges under uniform compressive stress and the one for the tensile strength of aluminum alloy materials, respectively

The tensile strength σ_B of aluminum alloy materials is shown in Table 3.5.1.

The load-carrying capacity σ_u of plates restrained along two edges under uniform compressive stress is given by the following equations:

$$\sigma_u = \eta \sigma_{0.2} \tag{3.5.2a}$$

$$\eta = \begin{cases} 1 & (R \le R_1) \\ 1 - 0.4\dfrac{R - R_1}{R_2 - R_1} & (R_1 < R < R_2) \\ 0.6\left(\dfrac{R_2}{R}\right)^p & (R_2 \le R \le 2) \end{cases} \tag{3.5.2b}$$

$$R = c\frac{b}{t} \tag{3.5.2c}$$

where

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 3.5.1

R_1, R_2, p = constant with the values shown in Table 3.5.2

c = constant with the values shown in Table 3.5.1

b = plate width (See Figure 3.5.1)

t = plate thickness (See Figure 3.5.1)

In the case of partially thickened joined plates in Table 3.5.2, the thickness of the joints must be partially increased according to 5.2 or 6.2. However, the thickness of the partially thickened joints is assumed to be the same as that of the base material.

Table 3.5.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Aluminum Alloy Materials and Values for c

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm²)	0.2% proof stress $\sigma_{0.2}$ (N/mm²)	c
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125	2.22×10^{-2}
	A5083-O	$3 \leqq t \leqq 40$	275	125	2.22×10^{-2}
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245	3.11×10^{-2}
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245	3.11×10^{-2}
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120	2.18×10^{-2}
	A5083-O	$3 \leqq t \leqq 38$	275	120	2.18×10^{-2}
	A6061-T6	$3 \leqq t \leqq 40$	265	245	3.11×10^{-2}
	A6005C-T5	$3 \leqq t \leqq 6$	245	205	2.85×10^{-2}
		$6 < t \leqq 12$	225	175	2.63×10^{-2}
	A6005C-T6	$3 \leqq t \leqq 6$	265	235	3.05×10^{-2}

Table 3.5.2 Values for R_1, R_2 and p

Aluminum alloys	Non-joined plates	Partially thickened joined plates	Joined plates
5000 series	B	−	C
6000 series	A	A	−

Identification symbols	R_1	R_2	p
A	0.52	1.26	0.67
B	0.44	1.05	0.64
C	0.42	0.98	0.67

Figure 3.5.1 shows how to set the width of the flange and web of a box-shaped cross-section member and that of the web of an I-shaped cross-section member.

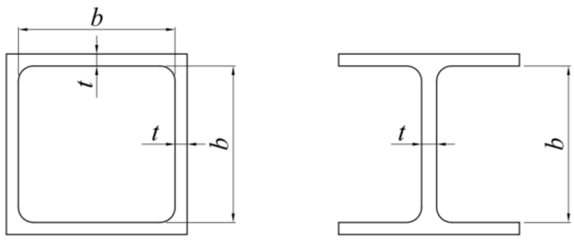


Figure 3.5.1 Flange and Web of Box-Shaped Cross-Section Member and Web of I-Shaped Cross-Section Member

3.6 Design Compressive Strength of Outstanding Plates

The design compressive strength of outstanding plates that are subjected to uniform compressive stress is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (3.6.1a)

For the tensile strength, $\sigma_{tBd} = \phi_B \sigma_B$ (3.6.1b)

where

σ_{cud} = design compressive strength for the load-carrying capacity of outstanding plates under uniform compressive stress

σ_{tBd} = design tensile strength for the tensile strength of aluminum alloy materials

σ_u = load-carrying capacity of outstanding plates under uniform compressive stress

σ_B = tensile strength of aluminum alloy materials

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of outstanding plates under uniform compressive stress and the one for the tensile strength of aluminum alloy materials, respectively

The tensile strength σ_B of aluminum alloy materials is shown in Table 3.6.1.

The load-carrying capacity σ_u of outstanding plates under uniform compressive stress is given by the following equations:

$$\sigma_u = \eta \sigma_{0.2} \quad (3.6.2a)$$

$$\eta = \begin{cases} 1 & (R \leq R_1) \\ 1 - 0.35\left(\dfrac{R - R_1}{R_2 - R_1}\right)^2 & (R_1 < R < R_2) \\ 0.65\left(\dfrac{R_2}{R}\right)^p & (R_2 \leq R \leq 2) \end{cases} \tag{3.6.2b}$$

$$R = c\frac{b}{t} \tag{3.6.2c}$$

where

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 3.6.1

R_1, R_2, p = constant with the values shown in Table 3.6.2

c = constant with the values shown in Table 3.6.1

b = plate width (See Figure 3.6.1)

t = plate thickness (See Figure 3.6.1)

In the case of partially thickened joined plates in Table 3.6.2, the thickness of the joints must be partially increased according to 5.2 or 6.2. However, the thickness of the partially thickened joints is assumed to be the same as that of the base material.

Table 3.6.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Aluminum Alloy Materials and Values for c

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)	c
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125	6.82×10^{-2}
	A5083-O	$3 \leqq t \leqq 40$	275	125	6.82×10^{-2}
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245	9.55×10^{-2}
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245	9.55×10^{-2}
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120	6.68×10^{-2}
	A5083-O	$3 \leqq t \leqq 38$	275	120	6.68×10^{-2}
	A6061-T6	$3 \leqq t \leqq 40$	265	245	9.55×10^{-2}
	A6005C-T5	$3 \leqq t \leqq 6$	245	205	8.73×10^{-2}
		$6 < t \leqq 12$	225	175	8.07×10^{-2}
	A6005C-T6	$3 \leqq t \leqq 6$	265	235	9.35×10^{-2}

Table 3.6.2 Values for R_1, R_2 and p

Aluminum alloys	Non-joined plates	Partially thickened joined plates	Joined plates
5000 series	B	−	B
6000 series	A	A	−

Identification symbols	R_1	R_2	p
A	0.60	1.24	0.16
B	0.40	1.02	0.20

Figure 3.6.1 shows how to set the width of the flange of an I-shaped cross-section member.

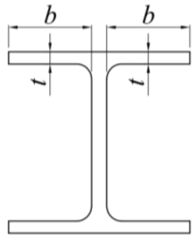


Figure 3.6.1 Flange of I-Shaped Cross-Section Member

3.7 Design Compressive Strength of Longitudinally Stiffened A6061-T6 Plates Restrained along Two Edges

The design compressive strength of plates made of aluminum alloy A6061-T6 extrusions with one longitudinal stiffener as shown in Figure 3.7.1, that are restrained along two edges, under uniform compressive stress is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (3.7.1a)

For the tensile strength, $\sigma_{tBd} = \phi_B \times 265$ N/mm² (3.7.1b)

where

σ_{cud} = design compressive strength for the load-carrying capacity of the above-mentioned plates

σ_{tBd} = design tensile strength for the tensile strength of A6061-T6 extrusions

σ_u = load-carrying capacity of the above-mentioned plates

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned plates and the one for the tensile strength of A6061-T6 extrusions, respectively

The load-carrying capacity σ_u of the above-mentioned plates is given by the following equations:

$$\sigma_u = 245\eta \quad \text{N/mm}^2 \tag{3.7.2a}$$

$$\eta = \begin{cases} 1 & \left(19 \le \dfrac{b}{t} \le 26\right) \\ 0.854 + 0.942R - 1.771R^2 + 0.877R^3 - 0.141R^4 & \left(26 < \dfrac{b}{t} \le 129\right) \end{cases} \tag{3.7.2b}$$

$$R = \frac{b}{64.3t} \tag{3.7.2c}$$

where

b = plate width (See Figure 3.7.1)

t = plate thickness (See Figure 3.7.1)

The cross-sectional shape of the plates that provide the design compressive strength of Eq. (3.7.1a) for the load-carrying capacity is given by the following equations:

$$\frac{t_r}{t} = 2.77 \times 10^{-3}\frac{b}{t} + 1.18 \quad \left(19 \le \frac{b}{t} \le 129\right) \tag{3.7.3a}$$

$$\frac{b_r}{t_r} = 6.28 \tag{3.7.3b}$$

where

b_r = width of a longitudinal stiffener (See Figure 3.7.1)

t_r = thickness of a longitudinal stiffener (See Figure 3.7.1)

The cross-sectional shape given by Eqs. (3.7.3) is the one that maximizes the buckling strength of a rectangular plate of aluminum alloy A6061-T6 with a single longitudinal stiffener, which is subjected to uniform compressive stress.

When calculating the compressive stress acting on the plate restrained along two edges, the cross-sectional area of the longitudinal stiffener is added to that of the plate.

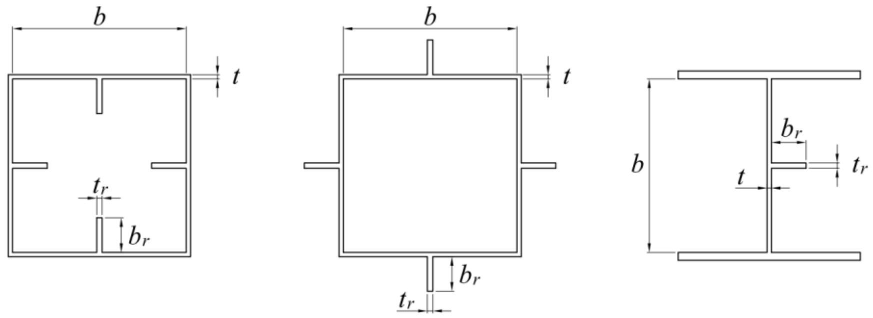


Figure 3.7.1 Plates Restrained along Two Edges with One Longitudial Stiffener

4. Design of Members

4.1 Design Axial Compressive Strength of Members

The design axial compressive strength of members with a biaxially symmetric I-shaped cross-section or a box-shaped cross-section is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (4.1.1a)

For the tensile strength, $\sigma_{tBd} = \phi_B \sigma_B$ (4.1.1b)

where

σ_{cud} = design axial compressive strength for the load-carrying capacity of the above-mentioned members

σ_{tBd} = design tensile strength for the tensile strength of aluminum alloy materials

σ_u = load-carrying capacity of the above-mentioned members

σ_B = tensile strength of aluminum alloy materials

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned members and the one for the tensile strength of aluminum alloy materials, respectively

The tensile strength σ_B of aluminum alloy materials is shown in Table 4.1.1.

The load-carrying capacity σ_u of the above-mentined members is given by the following equations:

$$\sigma_u = Q\eta\sigma_{0.2} \quad (4.1.2a)$$

$$\eta = \begin{cases} 1 & (\lambda \leq \lambda_1) \\ a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3 + a_4\lambda^4 & (\lambda_1 < \lambda \leq 2) \end{cases} \quad (4.1.2b)$$

$$\lambda = c\sqrt{Q}\frac{l}{r} \quad (4.1.2c)$$

where

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 4.1.1

$a_0, a_1, a_2, a_3, a_4, \lambda_1$ = constant with the values shown in Table 4.1.2

c = constant with the values shown in Table 4.1.1

Q = coefficient given by Eq. (4.1.4)

l = effective buckling length of the above-mentioned members

r = radius of gyration of the above-mentioned members

In the case of partially thickened joined plates in Table 4.1.2, the thickness of the joint must be partially increased according to 5.2 or 6.2. However, the thickness of the partially thickened joint is assumed to be the same as that of the base material.

The effective buckling length l of the above-mentioned members is given by the following equation:

$$l = KL \quad (4.1.3)$$

where

K = factor for the effective buckling length

L = length between the supporting points of the above-mentioned members or the length for cantilever members

The values for the factor K for the effective buckling length are given, depending on the restrained state at the ends of a member.

Table 4.1.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Aluminum Alloy Materials and Values for c

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)	c
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125	1.35×10^{-2}
	A5083-O	$3 \leqq t \leqq 40$	275	125	1.35×10^{-2}
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245	1.88×10^{-2}
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245	1.88×10^{-2}
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120	1.32×10^{-2}
	A5083-O	$3 \leqq t \leqq 38$	275	120	1.32×10^{-2}
	A6061-T6	$3 \leqq t \leqq 40$	265	245	1.88×10^{-2}
	A6005C-T5	$3 \leqq t \leqq 6$	245	205	1.72×10^{-2}
		$6 < t \leqq 12$	225	175	1.59×10^{-2}
	A6005C-T6	$3 \leqq t \leqq 6$	265	235	1.84×10^{-2}

Table 4.1.2 Values for a_0, a_1, a_2, a_3, a_4 and λ_1

Aluminum alloys	Non-joined plates	Partially thickened joined plates	Joined plates
5000 series	B	−	C
6000 series	A	A	−

Identification symbols	a_0	a_1	a_2	a_3	A_4	λ_1
A	1.01	-0.03	-0.30	-0.04	0.05	0.13
B	1.00	0.10	-1.13	0.72	-0.14	0.09
C	1.00	0.10	-1.33	0.88	-0.17	0.09

The coefficient Q is given by the following equation:

$$Q = \frac{\sum \eta_i A_i}{\sum A_i} \tag{4.1.4}$$

where

η_i = coefficient that gives the compressive load-carrying capacity of the plate element i that constitutes a compression member

A_i = cross-sectional area of the plate element i

Eqs. (3.5.2b), (3.6.2b) and (3.7.2b) are used as the coefficient η_i for a plate restrained along two edges, an outstanding plate, and a longitudinally stiffened A6061-T6 plate restrained along two edges, respectively.

4.2 Design Bending Compressive Strength of Unstiffened Web Girders

The design bending compressive strength of vertically symmetrical I-shaped cross-section girders where webs are not stiffened is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (4.2.1a)

For the tensile strength, $\sigma_{tBd} = \phi_B \sigma_B$ (4.2.1b)

where

σ_{cud} = design bending compressive strength for the load-carrying capacity of the above-mentioned girders

σ_{tBd} = design tensile strength for the tensile strength of aluminum alloy materials

σ_u = bending load-carrying capacity of the above-mentioned girders

σ_B = tensile strength of aluminum alloy materials

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned girders and the one for the tensile strength of aluminum alloy materials, respectively

The tensile strength σ_B of aluminum alloy materials is shown in Table 4.2.1.

The bending load-carrying capacity σ_u of the above-mentioned girders is given by the following equations:

$$\sigma_u = \sigma_{fu} g_w \tag{4.2.2a}$$

$$\sigma_{fu} = \min(\sigma_{fgu}, \sigma_{flu}) \tag{4.2.2b}$$

$$\sigma_{fgu} = \eta \sigma_{0.2} \tag{4.2.2c}$$

where

σ_{fu} = lateral load-carrying capacity of a compressive flange considering effects of the local buckling of the compressive flange

g_w = coefficient that gives the ultimate bending moment of a girder when neither local buckling nor lateral buckling occurs in a compressive flange

σ_{fgu} = lateral load-carrying capacity of a compressive flange without considering effects of the local buckling of the compressive flange

σ_{flu} = load-carrying capacity for the local buckling of a compressive flange

η = coefficient that gives σ_{fgu}

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 4.2.1

The coefficient η that provides σ_{fgu} is given by the following equations:

$$\eta = \begin{cases} 1 & (\lambda \leq \lambda_1) \\ a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3 + a_4\lambda^4 & (\lambda_1 < \lambda \leq 2) \end{cases} \tag{4.2.3a}$$

$$\lambda = cK\frac{l}{B_f} \tag{4.2.3b}$$

$$K = k_0 + k_1\frac{A_w}{A_f}\left(1 \leq \frac{A_w}{A_f} \leq 4\right) \tag{4.2.3c}$$

where

$a_0, a_1, a_2, a_3, a_4, \lambda_1$ = constant with the values shown in Table 4.2.2

c = constant with the values shown in Table 4.2.1

l = distance between the supporting points of a compressive flange

B_f = overall width of a compressive flange (See Figure 4.2.1)

A_f = cross-sectional area of a compressive flange (See Figure 4.2.1)

A_w = cross-sectional area of a web (See Figure 4.2.1)

k_0, k_1 = constant with the values shown in Table 4.2.3

For partially thickened joined girders in Table 4.2.2, the thickness of the joints in the web shall be partially increased according to 5.2 or 6.2. However, the thickness of the partially thickened joints is assumed to be the same as that of the base material. That is, when determining the cross-sectional area A_w of the web, the thickness of the partially thickened joints is the same as that of the base material.

Table 4.2.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Aluminum Alloy Materials and Values for c

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)	c
Plates	A5083-H112	4≦t≦40	275	125	4.66×10^{-2}
	A5083-O	3≦t≦40	275	125	4.66×10^{-2}
	A6061-T6	3≦t≦6.5	295	245	6.52×10^{-2}
	A6061-T651	6.5≦t≦40	295	245	6.52×10^{-2}
Extrusions	A5083-H112	3≦t≦40	275	120	4.57×10^{-2}
	A5083-O	3≦t≦38	275	120	4.57×10^{-2}
	A6061-T6	3≦t≦40	265	245	6.52×10^{-2}
	A6005C-T5	3≦t≦6	245	205	5.97×10^{-2}
		6＜t≦12	225	175	5.51×10^{-2}
	A6005C-T6	3≦t≦6	265	235	6.39×10^{-2}

Table 4.2.2 Values for a_0, a_1, a_2, a_3, a_4 and λ_1

Aluminum alloys	Non-joined girders	Partially thickened joined girders	Joined girders
5000 series	B	-	C
6000 series	A	A	−

Identification symbols	a_0	a_1	a_2	a_3	A_4	λ_1
A	1.01	-0.03	-0.30	-0.04	0.05	0.13
B	1.00	0.10	-1.13	0.72	-0.14	0.09
C	1.00	0.10	-1.33	0.88	-0.17	0.09

Table 4.2.3 Values for k_0 and k_1

Aluminum alloys	k_0	k_1
5000 series	0.91	0.09
6000 series	0.87	0.13

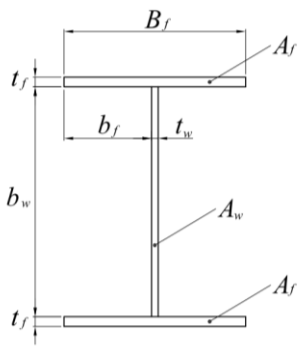


Figure 4.2.1 I-Shaped Cross-Section Girder

The load-carrying capacity σ_{flu} for the local buckling of a compressive flange is given by Eqs. (3.6.2) by considering the compressive flange on one side as an outstanding plate. However, the width-to-thickness ratio of the compressive flange on one side shall be less than the values shown in Table 4.2.4.

Table 4.2.4 Maximum Width-to-Thickness Ratio of Compressive Flange on One Side

Aluminum alloys		Thickness t (mm)	b_f/t_f
Plates	A5083-H112	$4 \leqq t \leqq 40$	17.5
	A5083-O	$3 \leqq t \leqq 40$	17.5
	A6061-T6	$3 \leqq t \leqq 6.5$	12.5
	A6061-T651	$6.5 \leqq t \leqq 40$	12.5
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	17.9
	A5083-O	$3 \leqq t \leqq 38$	17.9
	A6061-T6	$3 \leqq t \leqq 40$	12.5
	A6005C-T5	$3 \leqq t \leqq 6$	13.7
		$6 < t \leqq 12$	14.8
	A6005C-T6	$3 \leqq t \leqq 6$	12.8

b_f = width of a compressive flange on one side (See Figure 4.2.1)
t_f = thickness of a compressive flange (See Figure 4.2.1)

The coefficient g_w that gives the ultimate bending moment of a girder when neither local buckling nor lateral buckling occurs in a compressive flange is given by the following equation:

$$g_w = \begin{cases} \dfrac{1+\dfrac{A_w}{4A_f}}{1+\dfrac{A_w}{6A_f}} & \left(\dfrac{b_w}{t_w} \leq \beta_0\right) \\ 1-\dfrac{\dfrac{A_w}{A_f}}{12\left(1+\dfrac{A_w}{6A_f}\right)}\dfrac{\dfrac{b_w}{t_w}-\beta_1}{\beta_1-\beta_0} & \left(\beta_0 < \dfrac{b_w}{t_w} \leq \beta_2\right) \\ \dfrac{1+\dfrac{2A_w}{15A_f}\left(\beta_2\dfrac{t_w}{b_w}\right)^p}{1+\dfrac{A_w}{6A_f}} & \left(\beta_2 < \dfrac{b_w}{t_w} \leq \beta_3\right) \end{cases} \tag{4.2.4}$$

where

$\beta_0, \beta_1, \beta_2, \beta_3, p$ = constant with the values shown in Table 4.2.5
b_w = web width (See Figure 4.2.1)
t_w = web thickness (See Figure 4.2.1)

Table 4.2.5 Values for $\boldsymbol{\beta_0, \beta_1, \beta_2, \beta_3}$ and $\boldsymbol{p}$

Aluminum alloys		Thickness t (mm)	β_0	β_1	β_2	β_3	p
Plates	A5083-H112	$4 \leqq t \leqq 40$	30	90	114	220	0.67
	A5083-O	$3 \leqq t \leqq 40$	30	90	114	220	0.67
	A6061-T6	$3 \leqq t \leqq 6.5$	27	74	93	157	0.69
	A6061-T651	$6.5 \leqq t \leqq 40$	27	74	93	157	0.69
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	30	92	117	225	0.67
	A5083-O	$3 \leqq t \leqq 38$	30	92	117	225	0.67
	A6061-T6	$3 \leqq t \leqq 40$	27	74	93	157	0.69
	A6005C-T5	$3 \leqq t \leqq 6$	29	81	101	172	0.69
		$6 < t \leqq 12$	32	87	110	186	0.69
	A6005C-T6	$3 \leqq t \leqq 6$	27	75	95	160	0.69

4.3 Design Shearing Strength of Girders

(1) The design shearing strength of vertically symmetrical I-shaped cross-section girders with no intermediate transverse stiffeners, which is simply supported at both ends, is given by the following equations:

For the load-carrying capacity, $$\tau_{ud} = \phi_u \tau_u \qquad (4.3.1a)$$

For the tensile strength, $$\tau_{Bd} = \phi_B \frac{\sigma_B}{\sqrt{3}} \qquad (4.3.1b)$$

where

τ_{ud} = design shearing strength for the load-carrying capacity of the above-mentioned girders

τ_{Bd} = design shearing strength for the tensile strength of aluminum alloy materials

τ_u = shearing load-carrying capacity of the above-mentioned girders

σ_B = tensile strength of aluminum alloy materials

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned girders and the one for the tensile strength of aluminum alloy materials, respectively

The tensile strength σ_B of aluminum alloy materials is shown in Table 4.3.1.

