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Experimental investigation on strength and curling influence of bolted connections in thin-walled carbon steel

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ABSTRACT

Experimental studies regarding the influence of curling on the ultimate strength of cold-formed stainless steel bolted connections have been carried out by Kim et al. Basic data and modified equations for predicting the structural behaviors considering strength reduction due to curling through the finite element analysis method have also been suggested by previous researchers.

In this paper, single shear bolted connections fabricated with four bolts and thin-walled carbon steel commonly utilized in light-weight structural members were tested to investigate the fracture mechanism and curling influence on the ultimate strength. Main variables for test specimen are plate thicknesses and end distances parallel to the direction of loading. Curling (out-of-plane deformation in the direction of plate thickness) also occurred in thin-walled carbon steel bolted connections with a large end distance and thinner plate like previous cold-formed stainless steel connections. The curling occurrence reduced suddenly the ultimate strength of single shear carbon steel bolted connections and the influence pattern of curling on strength was affected according to the plate thickness and end distance. Current design specifications for block shear strength with the combination of tensile fracture and shear fracture are summarized and the ultimate strengths of test results are compared to the predicted design strengths. AISI (American Iron and Steel Institute) and EC3 (Eurocode 3) made conservative estimates of ultimate strength for thin-walled carbon steel bolted connections with no curling, whereas AIJ (Architectural Institute of Japan) and SSBA(Stainless Steel Building Association) manuals provided a good prediction for ultimate strength and fracture mode. Modified strength equations were recommended respectively for bolted connections with typical block shear fracture considering shear stress factor and severe curling accompanied by strength reduction.

1. Introduction

Thin-walled (cold-formed) carbon steel in buildings has been widely utilized as structural members thanks to light-weight and ease of fabrication. The demand of its usage has been also increased with the introduction of thin-walled steel into steel house frame. Winter [1] of Cornell University sponsored by AISI (American Iron and Steel Institute) with a focus on bolted connections initiated the research for light-gauge (thin-walled) steel as structural members of buildings. Since then, many researchers and institutes have modified the design manuals for cold-formed steel structural members. As a result, AISI NAS (North American Specification, S100-12) [2], Eurocode 3 Part1.3 [3] and AIJ (Architectural Institute of Japan) recommendations [4] have published design specifications for cold-formed steel structural members.

Bolted connections in industrial fields and building structures play an important role in transmitting mechanical and structural forces to supporting frames. Benhamena et al.[5] investigated the effect of clamping force (tightening torque) on the fretting fatigue behavior of single shear bolted connections with aluminum alloy A6000 series and high strength low alloy steel (HSLA355). They found that the wear mechanism and contact surface degradation depend on the magnitude of tightening torque and the adhesion. The size of slip zones on contact zone is related at the magnitude of tightening torque. Chakherlou et al. [6,7] studied the effect of bolt clamping force and friction factor on the fatigue behavior of

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aluminum alloy 2024-T3 double shear lap connection. The results show that clamping force increases fatigue life compared to clearance fit specimens. Also, lubrication of the connections between the plates reduced the benefit of increased torque and the fatigue life.

Recently, Teh et al. [8] and Clements et al [9] conducted the experimental and numerical researches on the mechanisms for block shear fractures of bolted connections in G450 steel sheets subjected to concentric loading. Based on the tensile rupture and shear yielding mechanism in the block shear failure, an in-plane shear lag factor and active shear planes to lie midway between the gross shear plane and the net shear planes, more accurate block shear equation was proposed compared to current design equations.

Rogers et al. [10,11] also referred to the curling behavior in the test results of bolted sheet steel connections. However, they assumed that curling had a slight influence on the ultimate strength of bolted connections, thus the curling has been not considered in estimating the ultimate behaviors. Recently, Kuwamura et al. [12,13] carried out the experimental researches into two types of single shear and double shear bolted connections fabricated from cold-formed austenitic stainless steel (SUS304, corresponds to ASTM 304) and carbon steel (SS400, corresponds to ASTM A36) for mechanical behavior comparison according to the difference of material properties.

Kim et al. [14] performed numerical simulation to verify the application of finite element (FE) analysis procedure for predicting the mechanical behaviors of single shear stainless steel bolted connections. Curling deformation occurred in single shear stainless steel bolted connection with a large end distance and edge distance. As a result, the curling reduced the ultimate strength of the bolted connections. Kim et al. also conducted a variety of parametric numerical studies for cold-formed stainless steel bolted connections using the FE analysis and thus proposed the modified strength equations considering the curling effect in connections with single bolt, two-bolt and four-bolt arrangement [15–17]. Experimental results conducted by Kim et al. [18] show that the ultimate behaviors such as ultimate strength after curling, curling deformation, strain distribution and fracture shape of bolted connections are different for two stainless steel materials; austenitic 304 type and ferritic 430 type.

