Study on Bending Strength of Web-Bolted Moment Joints of Aluminum Alloy Beam Exposed to Fire

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ABSTRACT

This study narrows the application temperature field of aluminum alloy to 350 °C or less, and examines the strength of web-bolted moment joints within that temperature range. Bending strength of web-bolted moment joints of aluminum alloy exposed to fire is investigated experimentally and analytically. It is observed that if splice plate length and the beam section are designed appropriately, it is possible that maximum bending strength is fully realized with the web-bolted moment joints. The transmission mechanism of the bending moments is thought to be based on prying action between the flanges and splice plate side edge. The effect of prying action contributes to the maximum bending strength. Maximum bending strength ratio is 90-60 %.

KEYWORDS: aluminum alloy beam, web-bolted joint, prying action, structural design, bending strength, FEM.

NOMENCLATURE LISTING

В	width of H and DW beam (mm)	$_{i}q_{x}$	prying force of prying element on splice plate portion in x direction (kN)
d	prying element length (mm)	j q x	prying force of prying element on web portion in x direction (kN)
Η	height of H and DW beam (mm)	$_{i}q_{y}$	prying force of prying element on splice plate portion in y direction (kN)
h_1	distance from upper flange face to center of upper bolt hole (mm)	$_{j}q_{y}$	prying force of prying element on web portion in y direction (kN)
h_2	distance from upper flange face to center of lower bolt hole (mm)	t_w	web thickness (mm)
Μ	bending moment $(kN \cdot m)$	t_f	flange thickness (mm)
M_P	peak bending moment (kN·m)	Greek	
P_{BU}	bearing force of upper bolt on web portion (kN)	δ	displacement (mm)
P_{BL}	bearing force of lower bolt on web portion (kN)	θ	deflection slope angle
D	communication former of floring contract (IN)	subscri	pts
P_C	compression force of mange contact (kiv)	В	bearing
P_{LC}	prying force between upper flange and splice plate on center side (kN)	С	compression
P_{LE}	prying force between upper flange and splice plate on edge side (kN)	L	prying
		Р	peak

INTRODUCTION

This study investigates the use of beams in atriums and pool roofs as architectural structures which employ aluminum alloys, and especially consider the transfer of the bending moments of beam joints exposed to fire. A temperature range of 20 °C to 350 °C is investigated; heating of specimens is by the use of an electric furnace.

Traditionally, the purpose of friction joints of beams has been to provide rigidity. These joints have a highstrength bolt going through splice plates, flanges and webs of H-beam steel beam sections (see Fig. 1a and Fig. 2). However, this type of joint is difficult to design and construct, because it is affected by bending moments (see Fig. 1b). It is possible to control the bending moment by using the web-bolted moment joint shown in Fig. 3. This type of joint has already been proposed [1]. In Fig. 3, the web-bolted moment joint connects only the web sections with high-strength bolts through the splice plates; the flange is not connected.

In an experiment of a steel H-beam [1], this connection was shown to adequately transmit bending moments. However, the direction of the bolt shearing force is different from that of a conventional bolt joint connection [2], which is the vertical direction. Consequently, in the web-bolted joint, the shearing force acts parallel to the axis of the member, and the splice plates are therefore bent as a result [3].









Fig. 3. Web-bolted moment joint in H-shape steel beam.

PURPOSE OF THIS STUDY

This study examines web-bolted moment joints made from aluminum alloy members. Examples are shown in Fig. 4 [4] and Fig. 5. In the web-bolted moment joints, the heights of the splice plates can be varied to depths that are within 1mm between the beam flanges and the edges of the splices. This lower gap limit allows considerable enhancement of the joint by increasing the height of the plate, unlike steel members. Therefore, the web-bolted moment joint is a method for beams extruded with high accuracy, such as with aluminum alloy beams. To use these connections in hollow beam sections, the splice plates are inserted without gaps, as shown in Fig. 5.

It is also easy to form the hollow section in aluminum alloy members instead of the H-steel beam that is commonly used. This joint method is referred to as a web-bolted moment joint of a double web-beam of aluminum alloy.



Fig. 4. Aluminum H-beam with web-bolted moment joint.



Fig. 5. Aluminum double web-beam with web-bolted moment joint.

In the fire case, good structural performance is expected from the frame, and the connection is not expected to fail prematurely before the frame collapse temperature [5]. Therefore, it is necessary to understand the maximum bending strength and the fracture properties of the joints in fire-engineering designs. However, there are no studies focusing on the maximum bending strength in beams subjected to the heat of a fire, although there have been studies on the tensile components of high-strength bolt friction joints in aluminum alloy members [7] and tensile tests at high temperatures [5].