The shearing load-carrying capacity τ_u of the above-mentioned girders is given by the following equations:

$$\tau_u = \eta \frac{\sigma_{0.2}}{\sqrt{3}} \qquad (4.3.2a)$$

$$\eta = \begin{cases} 1 & (R \le R_1) \\ \dfrac{a_1}{R} - \dfrac{a_2}{R^2} & (R_1 < R \le R_2) \\ 0.8\left(\dfrac{R_2}{R}\right)^p & (R_2 < R \le 3) \end{cases} \qquad (4.3.2b)$$

$$R = \frac{cF}{\sqrt{5.34 + \dfrac{4}{\left(\dfrac{a_L}{b_w}\right)^2}}} \frac{b_w}{t_w} \qquad \left(1 \le \frac{a_L}{b_w}\right) \qquad (4.3.2c)$$

$$F = 8.5 \times 10^{-3} \frac{A_w}{A_f} \frac{a_L}{b_w} + 0.75 \le 1 \qquad \left(1 \le \frac{A_w}{A_f} \le 4\right) \qquad (4.3.2d)$$

where

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 4.3.1

R_1, R_2, a_1, a_2, p = constant with the values shown in Table 4.3.2

c = constant with the values shown in Table 4.3.1

b_w = web width (See Figure 4.3.1)

t_w = web thickness (See Figure 4.3.1)

F = coefficient for considering effects of flanges on the shearing load-carrying capacity of girders

A_f = cross-sectional area of a flange (See Figure 4.3.1)

A_w = cross-sectional area of a web (See Figure 4.3.1)

a_L = distance between end stiffeners (See Figure 4.3.2)

The design of end stiffeners complies with 4.7.1.

Table 4.3.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$ of Aluminum Alloy Materials and Values for c

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)	c
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125	3.38×10^{-2}
	A5083-O	$3 \leqq t \leqq 40$	275	125	3.38×10^{-2}
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245	4.73×10^{-2}
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245	4.73×10^{-2}
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120	3.31×10^{-2}
	A5083-O	$3 \leqq t \leqq 38$	275	120	3.31×10^{-2}
	A6061-T6	$3 \leqq t \leqq 40$	265	245	4.73×10^{-2}
	A6005C-T5	$3 \leqq t \leqq 6$	245	205	4.33×10^{-2}
		$6 < t \leqq 12$	225	175	4.00×10^{-2}
	A6005C-T6	$3 \leqq t \leqq 6$	265	235	4.63×10^{-2}

Table 4.3.2 Values for R_1, R_2, a_1, a_2 and p

Aluminum alloys	R_1	R_2	a_1	a_2	p
5000 series	0.53	0.92	1.02	0.26	0.76
6000 series	0.60	1.09	1.20	0.36	0.81

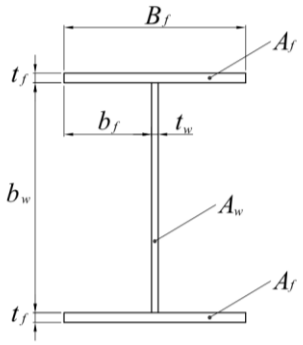


Figure 4.3.1 I-Shaped Cross-Section Girder

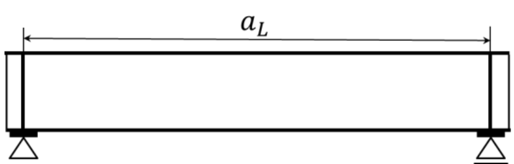


Figure 4.3.2 Girder with No Intermediate Transverse Stiffeners

(2) In 6000 series aluminum alloy materials, the strength of the welded part decreases. If intermediate transverse stiffeners are connected to the web of 6000 series aluminum alloys by welding, the overall strength as a girder is reduced, since the weld crosses the web. Therefore, it is not possible that intermediate vertical stiffeners are provided on girders of 6000 series aluminum alloys.

(3) The design shearing strength of vertically symmetrical I-shaped cross-section girders made of 5000 series aluminum alloys with intermediate transverse stiffeners that are simply supported at both ends is given by the following equations:

For the load-carrying capacity, $\tau_{ud} = \phi_u \tau_u$ (4.3.3a)

For the tensile strength, $\tau_{Bd} = \phi_B \times 159$ N/mm² (4.3.3b)

where

τ_{ud} = design shearing strength for the load-carrying capacity of the above-mentioned girders

τ_{Bd} = design shearing strength for the tensile strength of 5000 series aluminum alloy materials

τ_u = shearing load-carrying capacity of the above-mentioned girders

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned girders and the one for the tensile strength of 5000 series aluminum alloy materials, respectively

The shearing load-carrying capacity τ_u of the above-mentioned girders is given by the following equations:

$$\tau_u = 72\eta \quad \text{N/mm}^2 \tag{4.3.4a}$$

$$\eta = \begin{cases} 1 & (R \le 0.53) \\ \dfrac{1.02}{R} - \dfrac{0.26}{R^2} & (0.53 < R \le 0.92) \\ \dfrac{0.75}{R^{0.76}} & (0.92 < R \le 3) \end{cases} \tag{4.3.4b}$$

$$R = 3.38 \times 10^{-2} \frac{F}{\sqrt{k}} \frac{b_w}{t_w} \qquad \left(\frac{b_w}{t_w} \le 220\right) \tag{4.3.4c}$$

$$F = \begin{cases} \left(0.022\dfrac{A_w}{A_f} - 0.167\right)\dfrac{a}{b_w} + 0.015\dfrac{A_w}{A_f} + 0.875 & \left(0.5 \le \dfrac{a}{b_w} \le 1\right) \\ \left(0.020\dfrac{A_w}{A_f} - 0.009\right)\dfrac{a}{b_w} + 0.017\dfrac{A_w}{A_f} + 0.717 & \left(1 < \dfrac{a}{b_w} \le 2\right) \end{cases} \qquad \left(1 \le \frac{A_w}{A_f} \le 4\right) \tag{4.3.4d}$$

$$k = \begin{cases} 4 + \dfrac{5.34}{\left(\dfrac{a}{b_w}\right)^2} & \left(0.5 \le \dfrac{a}{b_w} \le 1\right) \\ 5.34 + \dfrac{4}{\left(\dfrac{a}{b_w}\right)^2} & \left(1 < \dfrac{a}{b_w} \le 2\right) \end{cases} \tag{4.3.4e}$$

where

k = shearing buckling coefficient of rectangular plates simply supported at four edges

a = distance between adjacent intermediate transverse stiffeners (See Figure 4.3.3)

The design of end stiffeners and intermediate transverse stiffeners complies with 4.7.1 and 4.7.2, respectively.

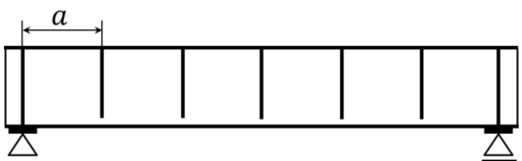


Figure 4.3.3 Girder with Intermediate Transverse Stiffeners

4.4 Design of A6061-T6 Girders with Longitudinally Stiffened Web

(1) A6061-T6 Girders with Longitudinally Stiffened Web

Figure 4.4.1 shows an I-shaped cross-section girder that is produced by butt-joining extrusions of aluminum alloy A6061-T6 by friction stir welding and that has the web stiffened by three longitudinal stiffeners at equal intervals. The girder is vertically symmetrical. The cross-sectional dimensions of the longitudinal stiffeners are given by the following equations:

$$\frac{t_r}{t_w} = 0.578\left(\frac{b_w}{t_w} - 12.5\right)^{0.148} \quad \left(44 \le \frac{b_w}{t_w} \le 294\right) \tag{4.4.1a}$$

$$\frac{b_r}{t_r} = 6.28 \tag{4.4.1b}$$

where

b_r = width of longitudinal stiffeners (See Figure 4.4.2)

t_r = thickness of longitudinal stiffeners (See Figure 4.4.2)

b_w = web width (See Figure 4.4.2)

t_w = web thickness (See Figure 4.4.2)

The thickness of the friction stir welded part of the web must be increased to more than 2.33 times the web thickness in the range of 25 mm on each side from the joining center, that is, in the range of 50 mm (See 6.2). However, the thickness of the increased part is assumed to be the same as the web thickness.

The cross section of the longitudinal stiffeners is introduced in calculating the bending compressive stress acting on the flange. However, it is not in calculating the shearing stress acting on the web.

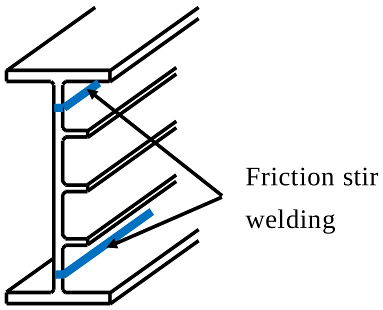


Figure 4.4.1 Aluminum Alloy Girder with Longitudinally Stiffened Web

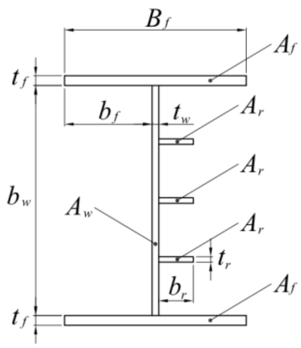


Figure 4.4.2 Cross Section of Aluminum Alloy Girder

(2) Design Bending Compressive Strength

The design bending compressive strength of A6061-T6 girders with a longitudinally stiffened web that is specified in (1) is given by the following equations:

For the load-carrying capacity, $\sigma_{cud} = \phi_u \sigma_u$ (4.4.2a)

For the tensile strength, $\sigma_{tBd} = \phi_B \times 265$ N/mm^2 (4.4.2b)

where

σ_{cud} = design bending compressive strength for the load-carrying capacity of the above-mentioned girders

σ_{tBd} = design tensile strength for the tensile strength of A6061-T6 extrusions

σ_u = bending load-carrying capacity of the above-mentioned girders

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned girders and the one for the tensile strength of A6061-T6 extrusions, respectively

The bending load-carrying capacity σ_u of the above-mentioned girders is given by the following equation:

$$\sigma_u = \min(245\eta_g, 245\eta_l) \times g_w \qquad \text{N/mm}^2 \tag{4.4.3}$$

where

η_g = coefficient that gives the lateral load-carrying capacity of a compressive flange without considering effects of the local buckling of the compressive flange in the above-mentioned girders

η_l = coefficient that gives the load-carrying capacity for the local buckling of a compressive flange in the above-mentioned girders

g_w = coefficient that gives the ultimate bending moment of a girder when neither local buckling nor lateral buckling occurs in a compressive flange in the above-mentioned girders

The coefficient η_g is given by the following equations:

$$\eta_g = \begin{cases} 1 & (\lambda \le 0.13) \\ 1.01 - 0.03\lambda - 0.30\lambda^2 - 0.04\lambda^3 + 0.05\lambda^4 & (0.13 < \lambda \le 2) \end{cases} \tag{4.4.4a}$$

$$\lambda = 6.52 \times 10^{-2} K \frac{l}{B_f} \tag{4.4.4b}$$

$$K = 0.97 + 0.07\frac{A_{wr}}{A_f} \qquad \left(1 \le \frac{A_{wr}}{A_f} \le 4\right) \tag{4.4.4c}$$

$$A_{wr} = A_w + \frac{3}{2}A_r \tag{4.4.4d}$$

where

l = distance between the supporting points of a compressive flange

B_f = overall width of a compressive flange (See Figure 4.4.2)

A_f = cross-sectional area of a flange ($= B_f t_f$) (See Figure 4.4.2)

A_w = cross-sectional area of a web ($= b_w t_w$) excluding that of longitudinal stiffeners (See Figure 4.4.2)

A_r = cross-sectional area of a longitudinal stiffener ($= b_r t_r$) (See Figure 4.4.2)

The coefficient η_l is given by the following equation:

$$\eta_l = \begin{cases} 1 & \left(\frac{b_f}{t_f} \le 6.3\right) \\ 1.0 - 7.79 \times 10^{-3}\left(\frac{b_f}{t_f} - 6.3\right)^2 & \left(6.3 < \frac{b_f}{t_f} \le 12.5\right) \end{cases} \tag{4.4.5}$$

where

b_f = width of a compressive flange on one side (See Figure 4.4.2)

t_f = thickness of a compressive flange (See Figure 4.4.2)

The coefficient g_w is given by the following equation:

$$g_w = \begin{cases} \dfrac{1+\dfrac{A_{wr}}{4A_f}}{1+\dfrac{A_{wr}}{6A_f}} & \left(44 \le \dfrac{b_w}{t_w} \le 62\right) \\ 1-\dfrac{\dfrac{A_{wr}}{A_f}}{1200\left(1+\dfrac{A_{wr}}{6A_f}\right)}\left(\dfrac{b_w}{t_w}-162\right) & \left(62 < \dfrac{b_w}{t_w} < 202\right) \\ \dfrac{1+\dfrac{2A_{wr}}{15A_f}\left(\dfrac{202}{\dfrac{b_w}{t_w}}\right)^{0.94}}{1+\dfrac{A_{wr}}{6A_f}} & \left(202 \le \dfrac{b_w}{t_w} \le 294\right) \end{cases} \tag{4.4.6}$$

(3) Design Shearing Strength

The design shearing strength of A6061-T6 girders with a longitudinally stiffened web that is specified in (1) is given by the following equations:

For the load-carrying capacity, $\tau_{ud} = \phi_u \tau_u$ (4.4.7a)

For the tensile strength, $\tau_{Bd} = \phi_B \times 153$ N/mm^2 (4.4.7b)

where

τ_{ud} = design shearing strength for the load-carrying capacity of the above-mentioned girders

τ_{Bd} = design shearing strength for the tensile strength of A6061-T6 extrusions

τ_u = shearing load-carrying capacity of the above-mentioned girders

ϕ_u, ϕ_B = resistance factor for the load-carrying capacity of the above-mentioned girders and the one for the tensile strength of A6061-T6 extrusions, respectively

The shearing load-carrying capacity τ_u of the above-mentioned girders is given by the following equations:

$$\tau_u = 141\eta_s \quad \text{N/mm}^2 \tag{4.4.8a}$$

$$\eta_s = \begin{cases} 1 & (R \le 1.12) \\ \dfrac{5.79}{R} - \dfrac{3.29}{R^2} - 1.55 & (1.12 < R \le 1.57) \\ \dfrac{1.36}{R^{1.18}} & (1.57 < R \le 3.5) \\ \dfrac{0.858}{R^{0.81}} & (3.5 < R \le 6) \end{cases} \tag{4.4.8b}$$

$$R = \frac{4.73 \times 10^{-2} F}{\sqrt{5.34 + \dfrac{4}{\left(\dfrac{a_L}{b_w}\right)^2}}} \frac{b_w}{t_w} \qquad \left(\frac{a_L}{b_w} \ge 1\right) \qquad \left(44 \le \frac{b_w}{t_w} \le 294\right) \tag{4.4.8c}$$

$$F = 8.5 \times 10^{-3} \frac{A_w}{A_f}\frac{a_L}{b_w} + 0.75 \le 1 \qquad \left(1 \le \frac{A_w}{A_f} \le 4\right) \tag{4.4.8d}$$

where

a_L = distance between end stiffeners (See Figure 4.4.3)

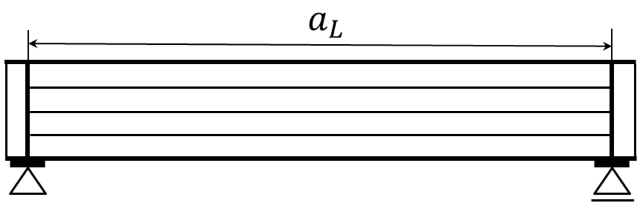


Figure 4.4.3 Aluminum Alloy Girder with Longitudinally Stiffened Web

(4) High-Strength Bolted Friction-Type Joints in A6061-T6 Girders with Longitudinally Stiffened Web

As shown in Figure 4.4.4, connection plates are provided on the upper and lower surfaces of the longitudinal stiffeners. On the web surface without the longitudinal stiffeners, one connection plate is provided over the web width. When friction stir welding is done on the web, no connection plates are provided at the protruding part of the thickened part [See Figure 6.3.1 (b)]. The normal stress generated in the web is designed as two surfaces for friction, and the shearing stress generated in the web is designed as one surface for friction.

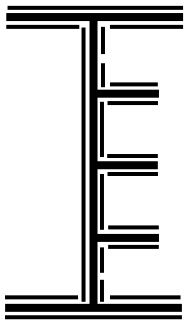


Figure 4.4.4 Section of High-Strength Bolted Friction-Type Joint in A6061-T6 Girder with Longitudinally Stiffened Web (See Figure 4.4.1)

(5) Dissimilar Aluminum Alloy Girders

According to 4.7.1(3), if high-strength bolted friction-type joints are used for connection of end stiffeners, it is necessary to devise so that the heads of high-strength bolts connecting the end stiffeners to the upper and lower flanges do not appear on the flange surface. To avoid this, it is possible to use the structure shown in Fig. 4.4.5 in which an A5083-O girder is placed at the supporting point and is connected to the A6061-T6 girder by a high-strength bolted friction-type joint. The end of the longitudinal stiffeners of the A6061-T6 girder is stretched near the edge of the connection plate of the joint. If friction stir welding is applied to the web of the A6061-T6 girder, the protruding part of the thickened part [See Figure 6.3.1 (b)] under the connection plate is removed and flattened.

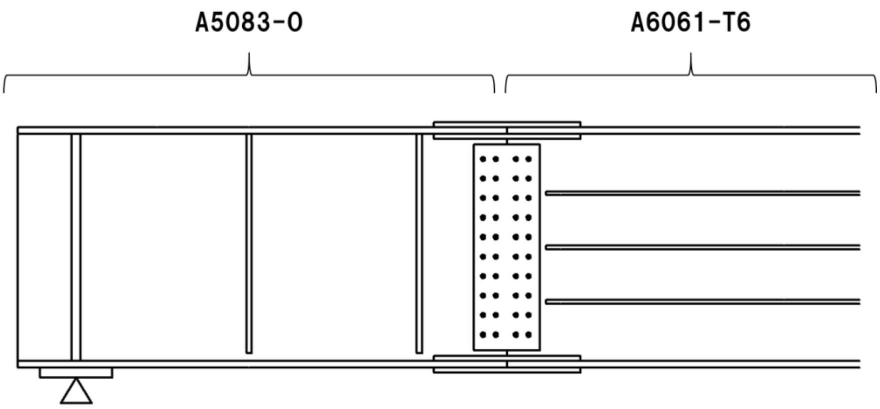


Figure 4.4.5 Dissimilar Aluminum Alloy Girder

4.5 Stress Check for Girders Subjected to Unequal Bending Moments

The stress caused in girders on which unequal bending moments act is checked by the following 1) and 2):

1) For the load-carrying capacity,

$$\sigma_1 \leq \sigma_{1cud} = \begin{cases} \dfrac{1}{0.6 + 0.4\kappa}\sigma_{cud} & (1 \geq \kappa \geq -0.5) \\ 2.5\sigma_{cud} & (-0.5 \geq \kappa \geq -1) \end{cases} \tag{4.5.1a}$$

$$\kappa = \frac{M_2}{M_1}(M_1 \geq M_2) \tag{4.5.1b}$$

where

σ_1 = bending compressive stress at the flange edge at the position where the larger bending moment acts

σ_{1cud} = design bending compressive strength at the position where the larger bending moment acts

σ_{cud} = design bending compressive strength of a girder with a uniform bending moment

M_1 = larger acting bending moment

M_2 = smaller acting bending moment

The design bending compressive strength σ_{cud} of a girder on which a uniform bending moment acts is given by Eq. (4.2.1a) or Eq. (4.4.2a).

2) For the tensile strength,

$$\sigma_1 \leq \sigma_{tBd} \tag{4.5.2}$$

where

σ_{tBd} = design tensile strength for the tensile strength of aluminum alloy materials

The design tensile strength σ_{tBd} for the tensile strength of aluminum alloy materials is given by Eq. (4.2.1b) or Eq. (4.4.2b).