In this regard, this paper will investigate the ultimate strength and the influence of curling in thin-walled carbon steel bolted connections with four bolts, varied end distances and plate thicknesses.

2. Experimental works

2.1. Assembly of test specimen and material property

Specimens for single shear bolted connections are assembled by four bolts (2 × 2 bolt arrangement) as shown in Fig. 1(a). The bolted connections have a relatively large fixed edge distance (b=60 mm) perpendicular to the direction of loading to have the specimens fail by block shear fracture instead of tensile net section fracture perpendicular to the direction of loading. The specimens are fastened with high strength bolt (F10T, corresponds to ASTM A490) of 12 mm diameter (d), pitch (p) and gage distance (g) of 36 mm(=3.0d) as a constant dimension. Main variables are the end distances (e=1.0d, 1.5d, 2.0d, 2.5d, 3.0d, 4.0d, 4.5d, or 5.0d) from the center of bolt hole to the end of the plate in the direction of applied force and plate thicknesses (t_n, nominal thickness); 1.5 mm, 3.0 mm, 6.0 mm. The list of 13 types of specimens is included in Table 1. Three specimens per each type, total 39 specimens are fabricated and tested for the reliability of test results. For example, specimen CT15E12 denotes that 'C' stands for carbon steel, 'TXX' is plate thickness (t=1.5 mm for T15, t=3.0 mm for T30 and t=6.0 mm for T60) and 'EXX' is end distance (e=12 mm for E12 and e=60 mm for

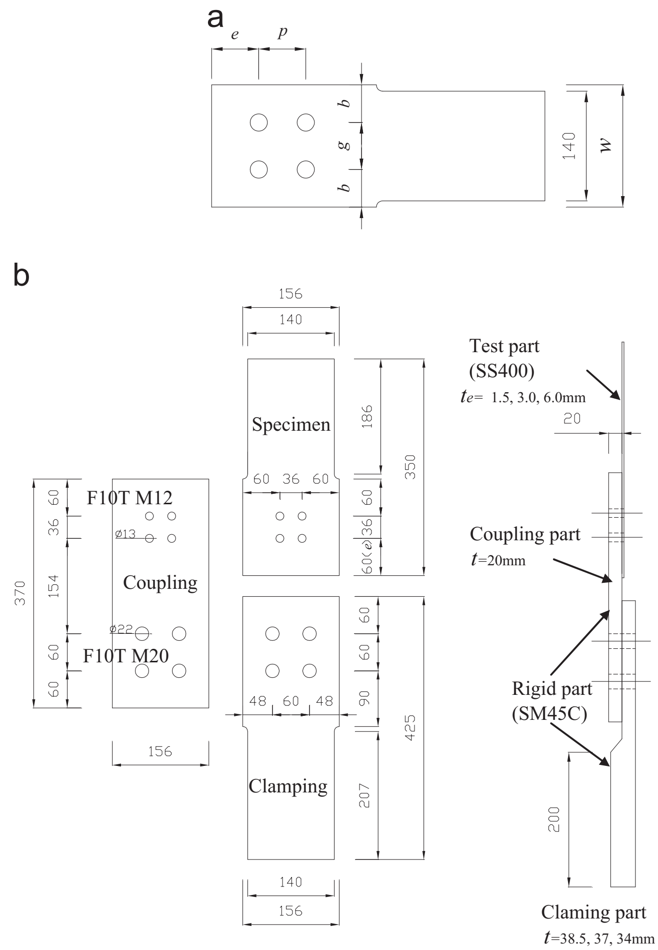

Fig. 1. Geometry and assembly of specimens. (a) Geometry of specimen and (b) Assembly of test part and rigid parts.

Table 1
List of specimens.

Specimens	Bolt arrangement (No. of bolts)	Nominal thickness t_n [mm]	End distance e [mm]	Remarks
CT15E12-1,2,3	2 × 2 (4)	1.5	1.0d (12 mm)	Bolt diameter (d)=12 mm
CT15E18-1,2,3			1.5d (18 mm)	
CT15E24-1,2,3			2.0d (24 mm)	
CT15E36-1,2,3			3.0d (36 mm)	Bolt hole(ø)= 13 mm
CT30E24-1,2,3		3.0	2.0d (24 mm)	
CT30E30-1,2,3			2.5d (30 mm)	
CT30E36-1,2,3			3.0d (36 mm)	Pitch(p), gauge(g)= 36 mm
CT30E48-1,2,3			4.0d (48 mm)	Edge distance (b)=60 mm
CT30E60-1,2,3			5.0d (60 mm)	
CT60E36-1,2,3		6.0	3.0d (36 mm)	
CT60E48-1,2,3			4.0d (48 mm)	
CT60E54-1,2,3			4.5d (54 mm)	
CT60E60-1,2 3			5.0d (60 mm)	