This study narrows the application temperature field of aluminum alloy to 350 °C or less, and examines the transformation of strength properties in web-bolted moment joints. The purpose of the study is to clarify the fracture properties in fire engineering designs of an aluminum alloy structures with maximum bending moments in the joints.

EXPERIMENT AND ANALYSIS

A bending strength experiment was conducted to clarify the maximum bending strength and fracture properties of the web-bolted moment joint for the H-beam [4] and double web-beam at elevated temperatures. The beam length was 600 mm.

The bolt layouts of the joints are shown in Fig. 6 and the experimental conditions are listed in Tables 1 and 2. The lengths and temperatures of the section shape, the splice plates, the bolt layouts, and the beam material were considered as factors affecting the bending strength and transfer performance in the webbolted moment joints. The bolt layouts, the temperatures of the bolts, and the lengths of the splice plates are compared by varying the five factors affecting bending strength: the bolt layout, temperature, beam material, the double web-beam shape and the H-beam shape [3]. Figures 7a and b show the results of the double-web beam at room temperature and 300 °C, respectively. Figures 8a and b show the results of the H-beam.



Fig. 6. Bolt arrays of specimens (for one joint).

Splice plate length (mm)	Bolts array	Room temperature	200 °C	300 °C
No joint	No splice plate	B0-C0-T000	B0-C0-T200	B0-C0-T300
405	1 line 1 row	B1-CL-T000	B1-CL-T200	B1-CL-T300
405	2 line 1 row	B2-CL-T000	B2-CL-T200	B2-CL-T300
405	2 line 2 row	B4-CL-T000	B4-CL-T200	B4-CL-T300
245	2 line 1 row	B2-CS-T000	B2-CS-T200	B2-CS-T300

Table 1. Bending experimental conditions of double-web beam.

Table 2. Bending experimental conditions of H-beam [4].

Bolts array	RT	100 °C	200 °C	250 °C	300 °C	350 °C
No splice plate	B0-T000	B0-T100	B0-T200	B0-T250	B0-T300	B0-T350
2 line 2 row	B2-T000	B2-T100	B2-T200	B2-T250	B2-T300	B2-T350
2 line 4 row	B4-T000	B4-T100	B4-T200	B4-T250	B4-T300	B4-T350

In these figures, vertical axis shows the ratio between experimental moment and plastic one at room temperature and horizontal axis shows the ratio between experimental deflection slope angle and limited one 1/150 mm.



Fig. 7. Experimental result Double web-beam of: (a) room temperature; (b) 300 °C.

Fig. 8. Experimental result H-beam of: (a) room temperature; (b) 300 °C.

The Maximum Bending Strength and Factors Affecting the Strength

In the web-bolted moment joints of the double-web beam (excluding the joint of splice plate length 245 mm), at room temperature and at 300 °C, the maximum bending strength was found to be equal to the beam with no joints (See Figs. 7a and b).

In the H-beam, at room temperature the maximum bending strength occurred for the beam with no joints, although at 300 °C and 350 °C the beam with no joints had a bending strength of 70 % of the maximum bending strength of that up to 250 °C [4] (See Figs. 8a and b).

It was concluded that the splice plate length is a factor affecting the maximum bending strength. In the double-web beam, 150 mm in width between the two webs, it was concluded that the splice plate length was a factor affecting the maximum bending strength. The beam with splice plates 245 mm in length had about 70 % of the maximum bending strength of the beam that had a 405 mm splice (see Figs. 7a and b).

In summary, the length of the splice plate greatly influences the maximum bending strength. The effect of the bolt arrays is minimal, even though the bolt array was assumed to be a factor. The equal, maximum bending strength was as a result of either one row one step (1 bolt) or two step two rows (4 bolts) (see Fig. 7a).

Collapse Properties

The deflection of the H-beam [4], and double-web beam and the rotation angle were not affected by the presence or absence of joints when the temperature exceeded 300 °C, and the fracture was up to 0.16 (four times value of the allowable limit indicated in ISO834) (see Fig. 9 and Fig. 10).

The joints did not easily collapse at 300 °C or higher, although there were specimens that collapsed after reaching the maximum bending strength at room temperature up to 250 °C (see Fig. 11). It was clarified that the work hardening and elongation at 250 °C and below were smaller for the aluminum alloy compared with steel, as shown by tension tests at elevated temperature.