Furthermore, the bending compressive stress σ_1 at the flange edge and the average shearing stress τ on the web which is given by the following equation must satisfy Eq. (4.6.1) in 4.6:

$$\tau = \frac{M_1 - M_2}{(b_w t_w)L} \tag{4.5.3}$$

where

b_w = width of a girder web

t_w = thickness of a girder web

L = distance between the positions where the bending moments of M_1 and M_2 act

4.6 Stress Check for Girders under Combined Bending and Shearing Loads

When neither lateral buckling nor local buckling occurs in a flange, the stresses caused in girders under combined bending and shearing loads are checked by the following 1) and 2):

1) For the load-carrying capacity,

$$\begin{cases} 0.81\left(\dfrac{\sigma_1}{\sigma_{cud}}\right)^4+\left(\dfrac{\tau}{\tau_{ud}}\right)^4\leq 1 & \left(0.66<\dfrac{\tau}{\tau_{ud}}\leq 1\right) \\ \dfrac{\sigma_1}{\sigma_{cud}}\leq 1 & \left(0\leq\dfrac{\tau}{\tau_{ud}}\leq 0.66\right) \end{cases} \tag{4.6.1}$$

where

σ_1 = bending compressive stress at the flange edge at the position where the larger bending moment acts

τ = average shearing stress on a web

σ_{cud} = design bending compressive strength of a girder with a vertically symmetrical I-shaped cross-section in the case where a flange does not laterally and locally buckle

τ_{ud} = design shearing strength of a web

The design bending compressive strength σ_{cud} is given by the following equation:

$$\sigma_{cud}=\phi_u g_w \sigma_{0.2} \tag{4.6.2}$$

where

ϕ_u = resistance factor for the load-carrying capacity of a girder with a vertically symmetrical I-shaped cross-section under bending

g_w = coefficient that provides the ultimate bending moment of a girder given by Eq. (4.2.4) or Eq. (4.4.6) when neither local buckling nor lateral buckling occurs in a compressive flange

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 3.1.1

The design shearing strength τ_{ud} is given by the following equation:

$$\tau_{ud}=\phi_u \eta \frac{\sigma_{0.2}}{\sqrt{3}} \tag{4.6.3}$$

where

ϕ_u = resistance factor for the load-carrying capacity of a girder with a vertically symmetrical I-shaped cross-section under shearing, which is simply supported at both ends

η = coefficient that provides the shearing load-carrying capacity of a girder with a vertically symmetrical I-shaped cross-section, which is simply supported at both ends, and that is given by Eq. (4.3.2b), Eq. (4.3.4b) or Eq. (4.4.8b)

$\sigma_{0.2}$ = 0.2% proof stress of aluminum alloy materials shown in Table 3.1.1

2) For the tensile strength,

$$\sigma_1\leq\phi_B\sigma_B \tag{4.6.4a}$$

$$\tau \leq \phi_B \frac{\sigma_B}{\sqrt{3}} \quad (4.6.4b)$$

where

σ_1 = bending compressive stress at the flange edge at the position where the larger bending moment acts

τ = average shearing stress on a web

ϕ_B = resistance factor for the tensile strength of aluminum alloy materials

σ_B = tensile strength of aluminum alloy materials shown in Table 3.1.1

4.7 Design of Transverse Stiffeners at Supporting Points and Intermediate Transverse Stiffeners

4.7.1 Design of Transverse Stiffeners at Supporting Points

(1) Transverse stiffeners at the supporting points are installed on both sides of the web and designed as columns on which an axial compressive force acts. The effective cross-sectional area of the column is the cross-sectional area of the transverse stiffener and of the web from the attaching point of the transverse stiffeners up to 12 times the web thickness on each side. However, it is 1.7 times or less than the cross-sectional area of the transverse stiffeners. The effective buckling length of the column is 1/2 of the web width. The axial compressive force given by the following equations is applied to the column, that is, the transverse stiffeners at the supporting points:

$$V = \tau_d b_w t_w \quad (4.7.1a)$$

$$\tau_d = \min(\tau_{0.2d}, \tau_{Bd}) \quad (4.7.1b)$$

where

V = axial compressive force to act on the transverse stiffeners at the supporting points

τ_d = design shearing strength in the case where buckling does not occur in a web

$\tau_{0.2d}$ = design shearing strength for the 0.2% proof stress given by Eq. (3.1.2a)

τ_{Bd} = design shearing strength for the tensile strength given by Eq. (3.1.2b)

b_w = web width

t_w = web thickness

The design axial compressive strength is calculated with respect to the middle plane of the web and that of the transverse stiffeners, and the smaller one is used as the design axial compressive strength.

(2) In order to prevent the local buckling of transverse stiffeners at the supporting points, the width-to-thickness ratio of the transverse stiffener on one side of a web should be less than the values shown in Table 4.7.1.

Table 4.7.1 Maximum Width-to-Thickness Ratio of Transverse Stiffeners at Supporting Points

Aluminum alloys		Thickness t (mm)	b_s/t_s
Plates	A5083-H112	$4 \leqq t \leqq 40$	5.87
	A5083-O	$3 \leqq t \leqq 40$	5.87
	A6061-T6	$3 \leqq t \leqq 6.5$	6.28
	A6061-T651	$6.5 \leqq t \leqq 40$	6.28
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	5.99
	A5083-O	$3 \leqq t \leqq 38$	5.99
	A6061-T6	$3 \leqq t \leqq 40$	6.28
	A6005C-T5	$3 \leqq t \leqq 6$	6.87
		$6 < t \leqq 12$	7.43
	A6005C-T6	$3 \leqq t \leqq 6$	6.42

b_s = width of the transverse stiffener on one side at the supporting points

t_s = thickness of the transverse stiffener

(3) To connect transverse stiffeners at the supporting points to the web and to the upper and lower flanges, welding is used for 5000 series aluminum alloy girders and high-strength bolted friction-type joints are for 6000 series aluminum alloy girders.

4.7.2 Design of Intermediate Transverse Stiffeners

(1) Intermediate transverse stiffeners can be used for girders made of 5000 series aluminum alloy plates.

(2) The geometrical moment of inertia I_v of one intermediate transverse stiffener must satisfy the following equations:

$$I_v \geq \frac{b_w {t_w}^3}{11} \gamma_v \tag{4.7.2a}$$

$$\gamma_v = 8.0 \left(\frac{b_w}{a}\right)^2 \tag{4.7.2b}$$

where

b_w = web width

t_w = web thickness

γ_v = required relative stiffness ratio of an intermediate transverse stiffener

a = interval between adjacent intermediate transverse stiffeners (See Figure 4.3.3)

When an intermediate transverse stiffener is provided on one side of a web, the geometrical moment of inertia about the web surface is used for I_v, and when it is provided on both sides of a web, the geometrical moment of inertia about the middle plane of the web is used for I_v.

(3) The width-to-thickness ratio of intermediate transverse stiffeners on one side of the web is set to a value less than the width-to-thickness ratio given by the following equation:

$$\frac{b_v}{t_v} = 5.87 \tag{4.7.3}$$

where

b_v = width of an intermediate transverse stiffener on one side of a web

t_v = thickness of an intermediate transverse stiffener

(4) The intermediate transverse stiffeners are connected to the compressive flange by welding. In order to prevent fatigue cracks from occurring in the tensile flange, they are not welded to the tensile flange and are terminated at a position about 35 mm from the surface of the tensile flange.

5. Welded Joints

5.1 Selection of Welding Materials and Usable Welded Joints

(1) The welding materials shown in Table 5.1.1 are used for the combination of base materials.

Table 5.1.1 Welding Materials Used for the Combination of Base Materials

Base materilas \ Base materials	A5083-H112 A5083-O	A6061-T6 A6061-T651 A6005C-T5 A6005C-T6
A5083-H112 A5083-O	A5183	A5356
A6061-T6 A6061-T651 A6005C-T5 A6005C-T6	A5356	A5356

(2) Usable welded joints must comply with the following items:

1) Full penetration groove welding or continuous fillet welding is used for the welded joints that carry stresses.
2) Full penetration groove welding is used to connect main members.
3) Lap joints are not used for main members.
4) For fillet welded T-joints and cruciform joints, fillet welds must be placed on both sides of a plate.
5) Full penetration groove welding must be used for T-joints where the intersection angle between pieces is less than 60°.

5.2 Partial Thickening in Full Penetration Groove Welded Joints

(1) When a full penetration groove welded joint is partially thickened by using extrusions, as shown in Figure 5.2.1, a wider range than the heat-affected range 25 mm on each side from the welding center [See 3.2(1)] shall be made thicker than the thickness given by the following equation:

$$t_j = \psi t \qquad (5.2.1)$$

where

ψ = magnification to increase the plate thickness (See Table 5.2.1)

t_j = increased plate thickness

t = thickness of a base material

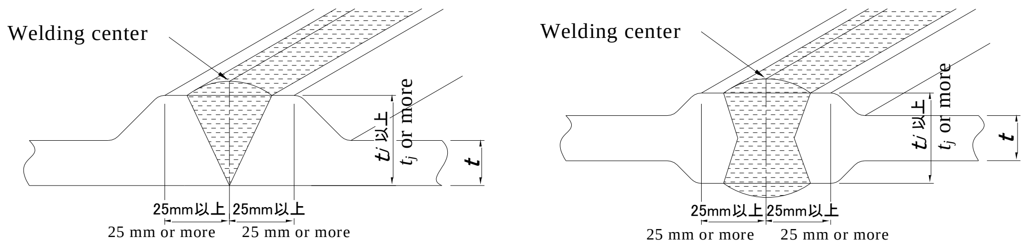


Figure 5.2.1 Thickened Range in Full Penetration Groove Welded Joints

Table 5.2.1 Magnification to Increase Plate Thickness

Aluminum alloys	Plate thickness t (mm)	Magnification ψ
A6061-T6	$3 \leqq t \leqq 40$	2.33
A6005C-T5	$3 \leqq t \leqq 6$	1.95
	$6 < t \leqq 12$	1.67
A6005C-T6	$3 \leqq t \leqq 6$	2.24

(2) The normal and thickened parts are smoothly continuous with a gradient of 45° or less. In case of being affected by fatigue, an arc with a radius of curvature of 40 mm or more is provided at the end of the thickened part, as shown in Figure 5.2.2.

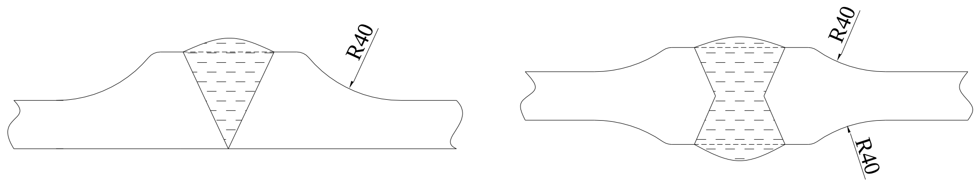


Figure 5.2.2 Thickened Shape against Fatigue

5.3 Full Penetration Groove Welded Joints with Different Cross Sections

In a full penetration groove welded joint with different cross sections, the thickness and width must be gradually changed in the longitudinal direction with a gradient of 1/5 or less, as shown in Figure 5.3.1.

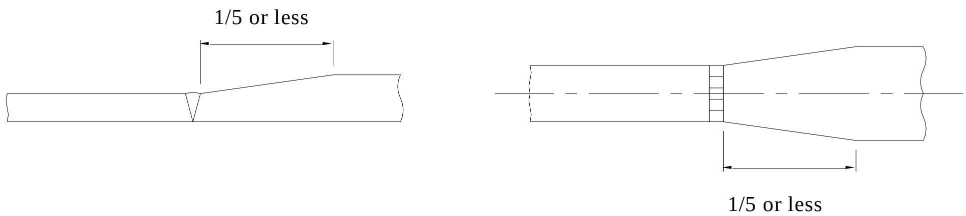


Figure 5.3.1 Full Penetration Groove Welded Joints with Different Cross Sections

5.4 Theoretical Throat Thickness and Effective Length of Welds

(1) Theoretical Throat Thickness

1) Full Penetration Groove Welding

Figure 5.4.1 shows the theoretical throat thickness in complete penetration groove welding. If the thickness of the left and right plates at the weld is different, the thickness of the thinner plate is the theoretical throat thickness. In the case of a partially thickened plate, the thickness of the thickened part is the theoretical throat thickness.

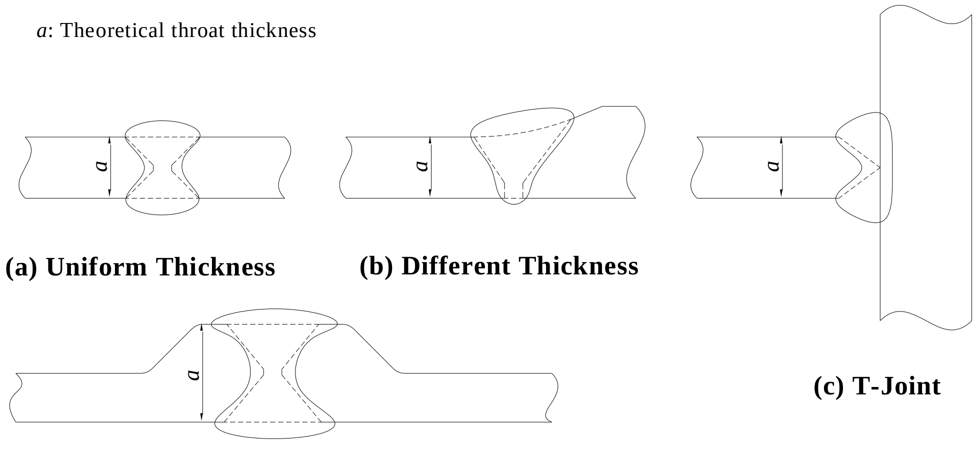


Figure 5.4.1 Theoretical Throat Thickness in Full Penetration Groove Welding

2) Fillet Welding

Figure 5.4.2 shows the theoretical throat thickness and size in fillet welding.

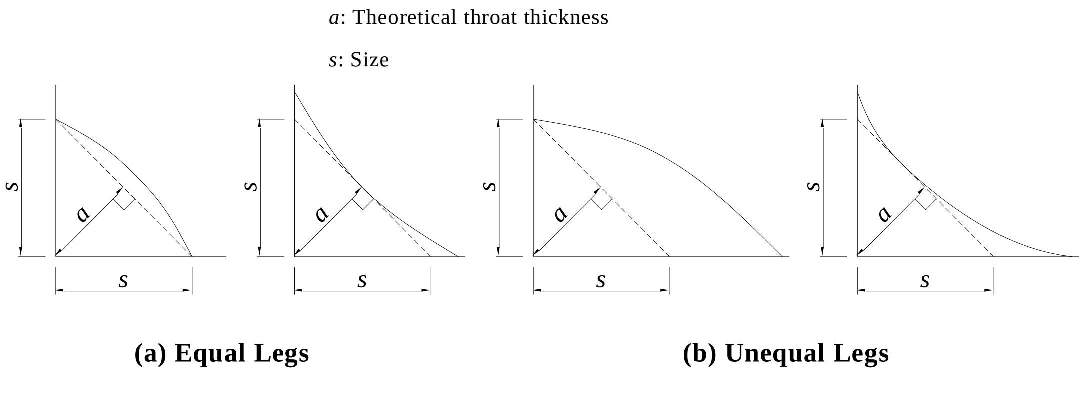


Figure 5.4.2 Theoretical Throat Thickness and Size in Fillet Welding

(2) Effective Length

1) The effective length of a weld is the length of the weld that holds the theoretical throat thickness. When the direction of stress is not at the right angle to the welding line, the effective length is the one projected in the direction orthogonal to the direction of stress.
2) The effective length does not include the end return in fillet welding.

5.5 Size of Fillet Weld and Minimum Effective Length

(1) The fillet welds of main members are equi-legged.

(2) The size of the fillet welds that carry the shearing stress of main members should be such that the total of the theoretical throat thicknesses is equal to or greater than the thickness of the base material.

(3) The minimum effective length in fillet welding for major members is the larger of 10 times the size and 80 mm.

5.6 Design of Welded Joints Subjected to Axial Force or/and Shearing Force

(1) Full Penetration Groove Welded Joints

1) The stress caused on a full penetration groove welded joint in which an axial force acts in the direction perpendicular to the welding line is checked as follows:

For the 0.2% proof stress, $$\sigma = \frac{T}{\sum al} \leq \sigma_{w0.2d} \tag{5.6.1a}$$

For the tensile strength, $$\sigma = \frac{T}{\sum al} \leq \sigma_{wBd} \tag{5.6.1b}$$

2) The stress caused on a full penetration groove welded joint in which a shearing force acts in the direction parallel to the welding line is checked as follows:

For the 0.2% proof stress, $$\tau = \frac{Q}{\sum al} \leq \tau_{w0.2d} \tag{5.6.2a}$$

For the tensile strength, $$\tau = \frac{Q}{\sum al} \leq \tau_{wBd} \tag{5.6.2b}$$

Referring to Figure 5.6.1,

σ = normal stress that occurs in the weld due to an axial force acting in the direction perpendicular to the welding line

τ = shearing stress generated in the weld due to a shearing force acting in the direction parallel to the welding line

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.1a)]

σ_{wBd} = design tensile strength for the tensile strength in the heat-affected range [Eq. (3.2.1b)]

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.2a)]

τ_{wBd} = design shearing strength for the tensile strength in the heat-affected range [Eq. (3.2.2b)]

T = axial force acting in the direction perpendicular to the welding line

Q = shearing force acting in the direction parallel to the welding line

a = theoretical throat thickness

l = effective length of a weld

Σ = symbol that represents the sum of effective lengths

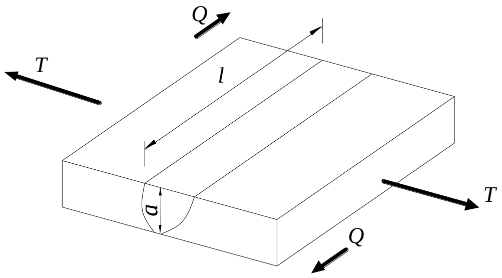


Figure 5.6.1 Forces Acting on Full Penetration Groove Welded Joint

3) The stresses caused on a full penetration groove welded joint when an axial force in the direction perpendicular to the welding line and a shearing force in the direction parallel to the welding line act simultaneously are checked as follows:

For the 0.2% proof stress, $$\left(\frac{\sigma}{\sigma_{w0.2d}}\right)^2 + \left(\frac{\tau}{\tau_{w0.2d}}\right)^2 \leq 1.2 \quad (5.6.3a)$$

However, $\sigma \leq \sigma_{w0.2d}$, $\tau \leq \tau_{w0.2d}$.

For the tensile strength, $$\left(\frac{\sigma}{\sigma_{wBd}}\right)^2 + \left(\frac{\tau}{\tau_{wBd}}\right)^2 \leq 1.2 \quad (5.6.3b)$$

However, $\sigma \leq \sigma_{wBd}$, $\tau \leq \tau_{wBd}$.

4) In the case of full penetration groove welded joints of aluminum alloys A6061-T6, A6005C-T5 and A6005C-T6, if the heat-affected range is thickened according to 5.2(1), in Eqs. (5.6.1), (5.6.2) and (5.6.3), the throat thickness a can be taken as the thickness t of the base material, and the design tensile strength ($\sigma_{w0.2d}$, σ_{wBd}) and the design shearing strength ($\tau_{w0.2d}$, τ_{wBd}) of the heat-affected range can be taken as the design tensile strength ($\sigma_{t0.2d}$, σ_{tBd}) and the design shearing strength ($\tau_{0.2d}$, τ_{Bd}) of the base material, respectively.

(2) Fillet Welded Joints

1) The stress caused on a fillet welded joint in which an axial force acts in the direction perpendicular to the welding line is checked as follows:

For welds,

For the 0.2% proof stress, $$\tau_{\perp} = \frac{T}{\sum al} \leq \tau_{w0.2d} \quad (5.6.4a)$$

For the tensile strength, $$\tau_{\perp} = \frac{T}{\sum al} \leq \tau_{wBd} \quad (5.6.4b)$$

For the heat-affected range of the base material,

For the 0.2% proof stress, $$\sigma = \frac{T}{tl} \leq \sigma_{w0.2d} \quad (5.6.5a)$$

For the tensile strength, $$\sigma = \frac{T}{tl} \leq \sigma_{wBd} \quad (5.6.5b)$$

Referring to Figure 5.6.2,

$\tau_{\perp}$ = shearing stress generated in the weld due to an axial force in the direction perpendicular to the welding line

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.2a)]

τ_{wBd} = design shearing strength for the tensile strength in the heat-affected range [Eq. (3.2.2b)]

σ = normal stress generated in the heat-affected range of the base material due to an axial force in the direction perpendicular to the welding line

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.1a)]

σ_{wBd} = design tensile strength for the tensile strength in the heat-affected range [Eq. (3.2.1b)]

T = axial force acting in the direction perpendicular to the welding line

a = theoretical throat thickness

l = effective length of a weld

t = thickness of a base material

Σ = symbol that represents the sum of effective lengths

2) The stress caused on a fillet welded joint where a shearing force acts in the direction parallel to the welding line is checked as follows:

For welds,

For the 0.2% proof stress, $$\tau_{\parallel} = \frac{Q}{\sum al} \leq \tau_{w0.2d} \tag{5.6.6a}$$

For the tensile strength, $$\tau_{\parallel} = \frac{Q}{\sum al} \leq \tau_{wBd} \tag{5.6.6b}$$

For the heat-affected range of the base material,

For the 0.2% proof stress, $$\tau = \frac{Q}{tl} \leq \tau_{w0.2d} \tag{5.6.7a}$$

For the tensile strength, $$\tau = \frac{Q}{tl} \leq \tau_{wBd} \tag{5.6.7b}$$

Referring to Figure 5.6.2,

$\tau_{\parallel}$ = shearing stress generated in the weld due to a shearing force in the direction parallel to the welding line

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.2a)]

τ_{wBd} = design shearing strength for the tensile strength in the heat-affected range [Eq. (3.2.2b)]

τ = shearing stress generated in the heat-affected range of the base material due to a shearing force in the direction parallel to the welding line

Q = shearing force in the direction parallel to the welding line

a = theoretical throat thickness

l = effective length of a weld

t = thickness of a base material

Σ = symbol that represents the sum of effective lengths

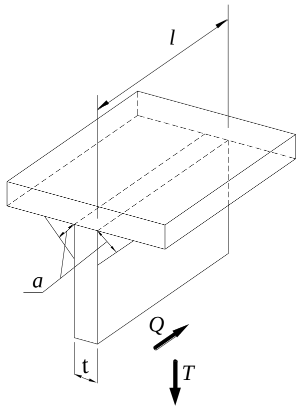


Figure 5.6.2 Forces Acting on Fillet Welded Joint

3) The stresses caused on a fillet welded joint when an axial force in the direction perpendicular to the welding line and a shearing force in the direction parallel to the welding line act simultaneously are checked as follows:

For welds,

For the 0.2% proof stress, $$\left(\frac{\tau_{\parallel}}{\tau_{w0.2d}}\right)^2 + \left(\frac{\tau_{\perp}}{\tau_{w0.2d}}\right)^2 \leq 1 \quad (5.6.8a)$$

For the tensile strength, $$\left(\frac{\tau_{\parallel}}{\tau_{wBd}}\right)^2 + \left(\frac{\tau_{\perp}}{\tau_{wBd}}\right)^2 \leq 1 \quad (5.6.8b)$$

For the heat-affected range of the base material,

For the 0.2% proof stress, $$\left(\frac{\sigma}{\sigma_{w0.2d}}\right)^2 + \left(\frac{\tau}{\tau_{w0.2d}}\right)^2 \leq 1.2 \quad (5.6.9a)$$

However, $\sigma \leq \sigma_{w0.2d}$, $\tau \leq \tau_{w0.2d}$.

For the tensile strength, $$\left(\frac{\sigma}{\sigma_{wBd}}\right)^2 + \left(\frac{\tau}{\tau_{wBd}}\right)^2 \leq 1.2 \quad (5.6.9b)$$

However, $\sigma \leq \sigma_{wBd}$, $\tau \leq \tau_{wBd}$.

5.7 Design of Welded Joints under Bending Moment

(1) Full Penetration Groove Welded Joints

The stress caused on a full penetration groove welded joint where a bending moment acts is checked as follows:

For the 0.2% proof stress, $$\sigma = \frac{M}{I_a} y_a \leq \sigma_{w0.2d} \quad (5.7.1a)$$

For the tensile strength, $$\sigma = \frac{M}{I_a} y_a \leq \sigma_{wBd} \quad (5.7.1b)$$

Referring to Figure 5.7.1,

σ = normal stress generated in the weld due to bending moment

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.1a)]

σ_{wBd} = design tensile strength for the tensile strength in the heat-affected range [Eq. (3.2.1b)]

M = bending moment acting on a full penetration groove welded joint

I_a = geometrical moment of inertia around the neutral axis for the cross section of the theoretical throat thickness on the joining surface

y_a = distance from the neutral axis for the cross section of the theoretical throat thickness on the joining surface to the position where the stress is calculated

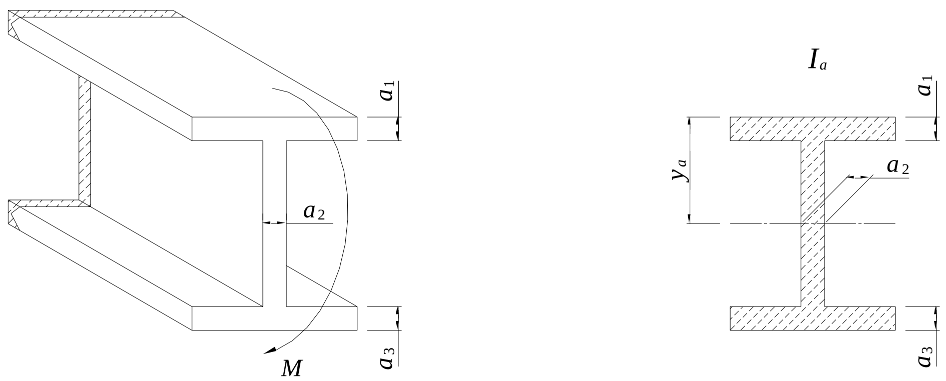


Figure 5.7.1 Full Penetration Groove Welded Joint Subjected to Bending Moment

(2) Fillet welded joints

The stress caused on a fillet welded joint which is subjected to bending moment is checked as follows:

For welds,

For the 0.2% proof stress, $$\tau_{\perp} = \frac{M}{I_a} y_a \leq \tau_{w0.2d} \quad (5.7.2a)$$

For the tensile strength, $$\tau_{\perp} = \frac{M}{I_a} y_a \leq \tau_{wBd} \quad (5.7.2b)$$

For the heat-affected range of the base material,

For the 0.2% proof stress, $$\sigma = \frac{M}{I} y \leq \sigma_{w0.2d} \quad (5.7.3a)$$

For the tensile strength, $$\sigma = \frac{M}{I} y \leq \sigma_{wBd} \quad (5.7.3b)$$

Referring to Figure 5.7.2,

$\tau_{\perp}$ = shearing stress generated in the weld due to bending moment

$\tau_{w0.2d}$ = design shearing strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.2a)]

τ_{wBd} = design shearing strength for the tensile strength in the heat-affected range [Eq. (3.2.2b)]

σ = normal stress generated in the heat-affected range of the base material due to bending moment

$\sigma_{w0.2d}$ = design tensile strength for the 0.2% proof stress in the heat-affected range [Eq. (3.2.1a)]

σ_{wBd} = design tensile strength for the tensile strength in the heat-affected range [Eq. (3.2.1b)]

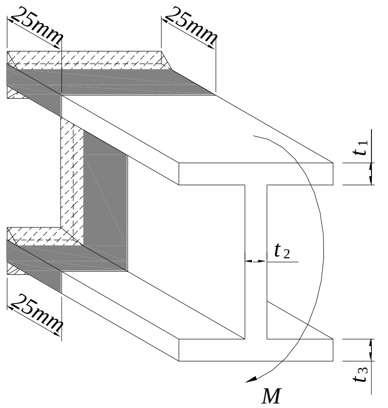
M = bending moment acting on a fillet welded joint

I_a = geometrical moment of inertia around the neutral axis for the cross section of the theoretical throat thickness on the joining surface

y_a = distance from the neutral axis for the cross section of the theoretical throat thickness on the joining surface to the position where the stress is calculated

I = geometrical moment of inertia of a base material

y = distance from the neutral axis of a base material to the position where the stress is calculated



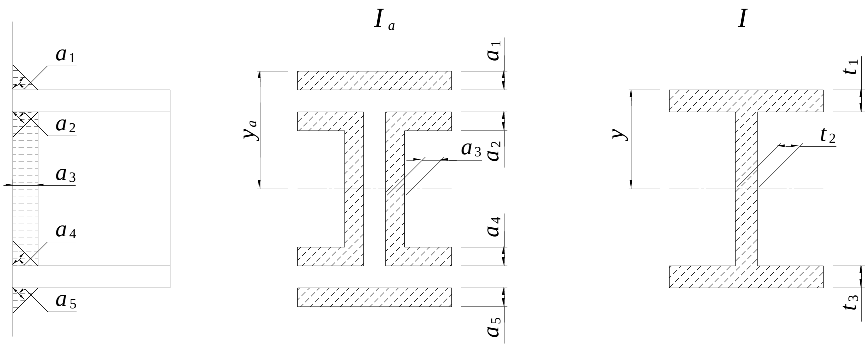


Figure 5.7.2 Fillet Welded Joint Subjected to Bending Moment

6. Friction Stir Welded Joints

6.1 General

Friction stir welding can be applied to butt joints.

6.2 Partial Thickening in Friction Stir Welded Joints

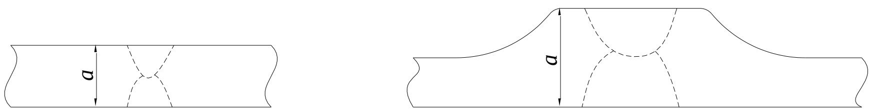
The partial thickening in friction stir welded joints follows 5.2.

6.3 Theoretical Throat Thickness and Effective Length of Friction Stir Welded Joints

(1) Theoretical Throat Thickness

The theoretical throat thickness of friction stir welded joints is shown in Figure 6.3.1. In the case of a partially thickened plate, the thickness of the thickened part is the theoretical throat thickness.

a: Theoretical throat thickness



(a) Uniform Thickness **(b) Partially Thickened Plate**

Figure 6.3.1 Theoretical Throat Thickness of Friction Stir Welded Joints

(2) Effective Length

The effective length of friction stir welded joints follows 5.4(2) 1).

6.4 Design of Friction Stir Welded Joints Subjected to Axial Force or/and Shearing Force

The design of friction stir welded joints subjected to axial force or/and shearing force follows 5.6(1).

7. Bolted Joints

7.1 Scope of Application

This chapter specifies the design of high-strength bolted friction-type joints and bearing-type joints for aluminum alloy structures in civil engineering and the components that make up them, which are used in normal temperature and atmosphere.

7.2 High-Strength Bolted Friction-Type Joints

7.2.1 General

(1) Sets of high-strength bolt made of steel are used for high-strength bolted friction-type joints for aluminum alloy plates.

(2) Aluminum alloy materials that can be used for connection plates of high-strength bolted friction-type joints are A6061-T6 and A6061-T651 alloys for plates and A6061-T6 and A6005C-T6 alloys for extrusions. Aluminum alloy materials other than these cannot be used for connection plates. In high-strength bolted friction-type joints that are subjected to fatigue loading, aluminum alloy materials other than these cannot be used for the base materials.

(3) When using high-strength bolted friction-type joints, it is necessary to prevent corrosion of steel high-strength bolts themselves and to prevent contact corrosion of dissimilar metals between a steel high-strength bolt and an aluminum alloy plate.

7.2.2 Steel High Strength Bolts

(1) For steel high-strength bolts, nuts and washers, the designations M12, M16, M20, M22 and M24 in the second class (F10T) specified in JIS B 1186[1)] are used.

1) JIS B 1186: Sets of high-strength hexagon bolt, hexagon nut and plain washers for friction grip joints, 2013.

(2) Hot dip galvanizing steel high-strength bolts and fluororesin-coated steel high-strength bolts are regarded as a high-strength bolt capable of preventing contact corrosion of dissimilar metals between a steel high-strength bolt and an aluminum alloy plate as well as rust prevention of steel high-strength bolts themselves.

(3) Fluororesin-coated steel high-strength bolts that can be used for friction-type connection shall meet the following requirements: After the friction-surface treatment specified in 9.4.2 is executed, a slip test is performed according to Appendix A on the friction-type joints for aluminum alloy plates fastened to the initial bolt axial force with 10% increase of the design bolt axial force for F10T shown in Table 9.4.1, and the slip coefficient obtained by the test shall be 0.45 or more.

(4) The grade of hot-dip galvanized steel high-strength bolts is considered F8T.

(5) The grade of fluororesin-coated steel high-strength bolts is F10T.

(6) The threaded part of bolts must not be located on the friction-surface between a base material and a connection plate.

7.2.3 Minimum Plate Thickness

(1) The minimum plate thickness of a base material and connection plate for the butt joint with two friction-surfaces shown in Figure 7.2.1 is the value given by the following equation:

$$t_1 = 0.4d \quad (7.2.1)$$

When a base material is 6000 series aluminum alloys excluding A6005C-T5 alloy,

$$t_2 = 0.5t_1 \quad (7.2.2a)$$

When a base material is 5000 series aluminum alloys and A6005C-T5 alloy,

$$t_2 = t_1 \quad (7.2.2b)$$

where

t_1, t_2 = thickness of a base material and connection plate, respectively

d = diameter of steel high-strength bolts for friction-type connection

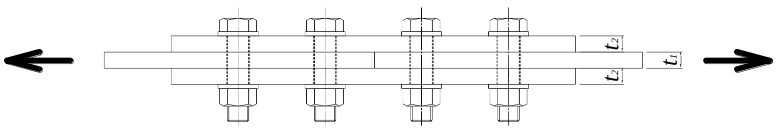


Figure 7.2.1 Butt Joint with Two Friction-Surfaces

(2) The minimum thickness of a base material and connection plate for the butt joint with one friction-surface shown in Figure 7.2.2 is the value given by the following equation:

$$t_1 = t_2 = 0.4d \quad (7.2.3)$$

where

t_1, t_2 = thickness of a base material and connection plate, respectively

d = diameter of steel high-strength bolts for friction-type connection

In this joint, 5000 series aluminum alloys and A6005C-T5 alloy cannot be used for the base material.

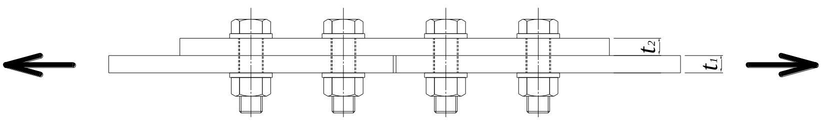


Figure 7.2.2 Butt Joint with One Friction-Surface

(3) The minimum plate thickness of a base material for the lap joint shown in Figure 7.2.3 is the value given by the following equation:

$$t_1 = 0.4d \quad (7.2.4)$$

where

t_1 = thickness of a base material

d = diameter of steel high-strength bolts for friction-type connection

In this joint, 5000 series aluminum alloys and A6005C-T5 alloy cannot be used for the base material.

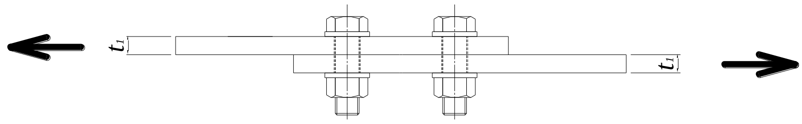


Figure 7.2.3 Lap Joint

7.2.4 Design Load Carrying Force of Steel High-Strength Bolts for Friction-Type Connection

(1) The design friction load carrying force of one steel high-strength bolt for friction-type connection is given by the following equations:

$$\rho_{fFd} = \phi_F \rho_F j \tag{7.2.5a}$$

$$j = \begin{cases} 1 & \text{(One friction-surface)} \\ 2 & \text{(Two friction-surfaces)} \end{cases} \tag{7.2.5b}$$

where

ρ_{fFd} = design friction load carrying force of one steel high-strength bolt for friction-type connection

ρ_F = nominal friction load carrying force per one friction-surface of one steel high-strength bolt for friction-type connection

ϕ_F = resistance factor for the friction load carrying force

Table 7.2.1 shows the nominal friction load carrying force ρ_F per one friction-surface of one steel high-strength bolt for friction-type connection.

Table 7.2.1 Nominal Friction Load Carrying Force ρ_F per One Friction-Surface of One Steel High-Strength Bolt for Friction-Type Connection

Grade of high-strength bolts	Designation of bolts	ρ_F (kN)	
		When the friction-surface treatment specified in 9.4.2 is executed	When no friction-surface treatment is executed
F8T	M12	18.4	6.9
	M16	34.2	12.8
	M20	53.3	20.0
	M22	65.9	24.7
	M24	76.8	28.8
F10T	M12	22.8	8.5
	M16	42.4	15.9
	M20	66.2	24.8
	M22	81.8	30.7
	M24	95.3	35.7

(2) The design fracture load carrying force of one steel high-strength bolt for friction-type connection is given by the following equations:

$$\rho_{fUd} = \min(\rho_{fSBd}, \rho_{fBBd}) \tag{7.2.6a}$$

$$\rho_{fSBd} = \phi_{SB} \frac{\pi d^2}{4} \frac{\sigma_{SB}}{\sqrt{3}} j \tag{7.2.6b}$$

$$j = \begin{cases} 1 & \text{(One friction-surface)} \\ 2 & \text{(Two friction-surfaces)} \end{cases} \tag{7.2.6c}$$

$$\rho_{fBBd} = \phi_B \times \min(dt_1 \times 2\sigma_{1B}, dt_{22} \times 2\sigma_{2B}) \tag{7.2.6d}$$

where

ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection

ρ_{fSBd} = design shearing fracture load of one steel high-strength bolt for friction-type connection

ρ_{fBBd} = design bearing fracture load of one steel high-strength bolt for friction-type connection

d = diameter of steel high-strength bolts for friction-type connection

σ_{SB} = tensile strength of steel high-strength bolts for friction-type connection (800 N/mm^2 for F8T and 1000 N/mm^2 for F10T)

t_1 = thickness of a base material

t_{22} = total thickness of connection plates

σ_{1B} = tensile strength of the aluminum alloy for a base material (See Table 7.2.2)

σ_{2B} = tensile strength of the aluminum alloy for connection plates (See Table 7.2.2)

ϕ_{SB}, ϕ_B = resistance factor for the tensile strength of steel high-strength bolts for friction-type connection and the one for the tensile strength of aluminum alloy materials, respectively

Table 7.2.2 Tensile Strength σ_B of Aluminum Alloy Materials

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)
Plates	A5083-H112	$4 \leqq t \leqq 40$	275
	A5083-O	$3 \leqq t \leqq 40$	275
	A6061-T6	$3 \leqq t \leqq 6.5$	295
	A6061-T651	$6.5 \leqq t \leqq 40$	295
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275
	A5083-O	$3 \leqq t \leqq 38$	275
	A6061-T6	$3 \leqq t \leqq 40$	265
	A6N01-T5	$3 \leqq t \leqq 6$	245
		$6 < t \leqq 12$	225
	A6N01-T6	$3 \leqq t \leqq 6$	265

7.2.5 Friction Load Design of High-Strength Bolted Friction-Type Joints

(1) As shown in Figure 7.2.4, the following equation is checked in the friction load design of high-strength bolted friction-type joints under uniformly distributed normal stress.

$$\rho_P = \frac{P}{n} \leq \rho_{fFd} \tag{7.2.7}$$

where

ρ_P = force acting on one bolt

P	= force acting on all bolts on one side with respect to the joining line
n	= total number of bolts on one side with respect to the joining line
ρ_{fFd}	= design friction load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.5)]

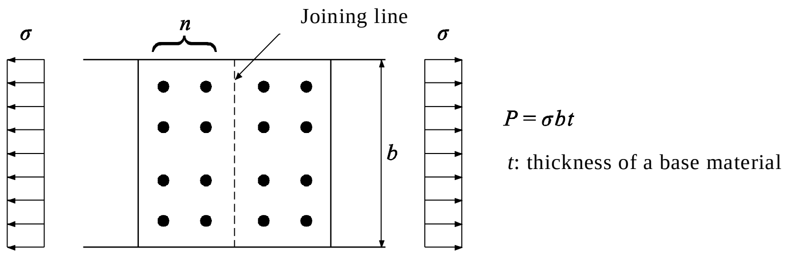


Figure 7.2.4 High-Strength Bolted Friction-Type Joint under Uniformly Distributed Normal Stress

(2) In the friction load design of high-strength bolted friction-type joints under normal stress that is not uniformly distributed as shown in Figure 7.2.5, the following equation is checked for bolts in each row:

$$\rho_{Pi} = \frac{P_i}{n_i} \leq \rho_{fFd} \tag{7.2.8}$$

where

ρ_{Pi}	= force acting on one bolt in the i-th row
P_i	= force acting on all bolts on one side with respect to the joining line in the i-th row
n_i	= total number of bolts on one side with respect to the joining line in the i-th row
ρ_{fFd}	= design friction load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.5)]

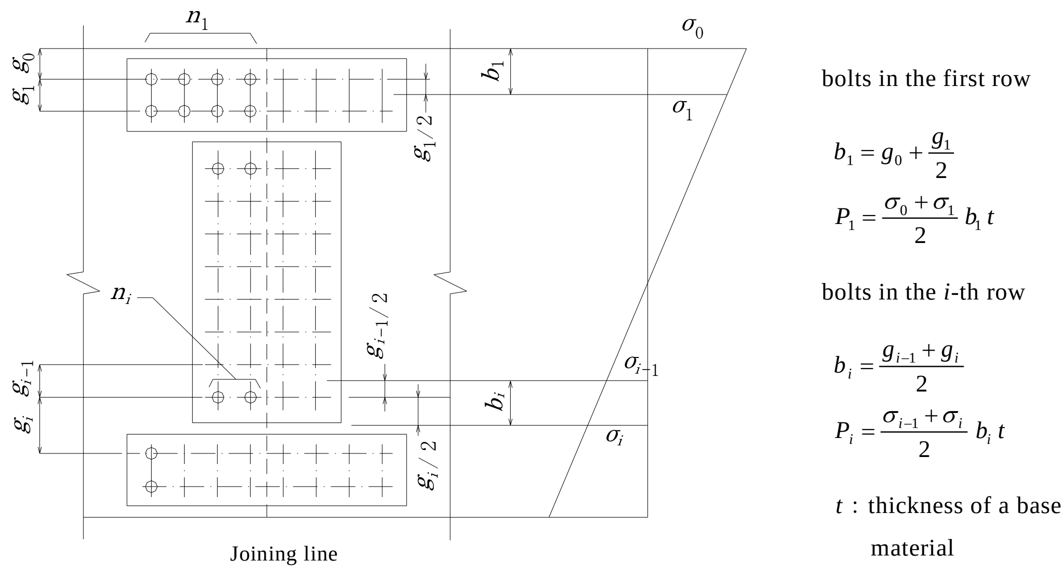


Figure 7.2.5 High-Strength Bolted Friction-Type Joint under Normal Stress That Is Not Uniformly Distributed

(3) In the friction load design of high-strength bolted friction-type joints under shearing force, the following equation is checked:

$$\rho_Q = \frac{Q}{n} \leq \rho_{fFd} \tag{7.2.9}$$

where

ρ_Q = force acting on one bolt

Q = force acting on all bolts on one side with respect to the joining line

n = total number of bolts on one side with respect to the joining line

ρ_{fFd} = design friction load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.5)]

(4) In the friction load design of high-strength bolted friction-type joints in which a normal stress and a shearing force act simultaneously, the following equation is checked:

$$\rho = \sqrt{\rho_P^2 + \rho_Q^2} \leq \rho_{fFd} \tag{7.2.10}$$

where

ρ = force acting on one bolt

ρ_P = force acting on one bolt due to normal stress

ρ_Q = force acting on one bolt due to shearing force

ρ_{fFd} = design friction load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.5)]

(5) The following equation should be checked in the friction load design of high-strength bolted friction-type joints that horizontally connect plates, subjected to shearing force due to bending, as shown in Figure 7.2.6:

$$\rho_H = \frac{QSp}{In} \leq \rho_{fFd} \tag{7.2.11}$$

where

ρ_H = force acting on one of the bolts that connect plates horizontally

Q = shearing force due to bending

S = geometrical moment of area outside the joining line

I = geometrical moment of inertia of a base material

p = pitch of bolts

n = number of bolts in the direction perpendicular to the joining line

ρ_{fFd} = design friction load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.5)]