In the H- beam, edge of collapse of the web occurred for specimens at room temperature up to 250 $^{\circ}$ C [4] (see Fig.13). In the double-web beam, punching shear caused tensile collapse of the flange (see Fig. 11) and near the web fillet (see Fig. 12). At 250 $^{\circ}$ C or less, the concentrated stress easily causes brittle collapse.

Fig. 9. Photograph of 2 line 2 row at splice plate 300 °C in double web-beam experimental result.

Fig. 10. Photograph of 1 line 1 row at beam joint 300 °C in double web-beam experimental result.

Fig. 11. Photograph of 1 line 1 row at beam joint 200 °C in double web-beam experimental result.

Fig.12. Photograph of 1 line 1 row at beam joint edge 200 °C in double web-beam experiment result.

Fig. 13. Photograph of 2 line 4 row at beam joint 100 °C in H-beam experimental result [4].

Fig. 14. Photograph of 2 line 2 row at beam joint RT in H-beam experimental result[4].

Effect of Prying Action

At 200 °C or higher in the high-strength bolt friction joint in the aluminum alloy, the bolt axis force decreases and tensile strength decreases rapidly, this decreasing phenomenon has been previously reported [7].

Due to the decrease of axis force in the high-strength bolt because of the rise in temperature, prying action is generated, as a result of bearing between the splice plate and the flange (see Fig. 14). Therefore, positive transmission of the bending moment is predicted by the prying action and not by the bending moment in the joint. It is thought that it is advantageous to be able to reduce the gap between the splice plates side edge and the flange when prying action is used.

In this study, it was assumed that transfer of bending moment is possible by prying action, and modeling of the web bolted moment joint of the prying action of the aluminum alloy beam was considered (see Fig. 15).

O This indicates are contact of beam flange and splice plate.

Fig. 15. Generation of prying reaction and bearing action in beam joint force.

The transmission of the bending moment with the web-bolted moment joint of the aluminum alloy beam is frictional at first, and after slipping there is rotation at the bolt section due to shearing of the bolt and bearing of the web plate. However, in this study, prying action by the bearing with the bolt between the web, splice plates, and beam flange is expected without transmission of the frictional bending moment.

The bearing influence on the bolts and the prying action between the beam flange and the splice plate was examined. The load ratio of the prying action between the splice plate and the maximum bending bearing force of the web-bolted moment joint and the flange was quantitatively evaluated by experiment. Figure 16 shows the model used. The bending strength ratio of prying action reached 90 % from 60 % of the maximum bending strength (see Fig. 18a).

Moreover, when a finite element analysis is conducted, the load ratio of the prying action, as shown in Fig. 17, was quantified and the result was different from that of the experimental result. In this case, the bending strength ratio of prying action reached 90 % from 70 % of the maximum bending strength (see Fig. 18b).

It is concluded that the bending moment with a web-bolted moment joint of an aluminum alloy beam is transmitted by friction, bearing, and prying action. Especially, it was clarified that the bending strength ratio of the prying action reaches 90 % from 60 % of the maximum bending strength.

Fig. 16. Transmission model of force in web-bolted moment joint (double web).

Fig. 17. Analytical model (double web).

Fig. 18. Prying action ratio of: (a) experimental result (rough estimate); (b) analysis result and rough estimate.

CONCLUSION

The following mechanisms of bending strength for the H-beam and double-web beam of aluminum alloy were observed experimentally and analytically.

- 1) The maximum bearing moment of the beam with the double web-bolted moment joint is almost equal to the moment of a beam without a joint. For H-beams it is 70 %.
- The effect of prying action contributes to the maximum bending strength. Prying action ratio is 90– 60 % of maximum bending strength.
- 3) In specimens tested in the range of room temperature to 250 °C, there was tensile fracture by the bearings, prying action between the boundary of the web and the flange portion, and punching shear fracture.
- 4) For the specimens tested at 300 °C and 350 °C, because the bending transformation by the prying action had progressed, brittle fracture was not seen.

When the web-bolted moment joint was used, valuable data concerning the bending moment transmission at fire temperatures was obtained. In the aluminum alloy structure, it is necessary to secure the toughness of the joint section if sustained loading was expected so that collapse is avoided at 300 °C or above. In the past, there has been no standard method concerning joints in the design of fire resistance in aluminum architectural structures. Information for fire resistance of the joints of aluminum structures was presented in this paper.

FUTURE TASKS

The following studies must be conducted:

- 1) Clarification of the behavior of beams subjected to shearing force.
- 2) Establishment of a design formula based on bending in the shearing study.
- 3) Development of practical section distribution of the prying force.

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