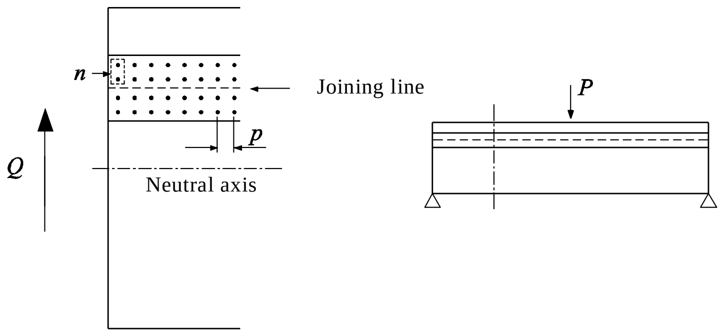


Figure 7.2.6 High-Strength Bolted Friction-Type Joint That Horizontally Connect Plates, Subjected to Shearing Force due to Bending

7.2.6 Fracture Load Design of High-Strength Bolted Friction-Type Joints

(1) The following equation is checked in the fracture load design of high-strength bolted friction-type joints under uniformly distributed normal stress, as shown in Figure 7.2.4.

$$\rho_P = \frac{P}{n} \leq \rho_{fUd} \qquad (7.2.12)$$

where

ρ_P = force acting on one bolt

P = force acting on all bolts on one side with respect to the joining line

n = total number of bolts on one side with respect to the joining line

ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.6)]

(2) In the fracture load design of high-strength bolted friction-type joints under normal stress that is not uniformly distributed, as shown in Figure 7.2.7, the following equation is checked:

$$\rho_n = \frac{M}{\sum y_i^2} y_n \leq \rho_{fUd} \qquad (7.2.13)$$

where

ρ_n = force acting on one bolt at the outermost location

M = bending moment

Σ = symbol that represents the sum of bolts on one side with respect to the joining line

y_i = distance from the neutral axis to bolts

y_n = distance from the neutral axis to the bolts at the outermost location

ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.6)]

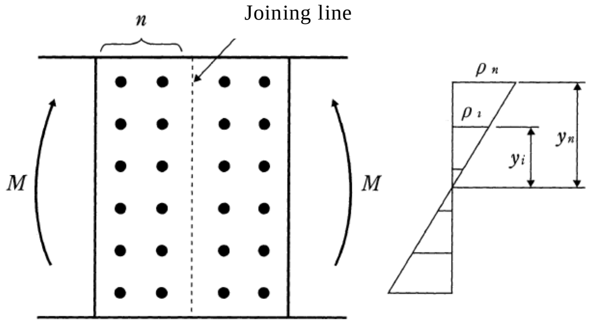


Figure 7.2.7 High Strength Bolted Friction-Type Joint under Bending Moment

(3) In the fracture load design of high-strength bolted friction-type joints under shearing force, the following equation is checked:

$$\rho_Q = \frac{Q}{n} \leq \rho_{fUd} \tag{7.2.14}$$

where

ρ_Q = force acting on one bolt
Q = force acting on all bolts on one side with respect to the joining line
n = total number of bolts on one side with respect to the joining line
ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.6)]

(4) In the fracture load design of high-strength bolted friction-type joints in which a normal stress and a shearing force act simultaneously, the following equation is checked:

$$\rho = \sqrt{\rho_P^2 + \rho_Q^2} \leq \rho_{fUd} \tag{7.2.15}$$

where

ρ = force acting on one bolt
ρ_P = force acting on one bolt due to normal stress
ρ_Q = force acting on one bolt due to shearing force
ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.6)]

(5) The following equation should be checked in the fracture load design of high-strength bolted friction-type joints that horizontally connect plates, subjected to shearing force due to bending, as shown in Figure 7.2.6:

$$\rho_H = \frac{QSp}{In} \leq \rho_{fUd} \tag{7.2.16}$$

where

ρ_H = force acting on one of bolts that connect plates horizontally
Q = shearing force due to bending
S = geometrical moment of area outside the joining line

I = geometrical moment of inertia of a base material

p = pitch of bolts

n = number of bolts in the direction perpendicular to the joining line

ρ_{fUd} = design fracture load carrying force of one steel high-strength bolt for friction-type connection [Eq. (7.2.6)]

7.2.7 Design of Connection Plates and Base Materials at Joints

(1) Welded or friction stir welded plates shall not be used as connection plates.

(2) The thickness of connection plates of butt joints with two friction-surfaces shall be equal.

(3) For connection plates under tensile force, it is checked that the stress occurring in the net cross section specified in 7.2.8 is less than the design tensile strength ($\sigma_{t0.2d}$ and σ_{tBd}) specified in 3.1.

(4) For connection plates under compressive force, it is checked that the stress occurring in the gross cross section is less than the design compressive strength (σ_{cud} and σ_{tBd}) specified in 3.5. Here, σ_u in Eq. (3.5.1a) that gives σ_{cud} is replaced by $\sigma_{0.2}$.

(5) For connection plates under bending moment, the following equation is checked.

$$\sigma = \frac{M}{I} y \leq \sigma_d \tag{7.2.17}$$

where

σ = stress at the outermost edge of connection plates

M = bending moment acting on connection plates

I = geometrical moment of inertia for the gross cross section of connection plates around the neutral axis of a member

y = distance from the neutral axis of a member to the outermost edge of the connection plates

σ_d =design tensile strength ($\sigma_{t0.2d}$ and σ_{tBd}) specified in 3.1 or the design compressive strength (σ_{cud} and σ_{tBd}) specified in 3.5 [Here, σ_u in Eq. (3.5.1a) that gives σ_{cud} is replaced by $\sigma_{0.2}$.]

(6) The design of a base material at joints is similar to that of connection plates. It is checked that when a tensile force acts, the stress occurring in the net cross section of the base material is less than the design tensile strength ($\sigma_{t0.2d}$ and σ_{tBd}), and when a compressive stress is applied, it is checked that the stress generated in the gross cross section is less than the design compressive strength (σ_{cud} and σ_{tBd}). Here, σ_u in Eq. (3.5.1a) that gives σ_{cud} is replaced by $\sigma_{0.2}$.

7.2.8 Calculation of Net Cross-Sectional Area

The calculation of the net cross-sectional area of plates on which a tensile force acts follows the items below:

(1) The net cross-sectional area is the product of the net width and the plate thickness. The net width of a plate is the gross width minus the width lost by bolt holes.

(2) The diameter of bolt holes used to calculate the net cross-sectional area of a plate is the value obtained by adding 3 mm to the diameter of bolts.

(3) The net width of staggered bolted plates is obtained by subtracting the diameter of the first bolt hole in the cross section of interest and sequentially subtracting w calculated by the following equation for each bolt hole:

$$w = D - \frac{p^2}{4g} \tag{7.2.18}$$

where

D = diameter of bolt holes

$p,\ g$ = pitch and gauge of bolts, respectively [See Figure 7.2.9(b)]

If the value of w is negative, the deduction of the bolt holes is ignored.

(4) For extrusions of angle section and channel section, the net cross section is calculated for the developed cross section as shown in Figure 7.2.8. The gross width of the developed cross section is $a+b-t$, and the gauge length g is the value obtained by subtracting the thickness t from the distance between the bolt lines measured along the back surface of the angle cross section.

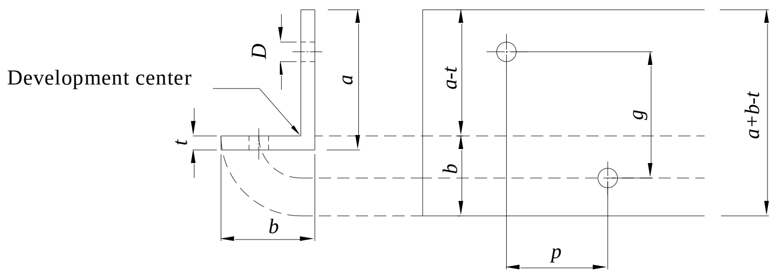


Figure 7.2.8 Development of Angle Cross Section

7.2.9 Bolt Center Spacing, and Edge and End Distances

(1) The minimum center spacing between bolts is the values shown in Table 7.2.2.

Table 7.2.2 Minimum Center Spacing between Bolts

Designation of bolts	Minimum center spacing (mm)
M12	40
M16	55
M20	65
M22	75
M24	85

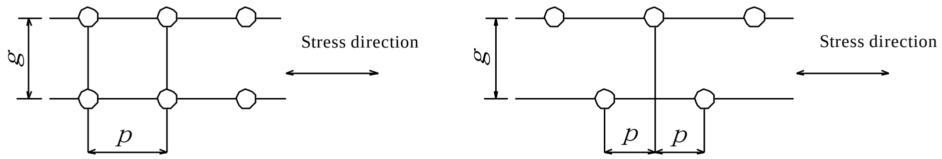
(2) The maximum center spacing between bolts is the values shown in Table 7.2.3.

Table 7.2.3 Maximum Center Spacing between Bolts

Members	p (mm)	g (mm)
Compression members	For rectangular bolt fastening, $8.5t$ For staggered bolt fastening, $10t - 3g/8$. However, $8.5t$ or less	$17t$
Tension members	For rectangular bolt fastening, $17t$ For staggered bolt fastening, $2(10t - 3g/8)$. However, $17t$ or less	$17t$

$t =$ thickness of connection plates

p, $g =$ pitch and gauge of bolts, respectively [See Figure 7.2.9]



(a) Rectangular Bolt Fastening **(b) Staggered Bolt Fastening**

Figure 7.2.9 Pitch and Gauge of Bolts

(3) The edge and end distances from bolts shown in Figure 7.2.10 follow the items below:

1) The distance from the center of a bolt hole to the edge of a connection plate (edge distance) shall be at least 1.5 times the diameter of the bolt hole.
2) The distance from the center of a bolt hole to the end of a connection plate (end distance) shall be at least twice the diameter of the bolt hole.
3) The maximum value of the edge and end distances in a connection plate is 5.5 times the thickness of a connection plate. However, it should not exceed 90 mm.

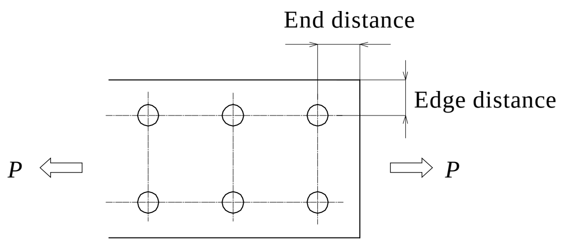


Figure 7.2.10 Edge and End Distances from Bolts

7.2.10 Minimum Number of Bolts

The minimum number of bolts on one side with regard to the joining line is 2.

7.3 Bearing-Type Joints

7.3.1 General

(1) Bearing-type joints can be used to fabricate accessories such as guard fences and inspection paths.

(2) Bolt sets that are made of steel, stainless steel or aluminum alloy and that have guaranteed strength must be used for bearing-type joints for aluminum alloy plates.

(3) Aluminum alloy materials that can be used for base materials and connection plates in bearing-type joints are A5083-H112, A5083-O, A6061-T6 and A6061-T651 alloys for plates and A5083-H112, A5083-O, A6061-T6, A6005C-T5 and A6005C-T6 alloys for extrusions.
(4) When using steel or stainless-steel bolts, it is necessary to prevent corrosion of bolts themselves as well as contact corrosion of dissimilar metals between a bolt and an aluminum alloy plate.
(5) The threaded part of bolts must not be located on the shearing plane between a base material and a connection plate.
(6) The design of riveted joints made of aluminum alloys follows that of bearing-type joints.

7.3.2 Design Load Carrying Force of Bolts for Bearing-Type Connection

(1) The design yield load carrying force for one bolt for bearing-type connection is given by the following equations:

$$\rho_{bYd} = \min(\rho_{bSYd}, \rho_{bB0.2d}) \tag{7.3.1a}$$

$$\rho_{bSYd} = \phi_{SY} \frac{\pi d^2}{4} \frac{\sigma_{SY}}{\sqrt{3}} j \tag{7.3.1b}$$

$$j = \begin{cases} 1 & \text{(One shearing-plane)} \\ 2 & \text{(Two shearing-planes)} \end{cases} \tag{7.3.1c}$$

$$\rho_{bB0.2d} = \phi_{0.2} \times \min\left(dt_1 \times 1.5\sigma_{1,0.2}, dt_{22} \times 1.5\sigma_{2,0.2}\right) \tag{7.3.1d}$$

where

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection
ρ_{bSYd} = design shearing yield load of one bolt for bearing-type connection
$\rho_{bB0.2d}$ = design bearing yield load of one bolt for bearing-type connection
d = diameter of bolts for bearing-type connection
σ_{SY} = yield stress or 0.2% proof stress of bolts for bearing-type connection
t_1 = thickness of a base material
t_{22} = total thickness of connection plates
$\sigma_{1,0.2}$ = 0.2% proof stress of the aluminum alloy for a base material (See Table 7.3.1)
$\sigma_{2,0.2}$ = 0.2% proof stress of the aluminum alloy for connection plates (See Table 7.3.1)
ϕ_{SY}, $\phi_{0.2}$ = resistance factor for the yield stress of bolts for bearing-type connection and the one for the 0.2% proof stress of aluminum alloy materials

(2) The design fracture load carrying force for one bolt for bearing-type connection is given by the following equations:

$$\rho_{bUd} = \min(\rho_{bSBd}, \rho_{bBBd}) \tag{7.3.2a}$$

$$\rho_{bSBd} = \phi_{SB} \frac{\pi d^2}{4} \frac{\sigma_{SB}}{\sqrt{3}} j \tag{7.3.2b}$$

$$j = \begin{cases} 1 & \text{(One shearing-plane)} \\ 2 & \text{(Two shearing-planes)} \end{cases} \tag{7.3.2c}$$

$$\rho_{bBBd} = \phi_B \times \min(dt_1 \times 2\sigma_{1B}, dt_{22} \times 2\sigma_{2B}) \tag{7.3.2d}$$

where

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection

ρ_{bSBd} = design shearing fracture load of one bolt for bearing-type connection

ρ_{bBBd} = design bearing fracture load of one bolt for bearing-type connection

d = diameter of bolts for bearing-type connection

σ_{SB} = tensile strength of bolts for bearing-type connection

t_1 = thickness of a base material

t_{22} = total thickness of connection plates

σ_{1B} = tensile strength of the aluminum alloy for a base material (See Table 7.3.1)

σ_{2B} = tensile strength of the aluminum alloy for connection plates (See Table 7.3.1)

ϕ_{SB}, ϕ_B = resistance factor for the tensile strength of bolts for bearing-type connection and the one for the tensile strength of aluminum alloy materials

Table 7.3.1 Tensile Strength σ_B and 0.2% Proof Stress $\sigma_{0.2}$

Aluminum alloys		Thickness t (mm)	Tensile strength σ_B (N/mm^2)	0.2% proof stress $\sigma_{0.2}$ (N/mm^2)
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125
	A5083-O	$3 \leqq t \leqq 40$	275	125
	A6061-T6	$3 \leqq t \leqq 6.5$	295	245
	A6061-T651	$6.5 \leqq t \leqq 40$	295	245
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120
	A5083-O	$3 \leqq t \leqq 38$	275	120
	A6061-T6	$3 \leqq t \leqq 40$	265	245
	A6005C-T5	$3 \leqq t \leqq 6$	245	205
		$6 < t \leqq 12$	225	175
	A6005C-T6	$3 \leqq t \leqq 6$	265	235

7.3.3 Design of Bearing-Type Joints

(1) The following equations are checked in the design of bearing-type joints under uniformly distributed normal stress, as shown in Figure 7.2.4:

For the yield load carrying force, $$\rho_P = \frac{P}{n} \leq \rho_{bYd} \tag{7.3.3a}$$

For the fracture load carrying force, $$\rho_P = \frac{P}{n} \leq \rho_{bUd} \tag{7.3.3b}$$

where

ρ_P = force acting on one bolt

P = force acting on all bolts on one side with respect to the joining line

n = total number of bolts on one side with respect to the joining line

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection [Eq. (7.3.1)]

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection [Eq. (7.3.2)]

(2) The following equations are checked in the design of bearing-type joints under the normal stress that is not uniformly distributed, as shown in Figure 7.2.7:

For the yield load carrying force, $$\rho_n = \frac{M}{\sum y_i^2} y_n \leq \rho_{bYd} \tag{7.3.4a}$$

For the fracture load carrying force, $$\rho_n = \frac{M}{\sum y_i^2} y_n \leq \rho_{bUd} \tag{7.3.4b}$$

where

ρ_n = force acting on one bolt at the outermost location

M = bending moment

Σ = symbol that represents the sum for bolts on one side with respect to the joining line

y_i = distance from the neutral axis to bolts

y_n = distance from the neutral axis to the bolts at the outermost location

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection [Eq. (7.3.1)]

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection [Eq. (7.3.2)]

(3) In the design of bearing-type joints under shearing force, the following equations are checked:

For the yield load carrying force, $$\rho_Q = \frac{Q}{n} \leq \rho_{bYd} \tag{7.3.5a}$$

For the fracture load carrying force, $$\rho_Q = \frac{Q}{n} \leq \rho_{bUd} \tag{7.3.5b}$$

where

ρ_Q = force acting on one bolt

Q = force acting on all bolts on one side with respect to the joining line

n = total number of bolts on one side with respect to the joining line

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection [Eq. (7.3.1)]

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection [Eq. (7.3.2)]

(4) In the design of bearing-type joints in which a normal stress and a shearing force act simultaneously, the following equations are checked:

For the yield load carrying force, $$\rho = \sqrt{\rho_P^2 + \rho_Q^2} \leq \rho_{bYd} \tag{7.3.6a}$$

For the fracture load carrying force, $$\rho = \sqrt{\rho_P^2 + \rho_Q^2} \leq \rho_{bUd} \tag{7.3.6b}$$

where

ρ = force acting on one bolt

ρ_P = force acting on one bolt due to normal stress

ρ_Q = force acting on one bolt due to shearing force

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection [Eq. (7.3.1)]

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection [Eq. (7.3.2)]

(5) The following equations are checked in the design of bearing-type joints that horizontally connect plates, subjected to shearing force due to bending, as shown in Fig. 7.2.6:

For the yield load carrying force,
$$\rho_H = \frac{QSp}{In} \leq \rho_{bYd} \quad (7.3.7a)$$

For the fracture load carrying force,
$$\rho_H = \frac{QSp}{In} \leq \rho_{bUd} \quad (7.3.7b)$$

where

ρ_H = force acting on one of bolts that connect plates horizontally

Q = shearing force due to bending

S = geometrical moment of area outside the joining line

I = geometrical moment of inertia of a base material

p = pitch of bolts

n = number of bolts in the direction perpendicular to the joining line

ρ_{bYd} = design yield load carrying force of one bolt for bearing-type connection [Eq. (7.3.1)]

ρ_{bUd} = design fracture load carrying force of one bolt for bearing-type connection [Eq. (7.3.2)]

7.3.4 Design of Connection Plates and Base Materials at Joints

The design of connection plates and base materials at joints complies with 7.2.7.

7.3.5 Calculation of Net Cross-Sectional Area

The calculation method of the net cross-sectional area of a plate under tensile force complies with 7.2.8. The diameter of bolt holes used to calculate the net cross-sectional area of a plate is the value obtained by adding 2 mm to the diameter of bolts.

7.3.6 Bolt Center Spacing, and Edge and End Distances

The center spacing between bolts and the edge and end distances from bolts comply with 7.2.9.

7.3.7 Minimum Number of Bolts

The minimum number of bolts complies with 7.2.10.

8. Fatigue Design

8.1 Scope of Application

This chapter stipulates the fatigue design of aluminum alloy structures in civil engineering, members that make up them, and joints which are used in normal temperature and atmosphere.

8.2 Safety Factors

The safety factor ν, which adjusts the level of safety in fatigue check, is set to 1 or more. The value of the safety factor ν is determined by taking into consideration redundancy (effects on the strength or function of an entire structure), importance (social effects when a structure fails due to fatigue) and inspectability (the possibility that cracks will be discovered before fatigue failure by periodic inspection during service of a structure), when fatigue cracks occur in members or joints to be designed.

8.3 Prerequisites for Fatigue Check

(1) Friction stir welded joint

Friction stir welded joints are those that are fabricated by double-sided friction stir welding that satisfies 9.3.

(2) High strength bolted friction-type joint

High-strength bolted friction-type joints are those that satisfies 7.2 and that have two friction-surfaces with a friction-surface treatment specified in 9.4.2 executed.

(3) Effect of corrosion

The effect of corrosion must be taken into consideration in the fatigue strength of components or joints without painting.

(4) Stress for fatigue check

The stress for fatigue check is the range of nominal stress (the stress calculated by structural mechanics or frame structure analysis) that acts on the cross section to be checked.

The stress for fatigue check at the position where a stress concentration occurs, such as the edge of openings, is the stress obtained by multiplying the range of nominal stress by the elastic stress concentration factor at such a position.

(5) Position of fatigue check

When members or joints with the same fatigue strength grades are continuous, the fatigue check is performed at the position where the stress range is maximum.

(6) Frequency distribution of stress range

The variation of stress expected at the position of interest during a design period is calculated for the fatigue design load, and the rain-flow method is applied to the fluctuating waveform to obtain a frequency distribution of stress range.

(7) Combined stresses

1) Combination of membrane stress and plate bending stress

When a membrane stress and plate bending stress act simultaneously, the range of normal stress given by the following equation is used for fatigue check:

$$\Delta\sigma = \Delta\sigma_m + \xi\Delta\sigma_b \quad (8.3.1)$$

where

ξ = 1 for base materials, friction stir welded joints and high strength bolted friction-type joints, and 0.8 for welded joints

$\Delta\sigma$ = range of normal stress

$\Delta\sigma_m$ = range of membrane stress

$\Delta\sigma_b$ = range of plate bending stress

2) Combination of normal and shearing stresses

When normal and shearing stresses act simultaneously, the range of principal stress is used as the stress range for fatigue check. When the acting direction of the principal stress is 45° or more and 135° or less with respect to the joining line, the fatigue strength in the direction perpendicular to the joining line is used for fatigue check. When the acting direction of the principal stress is more than -45° and less than 45° with respect to the joining line, the fatigue strength in the direction of the joining line is used for fatigue check.

8.4 Fatigue Check

8.4.1 Fatigue Check Based on Fatigue Limits

Members or joints that satisfy the following equations are safe against fatigue, and it is not necessary to perform the fatigue check in 8.4.2:

$$\nu\Delta\sigma_{\max} \leq Y_{c2}Y_t\Delta\sigma_{caf} \tag{8.4.1}$$

$$\nu\Delta\tau_{\max} \leq Y_{c2}\Delta\tau_{caf} \tag{8.4.2}$$

where

ν = safety factor

$\Delta\sigma_{\max}$, $\Delta\tau_{\max}$ = maximum of the normal stress range and that of the shearing stress range predicted during a design period, respectively

$\Delta\sigma_{caf}$, $\Delta\tau_{caf}$ = cut-off limit of the stress range for constant amplitude stress, for normal stress and the one for shearing stress, respectively

Y_{c2} = coefficient for corrosion effects on fatigue limits (See 8.5.4)

Y_t = coefficient for thickness effects (See 8.5.5)

8.4.2 Fatigue Check Based on S-N Curves

When members or joints under consideration do not satisfy Eq. (8.4.1) or Eq. (8.4.2), the fatigue check is performed using one of the following (1), (2) and (3):

(1) Fatigue Check by Cumulative Fatigue Damage Ratio

Members or joints that satisfy the following equation are safe against fatigue:

$$D \leq \frac{1}{\nu^m} \tag{8.4.3}$$

where

D = cumulative fatigue damage ratio

ν = safety factor

m = value representing the slope of S-N curves (See Table 8.4.1)

The cumulative fatigue damage ratio D is calculated by the following equation:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{8.4.4}$$

where

n_i = frequency of a certain stress range component $\Delta\sigma_i$ or $\Delta\tau_i$ in a frequency distribution of stress range

N_i = fatigue life for $\Delta\sigma_i$ or $\Delta\tau_i$

k = total number of divisions in a frequency distribution of stress range

The fatigue life N_i corresponding to a certain stress range component $\Delta\sigma_i$ for normal stress or a certain stress range component $\Delta\tau_i$ for shearing stress is calculated by the following equations, respectively:

$$N_i = \begin{cases} \dfrac{(Y_{c1}Y_t)^m c_a}{(\Delta\sigma_i)^m} & \left(\Delta\sigma_i > Y_{c2}Y_t\Delta\sigma_{vaf}\right) \\ \infty & \left(\Delta\sigma_i \leq Y_{c2}Y_t\Delta\sigma_{vaf}\right) \end{cases} \tag{8.4.5}$$

$$N_i = \begin{cases} \dfrac{Y_{c1}^m c_a}{(\Delta\tau_i)^m} & \left(\Delta\tau_i > Y_{c2}\Delta\tau_{vaf}\right) \\ \infty & \left(\Delta\tau_i \leq Y_{c2}\Delta\tau_{vaf}\right) \end{cases} \tag{8.4.6}$$

where

m = value representing the slope of S-N curves (See Table 8.4.1)

c_a = allowable fatigue resistance

$\Delta\sigma_{vaf}$, $\Delta\tau_{vaf}$ = cut-off limit of the stress range for variable amplitude stress

Y_{c1}, Y_{c2} = coefficient for corrosion effects on S-N curves and the one on fatigue limits, respectively (See 8.5.4)

Y_t = coefficient for thickness effects (See 8.5.5)

Table 8.4.1 Values of *m* Representing Slope of S-N Curves

Base materials and friction stir welded joints		6.17
Welded joints	When subjected to normal stress	3
	When subjected to shearing stress	5
High strength bolted friction-type joints		5.23

(2) Fatigue Check by Equivalent Stress Range

Members or joints that satisfy the following equations are safe against fatigue:

$$\nu\Delta\sigma_e \leq Y_{c1}Y_t\Delta\sigma_a \tag{8.4.7}$$

$$\nu\Delta\tau_e \leq Y_{c1}\Delta\tau_a \tag{8.4.8}$$

where

ν = safety factor

$\Delta\sigma_e$ = equivalent stress range for normal stress

$\Delta\tau_e$ = equivalent stress range for shearing stress

$\Delta\sigma_a$ = allowable stress range for normal stress

$\Delta\tau_a$ = allowable stress range for shearing stress

Y_{c1} = coefficients for corrosion effects on S-N curves (See 8.5.4)

Y_t = coefficient for thickness effects (See 8.5.5)

The equivalent stress ranges $\Delta\sigma_e$ and $\Delta\tau_e$ are calculated by the following equations, respectively:

$$\Delta\sigma_e = \left\{\sum_{i=1}^{k} (\Delta\sigma_i)^m \frac{n_i}{N_T}\right\}^{\frac{1}{m}} \tag{8.4.9}$$

$$\Delta\tau_e = \left\{\sum_{i=1}^{k} (\Delta\tau_i)^m \frac{n_i}{N_T}\right\}^{\frac{1}{m}} \tag{8.4.10}$$

where

m = value representing the slope of S-N curves (See Table 8.4.1)

$\Delta\sigma_i,\ \Delta\tau_i$ = one component of the stress range in a frequency distribution of stress range for normal stress and the one for shearing stress, respectively

n_i = frequency of $\Delta\sigma_i$ or $\Delta\tau_i$

$N_T = \sum_{i=1}^{k} n_i$ = total number of all repetitions during a design period

k = total number of divisions in a frequency distribution of stress range

Let $n_i = 0$ for the stress range below the cut-off limit $Y_{c2}Y_t\Delta\sigma_{vaf}$ or $Y_{c2}\Delta\tau_{vaf}$ for variable amplitude stress. Here, Y_{c2} is the coefficient for corrosion effects on fatigue limits (See 8.5.4), and Y_t is the coefficient for thickness effects (See 8.5.5).

The allowable stress ranges $\Delta\sigma_a$ and $\Delta\tau_a$ are calculated by the following equations, respectively:

$$\Delta\sigma_a = \left(\frac{c_a}{N_T}\right)^{\frac{1}{m}} \tag{8.4.11}$$

$$\Delta\tau_a = \left(\frac{c_a}{N_T}\right)^{\frac{1}{m}} \tag{8.4.12}$$

where

c_a = allowable fatigue resistance

(3) Fatigue Check by Cumulative Fatigue Damage

Members or joints that satisfy the following equations are safe against fatigue:

$$\nu^m q_\sigma \le (Y_{c1}Y_t)^m c_a \tag{8.4.13}$$

$$\nu^m q_\tau \le Y_{c1}^m c_a \tag{8.4.14}$$

where

ν = safety factor

m = value representing the slope of S-N curves (See Table 8.4.1)

q_σ = cumulative fatigue damage for normal stress

q_τ = cumulative fatigue damage for shearing stress

c_a = allowable fatigue resistance

Y_{c1} = coefficients for corrosion effects on S-N curves (See 8.5.4)

Y_t = coefficient for thickness effects (See 8.5.5)

The cumulative fatigue damages q_σ and q_τ are calculated by the following equations, respectively:

$$q_\sigma = \sum_{i=1}^{k} n_i (\Delta\sigma_i)^m \tag{8.4.15}$$

$$q_\tau = \sum_{i=1}^{k} n_i (\Delta\tau_i)^m \tag{8.4.16}$$

where

$\Delta\sigma_i,\ \Delta\tau_i$ = one component of stress range in a frequency distribution of stress range

n_i = frequency of $\Delta\sigma_i$ or $\Delta\tau_i$

k = total number of divisions in a frequency distribution of stress range

Let $n_i = 0$ for the stress range below the cut-off limit $Y_{c2}Y_t\Delta\sigma_{vaf}$ or $Y_{c2}\Delta\tau_{vaf}$ for variable amplitude stress. Here, Y_{c2} is the coefficient for the corrosion effects on fatigue limits (See 8.5.4), and Y_t is the coefficient for thickness effects (See 8.5.5).

8.5 Fatigue Strength

8.5.1 Fatigue Strength Grades of Base Materials and Friction Stir Welded Joints

Table 8.5.1 shows the fatigue strength grades of base materials of 6000 series aluminum alloys and friction stir welded joints. They are classified by the fatigue strength $\Delta\sigma_{20}$ at 200,000 cycles.

Table 8.5.1 Fatigue Strength Grades of Base Materials of 6000 Series Aluminum Alloys and Friction Stir Welded Joints

	Fatigue strength grades $\Delta\sigma_{20}$ (N/mm^2)	Allowable fatigue resistance c_a	Cut-off limit of stress range for constant amplitude stress $\Delta\sigma_{caf}$ (N/mm^2)	Cut-off limit of stress range for variable amplitude stress $\Delta\sigma_{vaf}$ (N/mm^2)
Base materials	92	2.60×10^{17}	74.0	37.0
Friction stir welded joints*	65	2.97×10^{16}	52.4	26.2

*: The fatigue strength grades are the same in the direction of the joining line and in the direction perpendicular to it.

8.5.2 Fatigue Strength Grades of Welded Joints

(1) The fatigue strength grades of welded joints are shown in Table 8.5.2. They are classified by the fatigue strength ($\Delta\sigma_{200}$ or $\Delta\tau_{200}$) at 2 million cycles.

Table 8.5.2 Fatigue Strength Grades of Welded Joints

(a) When Subjected to Normal Stress

Fatigue strength grades $\Delta\sigma_{200}$ (N/mm^2)	Allowable fatigue resistance c_a	Cut-off limit of stress range for constant amplitude stress $\Delta\sigma_{caf}$ (N/mm^2)	Cut-off limit of stress range for variable amplitude stress $\Delta\sigma_{vaf}$ (N/mm^2)
50	2.50×10^{11}	29.2	14.6
45	1.82×10^{11}	26.3	13.2

40	1.28×10^{11}	23.4	11.7
36	9.33×10^{10}	21.1	10.5
32	6.55×10^{10}	18.7	9.4
28	4.39×10^{10}	16.4	8.2
25	3.13×10^{10}	14.6	7.3
22	2.13×10^{10}	12.9	6.4
20	1.60×10^{10}	11.7	5.8
18	1.12×10^{10}	10.5	5.3

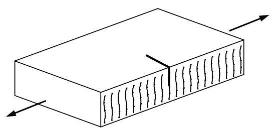
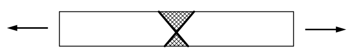
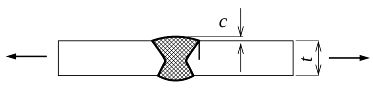
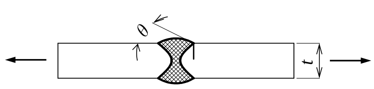
(b) When Subjected to Shearing Stress

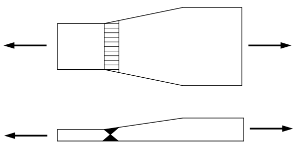
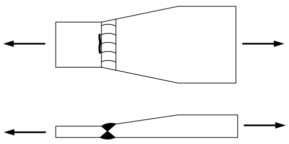
Fatigue strength grades $\Delta\tau_{200}$ (N/mm^2)	Allowable fatigue resistance c_a	Cut-off limit of stress range for constant amplitude stress $\Delta\tau_{caf}$ (N/mm^2)	Cut-off limit of stress range for variable amplitude stress $\Delta\tau_{vaf}$ (N/mm^2)
36	1.21×10^{14}	16.5	8.2
28	3.44×10^{13}	12.8	6.4

(2) The fatigue strength grades of welded joints are shown in Table 8.5.3 and 8.5.4 for normal and shearing stresses, respectively.

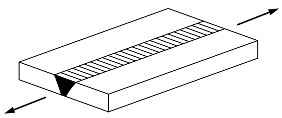
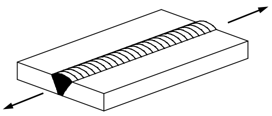
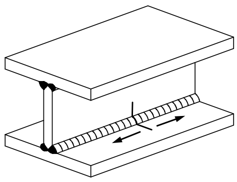
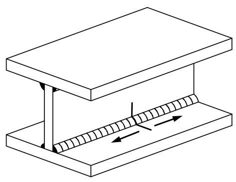
Table 8.5.3 Fatigue Strength Grades of Welded Joints under Normal Stress

(a) Lateral Butt Welded Joints

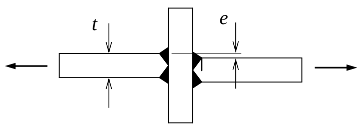
Types of welded joints	Remarks	Fatigue strength grades $\Delta\sigma_{200}$ (N/mm^2)
	Cutting ・ Make sure there are no cracks or scratches. ・ Chamfer of 0.5 mm or more at corners	40
	Lateral butt welded joints whose surface is finished with a grinder (X- or V-groove)	45
	Lateral butt welded joints fabricated in a downward position in a factory ・ Reinforcement $c < 0.1t$	36
	Lateral butt welded joints with a reinforcement 0.1 times or more the plate thickness ・ Toe angle $\theta \leq 50°$ ・ Toe angle $\theta > 50°$	 32 25

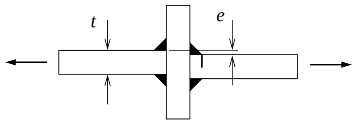
	Lateral butt-welded joints whose surface is finished flat with a grinder and that have a transition part with the thickness and width gradients of 1:5.	45
	Lateral butt welded joints fabricated in a downward position in a factory, that have a transition part with the thickness and width gradients of 1:5.	32

(b) Longitudinal Welded Joints

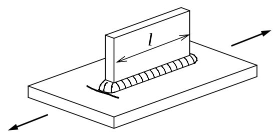
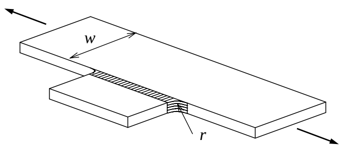
Types of welded joints	Remarks	Fatigue strength grades $\Delta\sigma_{200}$ (N/mm^2)
	Longitudinal butt welded joints ・ Grinding finish parallel to the loading direction so that both the front and back surfaces are flat.	50
	Longitudinal butt welded joints ・ No addition of welding rods ・ Addition of welding rods	45 36
	Continuous automatic longitudinal full penetration K-groove butt welded joints without addition of welding rods (check with a flange stress)	50
	Continuous automatic longitudinal both sided fillet welded joints without addition of welding rods (check with a flange stress)	45

(c) Load-Carrying Type Cruciform Joints and T-Joints

Types of welded joints	Remarks	Fatigue strength grades $\Delta\sigma_{200}$ (N/mm^2)
	Cruciform joints and T-joints ・ K-groove butt welding ・ Full penetration ・ Toe fracture ・ Eccentricity $e < 0.15t$ ・ Grinding finish at toes ・ No Grinding finish at toes	 28 25

	Cruciform joints and T-joints ・ Fillet welding ・ Toe fracture ・ Eccentricity $e < 0.15t$	22

(d) Gusset Connections

Types of welded joints	Remarks	Fatigue strength grades $\Delta\sigma_{200}$ (N/mm²)
	Fillet welded joints with an out-of-plane gusset Gusset length l $l < 50$ mm $l < 150$ mm $l < 300$ mm $l \geq 300$ mm	 28 25 20 18
	Joints with an in-plane gusset welded to a plate edge and to a flange edge of a girder ・ Arc-shaped transition section finished with a grinder $r > 150$ mm or $r/w > 1/3$ $1/6 < r/w \leq 1/3$ $r/w \leq 1/6$	 36 28 22

(e) Non-Load-Carrying Type Cruciform Joints and T-Joints

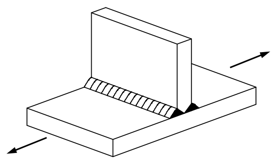
Types of welded joints	Remarks	Fatigue strength grades $\Delta\sigma_{200}$ (N/mm²)
	Cruciform joints and T-joints where the thickness of an attached plate is smaller than that of a main plate ・ K-groove butt welding, grinding finish at toes ・ Both sided fillet welded, grinding finish at toes ・ Fillet welding as-welded When the thickness of an attached plate is greater than that of a main plate	 36 36 28 25

Table 8.5.4 Fatigue Strength Grades of Welded Joints under Shearing Force

Types of welded joints	Fatigue strength grades $\Delta\tau_{200}$ (N/mm²)
Base materials, complete penetration groove welding	36
Fillet welding	28

8.5.3 Fatigue Strength Grades of High Strength Bolted Friction-Type Joints

Table 8.5.5 shows the fatigue strength grades of high strength bolted friction-type joints. They are classified by the fatigue strength σ_{200} at 2 million cycles. Referring to Figure 8.5.1, the ratio t_2/t_1 for plate thickness of a connection plate to a base material is 1 or more.

Table 8.5.5 Fatigue Strength Grade of High Strength Bolted Friction-Type Joints

Fatigue strength grades $\Delta\sigma_{200}$ (N/mm^2)	Allowable fatigue resistance c_a	Cut-off limit of stress range for constant amplitude stress $\Delta\sigma_{caf}$ (N/mm^2)	Cut-off limit of stress range for variable amplitude stress $\Delta\sigma_{vaf}$ (N/mm^2)
66	6.49×10^{15}	48.6	24.3

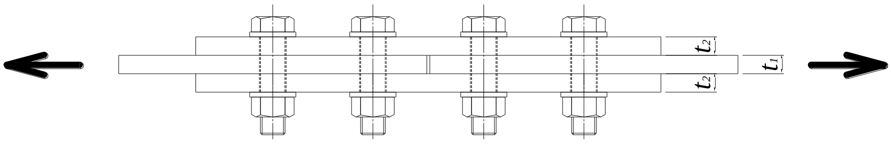


Figure 8.5.1 High Strength Bolted Friction-Type Joints

8.5.4 Coefficients for Corrosion Effects

Table 8.5.6 shows the coefficients for corrosion effects on members or joints without painting. Y_{c1} and Y_{c2} are the coefficients for corrosion effects on S-N curves and fatigue limits, respectively.

Table 8.5.6 Coefficients for Corrosion Effects

	Y_{c1} (S-N curves)	Y_{c2} (Fatigue limits)
Base materials	0.71	0.71
Friction stir welded joints	0.87	0.87
Welded joints	1	0.85
High strength bolted friction-type joints	1	1

The values of the coefficients Y_{c1} and Y_{c2} for corrosion effects for the case where an anticorrosion treatment such as painting is executed are both 1.

8.5.5 Coefficients for Thickness Effects

(1) Base Materials and Friction Stir Welded Joints

The coefficient Y_t for thickness effects of base materials and friction stir welded joints is 1.

(2) Welded Joints

The coefficient Y_t for thickness effects is given by the following equation for lateral butt welded joints except when the surface is finished flat with a grinder, load-carrying type cruciform joints and T-joints where the thickness of an attached plate exceeds 12 mm and non-load-carrying type cruciform joints and T-joints where the thickness of an attached plate exceeds 12 mm:

$$Y_t = \begin{cases} 1 & (t \leq 25\text{mm}) \\ \left(\dfrac{25}{t}\right)^{0.25} & (t > 25\text{mm}) \end{cases} \qquad (8.5.1)$$

where

t = plate thickness

The coefficient Y_t for thickness effects of welded joints other than the above is 1.

(3) High Strength Bolted Friction-Type Joints

The coefficient Y_t for thickness effects of high strength bolted friction-type joints is 1.

9. Fabrication

9.1 Machining

(1) Marking and Cutting

1) The cutting of members is performed by saw cutting, water jet, plasma, laser and shear.
2) After cutting, marking lines and punch marks do not remain on members.
3) Burrs or notches left on the cutting surface are smoothed with a grinder.
4) When painting or when considering the effects of fatigue, cutting corners of pieces are chamfered by 0.5 mm or more. In all other cases, burrs at the cutting corners of pieces exposed to the outside are removed.

(2) Drilling

1) Diameter of bolt holes

The diameter of bolt holes is shown in Table 9.1.1. The tolerance for diameter of bolt holes is +0.5 mm.

Table 9.1.1 Diameter of Bolt Holes

Designation of bolts	Friction-type connection (mm)	Bearing-type connection (mm)
M12	14.5	13.5
M16	18.5	17.5
M20	22.5	21.5
M22	24.5	23.5
M24	26.5	25.5

2) Drilling is done with a drill or a combination of drill and reamer. If the thickness of pieces is less than 10 mm and it is not necessary to consider the effects of fatigue, holes may be punched.
3) Burrs generated around holes due to drilling are removed.

(3) Cold Bending

When cold bending is done on main members, not only surface cracks and wrinkles are prevented, but also the quality after processing must be confirmed by the test specimens simulating cold bending to meet the required performance.

9.2 Welding

9.2.0 Definition of Terms

(1) Crater treatment

To hold a welding rod at the end of a bead for a certain period of time to prevent the formation of a crater (a dimple at the end of a bead which is caused by solidification shrinkage during welding).

(2) Gas flame heating method

One of the methods to correct the welding deformation. It is a method in which after locally heating using a gas welding torch, the material is cooled by water and the local heat shrinkage of the material eliminates the deformation.

(3) Interpass temperature

In multi-layer welding, the temperature of a weld bead just before starting the next pass. Here, one welding operation performed along the welding line is called a pass.

(4) Preflow

In gas shielded arc welding, to release the shielding gas for a certain period of time before starting welding in order to prevent the entrapment of air in the deposited metal.

(5) Strongback

In butt welding, a jig that is temporarily installed to correct misalignment between plates or to prevent angular deformation (a lateral bending deformation that occurs in members or structures due to welding) and twist.

9.2.1 General

(1) Welding of aluminum alloy materials is performed by MIG welding or TIG welding.
(2) There should be no oxide film, rust, paint, oil, etc. on the part to be welded.
(3) The oxide film is removed just before welding.
(4) Welding is performed, sufficiently drying the vicinity of the part to be welded.
(5) Welding is performed when the relative humidity in air is less than 80%.
(6) The preheating temperature is 200°C or less for A5083-O alloy and 100°C or less for A5083-H112, A6061-T6, A6061-T651, A6005C-T5 and A6005C-T6 alloys.

9.2.2 Welding Tests

(1) The welding tests must be performed before fabrication. However, if the welding tests were conducted in the past and there are fabricating experiences, they can be omitted by consultation between the parties.
(2) The types of tests shown in Table 9.2.1 are performed for the welding tests.
(3) Welding is performed in the actual welding position under the welding conditions which are used in actual fabrication.
(4) The material and cross-sectional shape of the specimen used in the welding tests should be the same as those used in actual fabrication. However, for joints made of the same type of aluminum alloy but with different plate thickness, the specimen may be made of the thinner aluminum alloy material.
(5) Non-destructive testing is performed before collecting the test pieces for destructive testing from the specimen. Visual inspection and radiographic test are performed on the overall length of the joint.
(6) As shown in Figure 9.2.1, tensile test pieces, bend test pieces and a macro observation test piece are taken from the specimen fabricated by complete penetration groove welding. The number of test pieces is 2 for the tensile test, 2 for the bend test, and 1 for the macro observation test. When collecting the test pieces, a space of about 10 mm between the test pieces is provided.

(7) Figure 9.2.2 shows the specimen used for macro observation for fillet welding.

(8) The methods for non-destructive testing and destructive testing and the quality criteria are in accordance with 9.2.3.

Table 9.2.1 Types of Welding Tests

Types of welded joints	Types of tests	
Full penetration groove welded joints	Destructive tests	Tensile test
		Bend test
		Macro observation
	Non-destructive tests	Visual inspection
		Radiographic test
Fillet welded joints	Destructive tests	Macro observation
	Non-destructive tests	Visual inspection

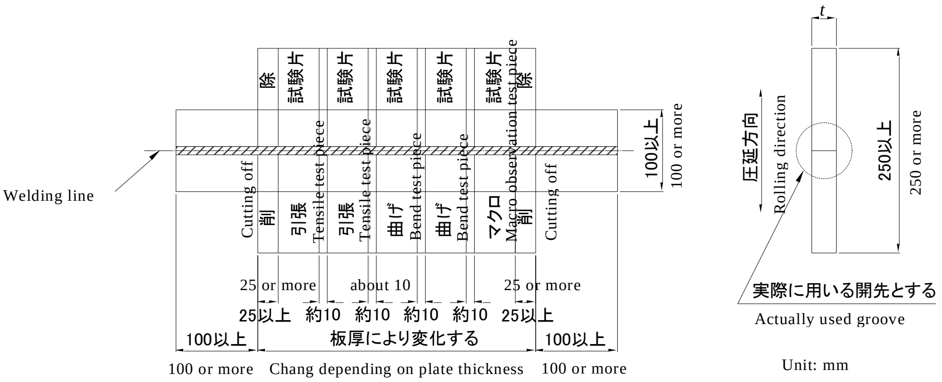


Figure 9.2.1 Specimen Used for Welding Tests for Complete Penetration Groove Welding

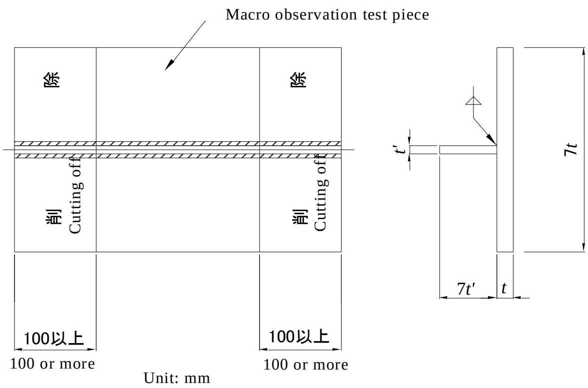


Figure 9.2.2 Specimen Used for Macro Observation for Fillet Welding

9.2.3 Testing Methods and Quality Criteria

(1) Non-Destructive Tests

1) Visual Inspection

The presence of surface defects in welds is visually inspected. The criteria for the surface defects in welds are shown in Table 9.2.2.

Table 9.2.2 Types of Surface Defects in Welds and Quality Criteria

Defect types	Parts to be inspected	Quality criteria
Cracks	Overall length of joints	Free of cracks. If in doubt, they are confirmed with a penetrant inspection test.
Pits on the weld bead surface (A small depression on the outer surface of welds)	Full penetration groove welded joints of main members	Free of pits.
	Fillet welded joints	Up to 3 per joint or 3 per 1 m joint length. If the pit size is 1 mm or less, three can be counted as one.
Unevenness on the weld bead surface	Overall length of joints	The height difference within the range of bead length of 25 mm must not exceed 3 mm.
Undercuts	The toe of the beads orthogonal to the primary stress acting on the pieces that make up main members	Allowable depth: 0.3mm
	The toe of the beads parallel to the primary stress acting on the pieces that make up main members	Allowable depth: 0.5mm
	The toe of the beads of secondary members	Allowable depth: 0.8mm
Overlaps	Overall length of joints	Free of overlaps.
Size of fillet welds	Overall length of joints	The size and throat thickness should not be less than the design values.

2) Radiographic Test

i) The test method complies with JIS Z 3105[1)].

ii) For welds subjected to tensile stress, the flaws for Grades 1 and 2 are accepted. For welds subjected to compressive stress, the flaws for Grade 3 or above are accepted. When affected by fatigue, the flaws for Grade 1 are accepted for both cases of tensile and compressive stresses.

(2) Destructive Tests

1) Tensile Test

i) The tensile test piece shall be the one specified in JIS Z 3121[2)]. The weld is placed in the center of the parallel part of the tensile test piece. The front and back surfaces of the tensile test piece shall be finished in the same way as the product.

ii) The tensile test method complies with JIS Z 2241[3)]. The stress acting on a tensile test piece is defined as the load divided by the cross-sectional area of the base material in the parallel part of the tensile test piece.

iii) The number of test pieces shall be two, and the tensile strength and 0.2% proof stress of each tensile test piece shall be the values shown in Table 9.2.3 or above.

Table 9.2.3 Tensile Strength and 0.2% Proof Stress of Welds

Aluminum alloys		Thickness t (mm)	Tensile strength (N/mm²)	0.2% proof stress (N/mm²)
Plates	A5083-H112	$4 \leqq t \leqq 40$	275	125
	A5083-O	$3 \leqq t \leqq 40$	275	125
	A6061-T6	$3 \leqq t \leqq 6.5$	165	105
	A6061-T651	$6.5 \leqq t \leqq 40$	165	105
Extrusions	A5083-H112	$3 \leqq t \leqq 40$	275	120
	A5083-O	$3 \leqq t \leqq 38$	275	120
	A6061-T6	$3 \leqq t \leqq 40$	165	105
	A6005C-T5	$3 \leqq t \leqq 6$	165	105
		$6 < t \leqq 12$	165	105
	A6005C-T6	$3 \leqq t \leqq 6$	165	105

2) Bend Test

i) The bend test piece is among those specified in JIS Z 3122[4)], and is the root bend test piece if the plate thickness is less than 19 mm and is the transverse side bend test piece if it is 19 mm or more. The weld is placed in the center of the test piece. The surface of the test piece that comes into contact with a bending fitting is finished flat. The reinforcement on the surface to be tested is deleted.

ii) The bend test method is one of the roller bend test, guided bend test and draw bend test specified in JIS Z 3122[4)]. The radius of a bending fitting in the bend test should be less than or equal to the value calculated by the following equations:

For A5083-H112 and A5083-O alloys,

$$R = 2.88t \tag{9.2.1}$$

For A6061-T6, A6061-T651, A6005C-T5 and A6005C-T6 alloys,

$$R = 4.75t \tag{9.2.2}$$

where

R = radius of a bending fitting

t = thickness of a bending test piece

iii) The number of test pieces shall be two, and each test piece shall not have surface cracks with a length of more than 3 mm unless it is affected by fatigue. If it is affected by fatigue, it shall be free of surface cracks.

3) Macro Observation

i) The test method complies with 7.4.4 of JIS Z 3422-2[5)].

ii) In macro observation, the macrostructure of welds shall be free of defects that are perceived as harmful.

1) JIS Z 3105: Methods of radiographic examination for welded joints in aluminum, 2003.

2) JIS Z 3121: Methods of tensile test for butt welded joints, 2013.

3) JIS Z 2241: Metallic materials-Tensile testing-Method of test at room temperature, 2011.

4) JIS Z 3122: Methods of bend test for butt welded joint, 2013.

5) JIS Z 3422-2: Specification and qualification of welding procedures for metallic materials-Welding procedure test-Arc welding of aluminum and its alloys, 2003.

9.2.4 Setting of Pieces

(1) The setting of pieces must be done so that welding defects do not occur and the eccentricity between members after welding does not occur.

(2) The setting of pieces is as follows:

1) Full penetration groove welded joints

i) The groove shape and root spacing are based on JIS Z 3604[1].

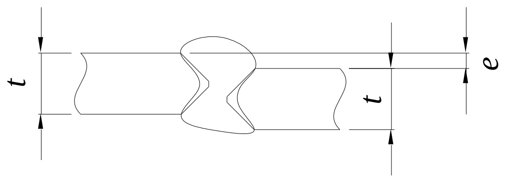
ii) The eccentricity *e* between pieces in the direction of the thickness shown in Figure 9.2.3(a) is 10% or less of the thickness *t*.

iii) The gap *e* between the backing strip and the piece shown in Figure 9.2.3(b) should be 0.5 mm or less.

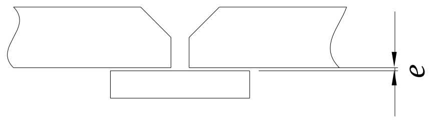
2) Fillet welded joints

i) The gap between pieces is based on JIS Z 3604[1].

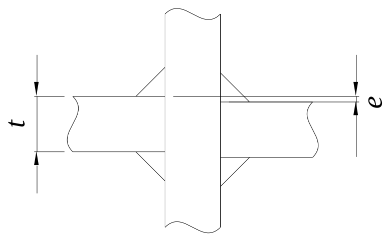
ii) The eccentricity *e* between pieces in the cruciform joints and T-joints shown in Figure 9.2.3(c) is 15% or less of the thickness *t*.



(a) Eccentricity between Pieces in the Thickness Direction



(b) Gap between Backing Strip and Piece



(c) Eccentricity between Pieces in Cruciform Joint and T-Joint

Figure 9.2.3 Setting of Pieces

1) JIS Z 3604: Recommended practice for inert gas shielded arc welding of aluminum and aluminum alloys, 2016.

9.2.5 Tack Welding

(1) When assembling members, auxiliary jigs are effectively used to enable tack welding in a posture with good conditions. The tack welding of dissimilar materials such as struts and strongbacks to a base material is avoided as much as possible.
(2) The black powder and oxide film generated by tack welding are removed before primary welding.
(3) It is confirmed that the length and throat thickness for tack welding are not too small.
(4) In tack welding, the preflow and crater treatment are sufficiently performed.

9.2.6 Correction of Welding Deformation

The deformation of members caused by welding is corrected by pressing, hydraulic jack or gas flame heating method. Table 9.2.4 shows the maximum heating temperature that can be applied to aluminum alloy materials when the deformation of members is corrected by a gas flame heating method.

Table 9.2.4 Maximum Heating Temperature

Aluminum alloys	Maximum heating temperature
A5083-O	450℃ or less
A5083-H112	350℃ or less
A6061-T6 A6005C-T5 A6005C-T6	250℃ or less

9.2.7 Fabrication

(1) In fabrication, the welding conditions that are determined by the welding tests to meet the quality criteria shall be used.
(2) The interpass temperature should be below the temperature determined in the welding tests.
(3) During fabrication, the weld inspection of a product must be performed according to 9.2.8.
(4) If welds do not meet the quality criteria for the weld inspection of a product, repair may be performed according to 9.2.9.
(5) End tub
  1) In full penetration groove welding, end tubs made of the same material as the base material and having the same groove shape as the base material are provided at the start and end of the welding. In fillet welding of a flange to a web of a main girder, end tubs of T-shaped cross-section, which are the same material as the base material and have the same cross-sectional shape as the base material, are provided at the start and end of the welding. By providing end tubs, the start and end of the welding do not enter a member.
  2) After welding, end tubs are cut and removed, and the remaining parts are polished with a grinder to finish smoothly.
(6) Fillet welding

1) If an additional welding rod is needed, the crater treatment shall be performed. If cracks are observed at the place where a welding rod is added, the end of the bead is removed, and after confirming that there are no defects, the next welding is done.

2) Welding is turned at the corners of a piece.

(7) Reinforcement and finish in full penetration groove welding

The height of reinforcements in full penetration groove welding without finish designation is according to Table 9.2.5. When affected by fatigue, the height of reinforcements and the finish shown in Table 8.5.3(a), (b) and (c) are followed.

Table 9.2.5 Height of Reinforcements

Thickness t (mm)	Height of reinforcements (mm)
$3 \leq t \leq 6$	2 or less
$6 < t \leq 15$	$t/3$ or less
$15 < t \leq 25$	5 or less
$25 < t$	7 or less

9.2.8 Weld Inspection of Product

(1) Visual inspection is performed on the overall length of full penetration groove welded joints and fillet welded joints.

(2) A radiographic test is performed on full penetration groove welded joints according to the following 1) and 2):

1) For factory welding, the sampling inspection shown in Table 9.2.6 is performed.

Table 9.2.6 Radiographic Test of Full Penetration Groove Welded Joints

Members			Inspection target	Number of shots
Tensile member			All joints	1 (End included)
Compression member			1 or more out of 5 joints*	1 (End included)
Bending member	Tensile flange		All joints	1 (End included)
	Compressive flange		1 or more out of 5 joints*	1 (End included)
	Web	Joints perpendicular to normal stress	All joints	1 (Tension side)
		Joints parallel to normal stress	All joints	1 (End included)
Aluminum deck			All joints	1 (End included)

*: If unsuccessful, all remaining joints are inspected.

2) For site welding, the overall length of joints is inspected.

(3) The visual inspection and radiographic test and the quality criteria are in accordance with 9.2.3.

9.2.9 Repair

(1) Joints that fail the visual inspection may be repaired according to (3). The repaired part must satisfy 9.2.3(1) 1).

(2) For a full penetration groove welded joint that fails the radiographic test, the overall length of the joint is inspected by the radiographic test to identify the range of defects and they may be repaired according to (3). The repaired part must satisfy 9.2.3(1) 2).

(3) Table 9.2.7 shows repairing methods for defects. The length of the weld bead to be repaired is 40 mm or more.

Table 9.2.7 Repairing Methods for Defects

Defect types	Repairing method
Crack	Completely remove cracks and weld.
Blowhole	Welding is performed after scraping.
Overlap	Grind with a grinder to make it smooth.
Undercut	Depending on the degree, grinder finish only or after welding grinder finish.
Pit on the weld bead surface	Depending on the need, finish the surface or weld.
Unevenness on the surface of weld beads	Finish with a grinder.

9.3 Friction Stir Welding

9.3.0 Definition of Terms

(1) Backing member

A supporting member provided on the back side of a metal piece during welding (See Figure 9.3.1).

(2) Double-sided friction stir welding

A joint obtained by performing friction stir welding as shown in Figure 9.3.1, then turning it over and performing friction stir welding from the opposite surface.

(3) Face bend test piece

In the case of friction stir welding shown in Figure 9.3.1, a test piece in which the surface opposite to the tool insertion side contacts with a bending fitting in the bend test. In the case of double-sided friction welding, a test piece in which the surface opposite to the tool insertion side in the first friction stir welding contacts the bending fitting in the bend test.

(4) Joint finishing conditions

Finishing conditions for the front and back surfaces of a joint.

(5) First product

In fabrication, the friction stir welded block made first.

(6) Friction stir welding

As shown in Figure 9.3.1, the friction stir welding uses a rotation tool that is inserted in the butt-joining line between two metal pieces. The rotation of the tool generates frictional heat inducing plastic flow of the metal, and by moving the tool along the butted surfaces, a joint is created.

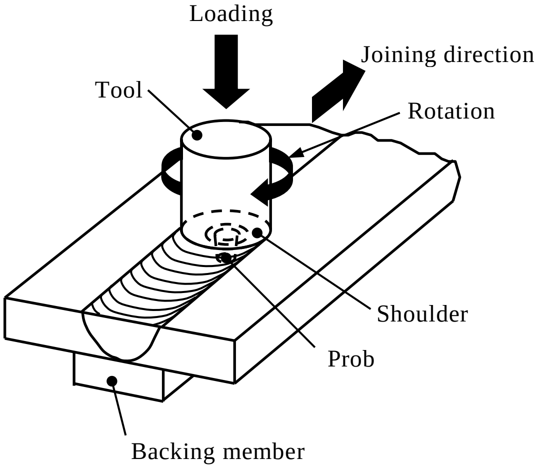


Figure 9.3.1 Friction Stir Welding

(7) Friction stir welded block

A block that has joining lines in the same direction in fabrication and that does not undergo any further friction stir welding (See Figure 9.3.2).

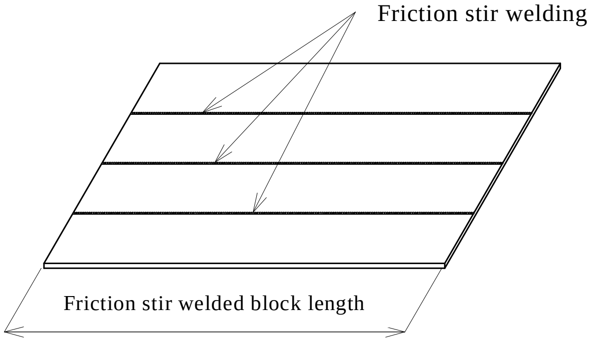


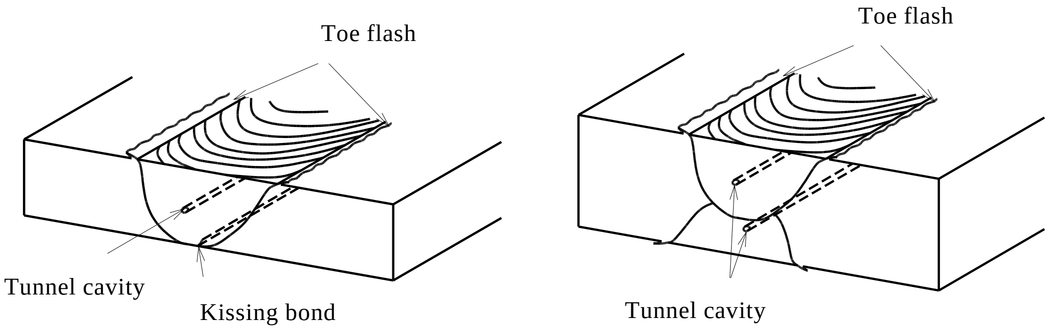
Figure 9.3.2 Friction Stir Welded Block

(8) Friction stir welded block length

The length of the friction stir welded block in the joining direction (See Figure 9.3.2).

(9) Kissing bond

Incompletely joined part that occurs near the tip of the probe due to insufficient stirring in friction stir welding [See Figure 9.3.3 (a)].



(a) Friction Stir Welding Shown in Figure 9.3.1 (b) Double-Sided Friction Stir Welding

Figure 9.3.3 Defects in Friction Stir Welded Joints

(10) Prob

The tip part of the tool that is inserted into the butted surfaces of a base metal and causes plastic flow in the base metal (See Figure 9.3.1).

(11) Root bend test piece

In the case of friction stir welding shown in Figure 9.3.1, a test piece in which the surface on the tool insertion side contacts a bending fitting in the bend test. In the case of double-sided friction welding, a test piece in which the surface on the tool insertion side in the first friction stir welding contacts the bending fitting in the bend test.

(12) Shoulder

A part of the tool that does not enter the butted surfaces but rubs with the metal surface (See Figure 9.3.1).

(13) Toe flash

A thin ridge that occurs on both sides of the joint surface (See Figure 9.3.3).

(14) Tool

A tool that generates frictional heat in the metal by rotation and causes plastic flow in the metal. It consists of a probe and a shoulder (See Figure 9.3.1).

(15) Tunnel cavity

A type of internal defect at the joint, and an elongated tunnel-shaped cavity that occurs in the direction of the joining line (See Figure 9.3.3).

(16) Welding conditions

Conditions for friction stir welding such as the shape of the tool and the rotational speed, traveling speed and inclination of the tool.

9.3.1 General

(1) When performing friction stir welding, it is not necessary to remove the oxide film at joints.

(2) The throat thickness of joints should not be less than the theoretical throat thickness.

(3) When affected by fatigue, double-sided friction stir welding shall be used.

9.3.2 Welding Tests

(1) The welding tests must be performed before fabrication. However, if the welding tests were conducted in the past and there are fabricating experiences, they can be omitted by consultation between the parties.

(2) In the welding tests, non-destructive tests of visual inspection, ultrasonic flaw detection test and radiographic test, and destructive tests of tensile test, bend test, macro and micro observations are performed. When affected by fatigue, fatigue tests are carried out in addition to those.

(3) The material and cross-sectional shape of the specimen used in the welding tests should be the same as those used in actual fabrication. As shown in Fig. 9.3.4, the length of the specimen shall be longer than the friction stir welded block length of a product.

(4) The non-destructive tests are performed before the test pieces for the destructive tests are collected from the specimen. The visual inspection and the ultrasonic flaw detection test are performed on the overall length of the joint of the specimen with the excessive length cut off. The radiographic test is performed at the end on the side where the friction stir welding starts, of the joint of the specimen with the excessive length cut off.

(5) As shown in Figure 9.3.4, the tensile test piece, the face bend test piece, the root bend test piece and the macro and micro observation test piece are collected in the direction perpendicular to the joining line of the friction stir welding from both ends and the middle part of the specimen with the excessive length cut off. When affected by fatigue, if the load acts in the direction perpendicular to the joining line, the fatigue test piece T is collected, and if the load acts in the direction of the joining line, the fatigue test piece L is collected. If the load acts in both directions, both fatigue test pieces T and L are taken. The number of test pieces in each part is 1 for tensile test, 1 for face bend test, 1 for root bend test, 1 for each of fatigue tests for T and L and 1 for the macro and micro observation test. When collecting the test pieces, a space of about 10 mm between the test pieces is left.

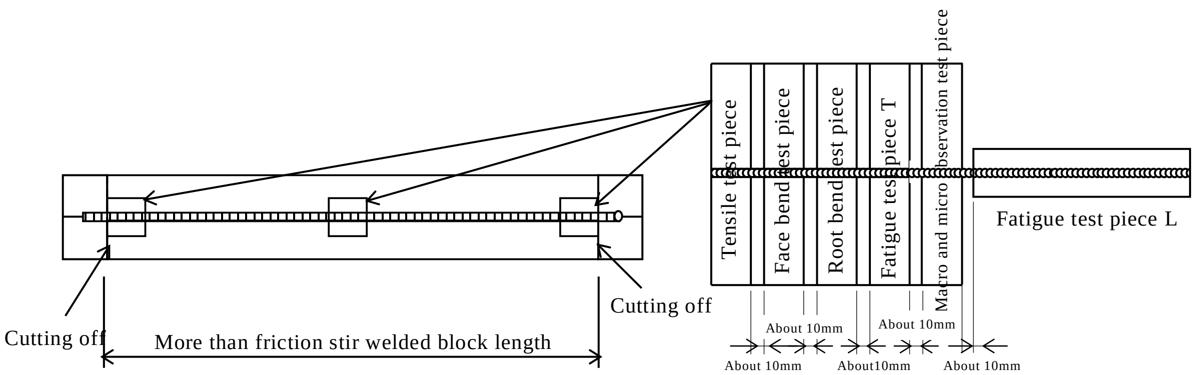


Figure 9.3.4 Specimen Used for Welding Tests

(6) The test methods for non-destructive testing and destructive testing and the quality criteria are in accordance with 9.3.3.

9.3.3 Testing Methods and Quality Criteria

(1) Non-Destructive Tests

1) Visual Inspection

After friction stir welding, the presence of surface defects in joints is visually inspected. The criteria for the surface defects in joints is decided through consultation between the parties.

2) Ultrasonic Flaw Detection Test

i) The test method complies with JIS Z 3080[1)].

ii) When not affected by fatigue, the flaws for Grades 1 and 2 in Class C are accepted. When affected by fatigue, the flaws for Grade 1 in Class C are accepted.

3) Radiographic Test

i) The test method complies with JIS Z 3105[2)].

ii) When not affected by fatigue, the flaws for Grades 1 and 2 are accepted. When affected by fatigue, the flaws for Grade 1 are accepted.

(2) Destructive Tests

1) Tensile Test

i) The tensile test piece shall be the Type 14B specified in JIS Z 2241[3)]. The friction stir welded joint is placed in the center of the parallel part of the tensile test piece. The front and back surfaces of the tensile test piece shall be finished in the same way as a product.

ii) The tensile test method complies with JIS Z 2241[3)]. The stress acting on a tensile test piece is defined as the load divided by the cross-sectional area of the base material in the parallel part of the tensile test piece.

iii) If the tensile strength and 0.2% proof stress of each of the three tensile test pieces are the values shown in Table 9.2.3 or above, the test is accepted.

2) Bend Test

i) The face bend test piece and the root bend test piece shall be the Type 1 specified in JIS Z 2248[4)]. The friction stir welded part is placed in the center of the test piece. The surface of the test piece that comes into contact with a bending fitting should be finished flat. The surface finish of the face bend test piece and the root bend test piece to be tested shall be the same as a product. If it is difficult to bend the test piece due to the original thickness, the back side of the face bend test piece and the front side of the root bend test piece is scraped to make a test piece with a plate thickness of 8 mm. If the original thickness is smaller than 8 mm, the original thickness is taken as the thickness of the test piece.

ii) The bend test method shall be the pressing bend method or the winding bend method specified in JIS Z 2248[4)]. The radius of a bending fitting in the bending test shall be less than or equal to the value calculated by the following equations:

For A5083-H112 and A5083-O alloys,

$$R = 2.88t \quad (9.3.1)$$

For A6061-T6, A6061-T651, A6005C-T5 and A6005C-T6 alloys,

$$R = 4.75t \quad (9.3.2)$$

where

R = radius of a bending fitting

t = thickness of a bending test piece

iii) When not affected by fatigue, all three of the face bend test pieces and those of the root bend test pieces shall not have surface cracks longer than 3 mm. When affected by fatigue, there should be no surface cracks.

3) Fatigue Test

i) The standard shape and dimensions of fatigue test pieces are shown in Figure 9.3.5. In the fatigue test piece T shown in Figure 9.3.5 (a), the joining line is placed at the center of the parallel part of the test piece, perpendicular to the axis of the test piece. In the fatigue test piece L shown in Figure 9.3.5 (b), the joining line is placed in the axial direction of the test piece, and the joining center is aligned with the center of the parallel part of the test piece. The front and back surfaces of the fatigue test piece shall be finished in the same way as a product. Both sides of the fatigue test piece are finished so that streaks remain in the longitudinal direction of the test piece. The width *w* of the parallel part of the fatigue test piece T shall be at least twice the plate thickness *t*. The width *w* of the fatigue test piece L shall be greater than or equal to the larger value in comparing the value obtained by adding 10 mm to the diameter of the shoulder (the larger diameter if the diameter of the shoulder of the first friction stir welding and that of the second friction stir welding are different in double-sided friction stir welding) and the value obtained by doubling the plate thickness *t*.

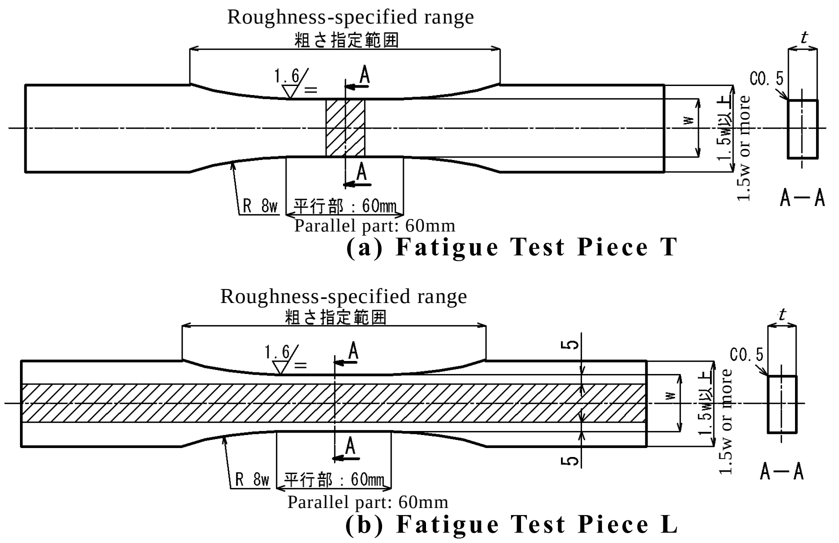


Figure 9.3.5 Shape and Dimensions of Fatigue Test Pieces

ii) The stress acting on the fatigue test piece is defined as the load divided by the cross-sectional area calculated by multiplying the plate thickness of the base material by the width of the parallel part of the fatigue test piece.

iii) The maximum stress applied to each of the three fatigue test pieces is 133 N/mm^2, and the minimum stress is 13 N/mm^2.

iv) If the fatigue life (the number of cycles the load is repeated until the fatigue test piece breaks) of each of the three fatigue test pieces is 1.7×10^5 cycles or more and the fatigue life of each of the two fatigue test pieces is 6.7×10^5 cycles or more, the test is accepted.

4) Macro and Micro Observation

i) The observation method complies with 7.4.4 of JIS Z 3422-2[5].

ii) In macro observation, the macrostructure of the joint should be free of tunnel cavities and of other perceived harmful defects.

1) JIS Z 3080: Methods of ultrasonic angle beam examination for butt welds of aluminum plates, 1995.
2) JIS Z 3105: Methods of radiographic examination for welded joints in aluminum, 2003.
3) JIS Z 2241: Metallic materials-Tensile testing-Method of test at room temperature, 2011.
4) JIS Z 2248: Metallic materials-Bend test, 2006.
5) JIS Z 3422-2: Specification and qualification of welding procedures for metallic materials-Welding procedure test-Arc welding of aluminum and its alloys, 2003.

9.3.4 Fabrication

(1) In fabrication, the welding conditions and the joint finishing conditions that are determined by the welding tests to meet the quality criteria must be used.

(2) During fabrication, the weld inspection of a product must be performed according to 9.3.5.

(3) If the joint does not meet the quality criteria for the weld inspection of a product due to tool wear, power failure, etc. during fabrication, repair may be performed only if 9.3.6 is satisfied. Repairs shall be carried out under the same conditions as the welding conditions and the joint finishing conditions determined by the welding tests.

(4) The starting end of the friction stir welding where the probe is inserted and the terminating end of the friction stir welding where the probe is pulled out are cut off.

9.3.5 Weld Inspection of Product

(1) In the weld inspection of a product, the visual inspection and the ultrasonic flaw detection test are performed.

(2) The visual inspection is performed on the overall length of the joints.

(3) The range of the ultrasonic flaw detection test is as follows:

1) In the first product, the overall length of the joints of the friction stir welded block.

2) After the first product, the 200 mm ranges at both ends and at the middle of the friction stir welded block, as shown in Figure 9.3.6.

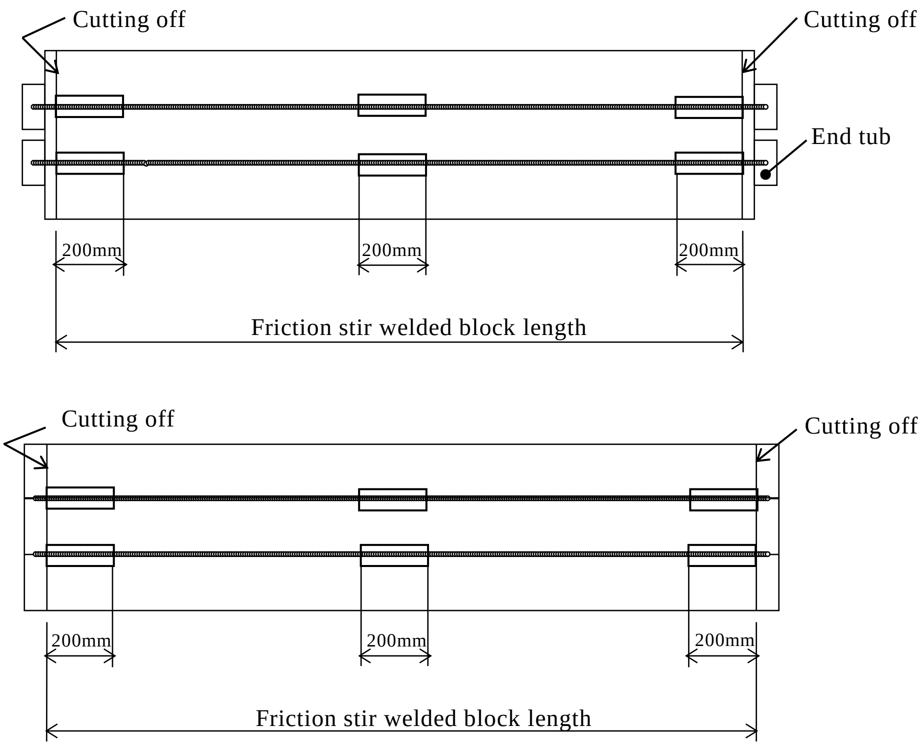


Figure 9.3.6 Scope of Ultrasonic Flaw Detection Test for Friction Stir Welded Blocks After First Product

(4) The test methods and the quality criteria for visual inspection and ultrasonic flaw detection test comply with 9.3.3 (1).

9.3.6 Repair

(1) When repairing, re-heat input may cause the strength of the joint to decrease. Therefore, it must be confirmed by the welding tests that the repaired joint passes the destructive tests in 9.3.3 (2).
(2) As a specimen for the test pieces used for the destructive tests of the repaired joint, the specimen in which friction stir welding is performed again on the surplus portion after the test pieces for the destructive tests are collected from the specimen used for the welding tests (See Figure 9.3.4) may be used.
(3) If the repaired joint does not pass the destructive tests of 9.3.3 (2), the product shall not be repaired.
(4) The weld inspection of product for the friction stir welded block that is repaired shall be the same as the first product.

9.4 High-Strength Bolted Friction-Type Joints

9.4.1 General

(1) Steel high-strength bolts that are long enough to tighten members shall be used.
(2) Steel high-strength bolts were used once shall not be reused.

9.4.2 Treatment of Friction-Surface

(1) Either or both in the friction-surfaces facing each other where a base material and a connection plate are in contact are blasted so that the surface roughness is Rz20 μm or more.

(2) When blasting connection plates, it is done on the inner area 5 mm away from the edge of a connection plate, as shown in Figure 9.4.1.

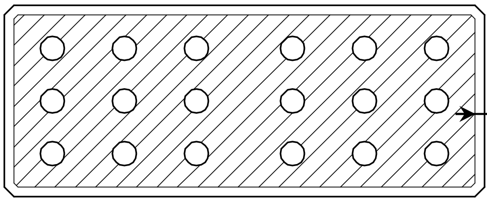


Figure 9.4.1 Range of Blast on Connection Plate (Hatching Part)

9.4.3 Tightening Bolts

(1) Table 9.4.1 shows the design bolt axial force of steel high-strength bolts used for friction-type connection.

Table 9.4.1 Design Bolt Axial Force

Bolt grades	Designation of bolts	Design bolt axial force (kN)
F8T	M12	45.9
	M16	85.4
	M20	133
	M22	165
	M24	192
F10T	M12	56.9
	M16	106
	M20	165
	M22	205
	M24	238

(2) Tightening of hot-dip galvanized steel high-strength bolts is performed in two steps: preliminary tightening and final tightening. The final tightening is done by the nut rotation method so that the design bolt axial force of F8T can be obtained.

1) Table 9.4.2 shows the tightening torque values for preliminary tightening.

Table 9.4.2 Torque Values for Preliminary Tightening

Designation of bolts	Torque values for preliminary tightening (N･m)
M12	About 50
M16	About 100
M20, M22	About 150
M24	About 200

2) After preliminary tightening, marking of the nuts, bolts, washers and pieces to be fastened is done.
3) For final tightening, the nut is rotated 90°, starting from the completion of preliminary tightening.
4) It is confirmed that the rotation angle of the high-strength bolt that is fully tightened is in the range of +30° to −0° with respect to the rotation amount of 90°. If the bolt is tightened beyond the range, it is replaced. For the bolt that does not reach the range, it is tightened up to the required nut rotation amount.
5) The nut, bolt and washers that rotate together shall be replaced.

(3) Fluororesin-coated steel high-strength bolts are tightened in two steps: preliminary tightening and final tightening. The final tightening is done by the torque control method so that an axial force that is 10% higher than the design bolt axial force of F10T can be obtained.
1) Before the tightening work, the torque coefficient of the bolt sets to be used is measured.
2) The preliminary tightening is performed up to about 60% of the tightening bolt axial force.
3) After preliminary tightening, marking of the nuts, bolts, washers and pieces to be fastened is done.
4) The bolt axial force in final tightening shall be 10% higher than the design bolt axial force.
5) The nut, bolt and washers that rotate together are replaced.
6) The bolt axial force is introduced by turning a nut. If it is unavoidable to turn the head, the change in the torque coefficient must be checked.

(4) The bolts are tightened from the center to the end of a connection plate, and after a series of preliminary tightening, the final tightening is performed.

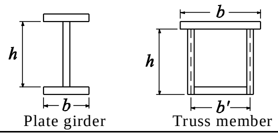
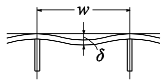
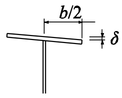
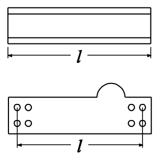
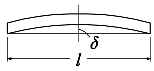
9.4.4 Durability and Corrosion Protection

The durability and anticorrosion performance of friction-type joints for aluminum alloy plates fastened with fluororesin-coated steel high-strength bolts are determined through consultation between the parties, taking into consideration the environment in which a structure is placed and the location where joints are provided in the structure.

9.5 Tolerance of Members

The tolerance of members is shown in Table 9.5.1.

Table 9.5.1 Tolerance of Members

<table>
<tr><th colspan="2">Items</th><th>Tolerance (mm)</th><th>Notes</th><th>Measurement items</th></tr>
<tr><td colspan="2">Flange width b (m)
Web height h (m)
Web spacing b' (m)</td><td>±2 $b \le 0.5$
±3 $0.5 < b \le 1.0$
±4 $1.0 < b \le 2.0$
$\pm(3+b/2)$ $2.0 < b$</td><td>b in the left column is representative of b, h and b'.</td><td>
</td></tr>
<tr><td rowspan="2">Flatness of plate
δ (mm)</td><td>Web of members such as plate girders and trusses</td><td>$h/250$</td><td>h : web height (mm)</td><td rowspan="2">
</td></tr>
<tr><td>Flange such as box girder and truss, and deck plate</td><td>$w/150$</td><td>w : web or rib spacing (mm)</td></tr>
<tr><td colspan="2">Right angle of flange δ (mm)</td><td>$b/200$</td><td>b : flange width (mm)</td><td>
</td></tr>
<tr><td rowspan="2">Member length
l (m)</td><td>Plate girder</td><td>±3 $l \le 10$
±4 $l > 10$</td><td rowspan="2"></td><td rowspan="2">
</td></tr>
<tr><td>Truss, arch, etc.</td><td>±2 $l \le 10$
±3 $l > 10$</td></tr>
<tr><td colspan="2">Deformation of compression member
δ (mm)</td><td>$l/1000$</td><td>l : member length (mm)</td><td>
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Appendix A Slip Test Method for Friction-Type Joints for Aluminum Alloy Plates

A.1 Scope of Application

A test method for determining the slip coefficient of friction-type joints for aluminum alloy plates fastened with fluororesin-coated steel high-strength bolts is specified.

A.2 Test pieces

(1) Table A.1 shows an example of the shape and dimensions for a test piece using F10T fluororesin-coated steel high-strength bolts. This corresponds to the case where plates of A6061-T6 and A6061-T651 alloys and extrusions of A6061-T6 and A6005C-T6 alloys are used for a base material and connection plates. The test piece shall be the joints with two friction-surfaces. Table A.1(a) corresponds to the case where the number of bolts on one side is two, and Table A.1(b) corresponds to the case where the number of bolts on one side is one. In the latter case, the bolts are fastened so that the axis of the test piece is straight.

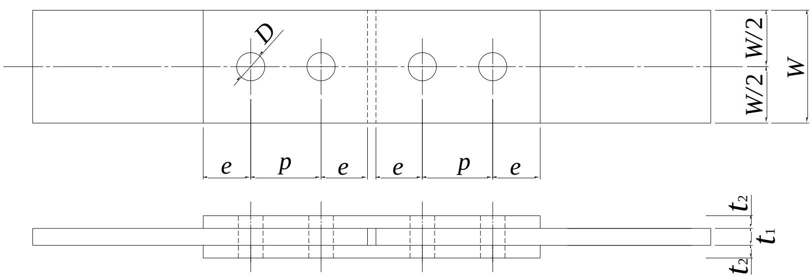
(2) The number of test pieces shall be 5 or more.

(3) The treatment of the friction-surface follows 9.4.2.

(4) Bolts are fastened by the torque control method, and the bolt axial force with 10% increase of the design bolt axial force (See Table 9.4.1) is introduced.

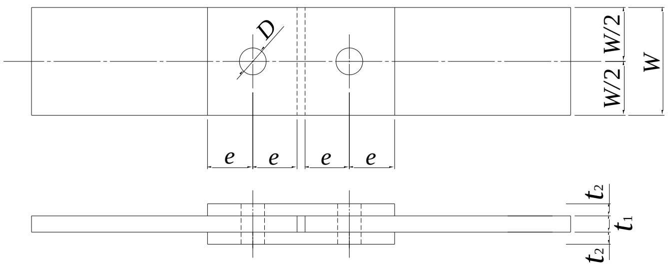
Table A.1 Example of Shape and Dimensions of Test Piece

(a) When the Number of Bolts on One Side is Two



Nominal diameter of bolts d (mm)	Diameter of bolt holes D (mm)	Thickness of base material t_1 (mm)	Thickness of connection plates t_2 (mm)	Plate width W (mm)	e (mm)	p (mm)
12	15	12	8	75	35	40
16	19	20	12	90	40	50
20	23	25	15	110	50	60
22	25	30	20	110	55	70
24	27	35	20	110	60	80

(b) When the Number of Bolts on One Side is one



Nominal diameter of bolts d (mm)	Diameter of bolt holes D (mm)	Thickness of base material t_1 (mm)	Thickness of connection plates t_2 (mm)	Plate width W (mm)	e (mm)
12	15	8	6	60	35
16	19	10	8	90	40
20	23	12	8	110	50
22	25	15	10	110	55
24	27	20	12	110	60

A.3 Test Method

(1) The slip test is performed after the sudden decrease in bolt axial force due to creep of aluminum alloy plates and fluororesin film immediately after bolt tightening is completed.

(2) The time from the bolt fastening to the slip test, the temperature of the test piece when the bolt is fastened and the one when the slip test is performed, are measured.

(3) The difference between the temperature of the test piece when the slip test is performed and the one when the bolt is fastened should be within ±10°C.

(4) The relationship between the load and the difference in displacement between the cross heads of the tensile tester, the relationship between the load and the displacement indicated by the displacement meter built into the tensile tester, or the relationship between the load and the elapsed time is recorded. In each relationship, the load immediately before the load first drops is defined as the slip load.

A.4 Slip Coefficient

The slip coefficient of each test piece is calculated by the following equation:

$$\mu = \frac{P}{2nN_0} \tag{A.1}$$

where

μ = slip coefficient

P = slip load

n = number of bolts on one side (= 1 or 2)

N_0 = initially introduced bolt axial force [the bolt axial force with 10% increase of the design bolt axial force (See Table 9.4.1)]