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Finite element modeling of bolted connections in thin-walled stainless steel plates under static shear

Tae Soo Kim[a,*], Hitoshi Kuwamura[b]

[a]Sustainable Building Research Center, Hanyang University, 1271, Sa-1-dong, SangNok-Gu, Ansan, Kyeunggi-do, 425-791, Republic of Korea
[b]Department of Architecture, Faculty of Engineering, The University of Tokyo, Tokyo, 113-8656, Japan

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Abstract

The recently performed experimental study indicates that the current Japanese steel design standards (AIJ) cannot be used to predict accurately the ultimate behavior of bolted connections loaded in static shear, which are fabricated from thin-walled (cold-formed) SUS304 austenite stainless steel plates and thus, modified formula for calculating the ultimate strength to account for the mechanical properties of stainless steel and thin-walled steel plates were proposed. In this study, based on the existing test data for calibration and parametric study, finite element (FE) model with three-dimensional solid elements using ABAQUS program is established to investigate the structural behavior of bolted shear connections with thin-walled stainless steel plate. Non-linear material and non-geometric analysis is carried out in order to predict the load–displacement curves of bolted connections. Curling, i.e., out of plane deformation of the ends of connection plates which occurred in test specimens was also observed in FE model without geometric imperfection, the effect of curling on the ultimate strength was examined quantitatively and the failure criteria which is suitable to predict failure modes of bolted connections was proposed. In addition, results of the FE analysis are compared with previous experimental results, failure modes and ultimate strengths predicted by recommended procedures of FE showed a good correlation with those of experimental results and numerical approach was found to provide estimates with reasonable accuracy.

Keywords: Thin-walled stainless steel; Bolted connection; Failure mode; Ultimate strength; Curling; Finite element analysis

1. Introduction

Stainless steel has a significant characteristic in its superior corrosion resistance, durability, fire resistance, ease of maintenance, aesthetic appeal, etc., while it has been rarely used in structural members of buildings due to high price. However, in the recent change of social trend from mass production and abundant consumption to ecological coexistence with natural environment, the concept of sustaining a long life of buildings is of much importance in construction engineering. In that context, stainless steel is expected to be promising material for building construction required to durability.

Research for utilizing stainless steel as structural members in building was initiated by Johnson, and Winter [1] of Cornell University sponsored by AISI in order to conform to the need for design specifications of stainless steels. Based on work results of Johnson and Winter and other many researchers, the first edition of "Specification for the design of light gage cold-formed stainless steel structural members" published by AISI (1968) [2] and "stainless steel cold-formed structural design manual" (1974) [3]. Subsequently, ANSI/ASCE-8-90 specification for design of cold-formed stainless steel structural members (LRFD specification) was also published in 1990 [4]. Recently, Eurocode 3: Part 1.4 (1996) [5], AS/NZS 4673 (2001) [6], and SEI/ASCE 8-02 (2002) [7] standards were published. On the other hand, Japanese research on structural stainless steel for building use dates back only to the late 1980s of virtual growth of economy accompanied with a construction rush of high-rise buildings, which tempted the engineers and researchers to use stainless steel in heavy steel constructions. This led to the

*Corresponding author. Tel.: +82 31 400 4690; fax: +82 31 406 7118.
E-mail address: tskim0709@hanyang.ac.kr (T. Soo Kim).

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establishment of specification of design and construction of heavy stainless steel structures published by Stainless Steel Building Association of Japan (SSBA) focused on hot-rolled stainless steel [8,9]. In recent years, the most promising use of stainless steel in buildings shows a tendency to be obviously changed in the form of light-weight members relying on its corrosion resistance, which may compensate for the high cost in fabrication as well as material of stainless steel. In fact, thin-walled (cold-formed) stainless steel members are being increasingly used for structural applications [8,10], a design method for thin-walled sections of stainless steel is required in Japan. From this view, Kuwamura et al. [11–15] investigated experimentally local buckling behaviors of stub column and flexural buckling behaviors of centrally loaded columns of thin-walled stainless steel with 1.5 and 3.0 mm thickness designated SUS304 and SUS301L3/4 H with yield strength of 235 and 440 N/mm^2, respectively, and ultimate behaviors of mechanically fastened shear type connections; single shear and double shear connections fabricated from SUS304 flat plates with 1.5 and 3.0 mm thickness. It was recommended that the effective width-thickness ratios should be expressed by different equations for the two strength grades in local buckling, consideration of effective width associated with the reduction of stiffness due to local buckling gave a rational evaluation of the flexural buckling strength of column and based on the fact that current design code (Architectural Institute of Japan; AIJ) tends to overestimate the ultimate strength of thin-walled stainless steel bolted connections, modified formulae for calculating the ultimate strength were proposed, which were found to provide a satisfactory prediction for failure mode and ultimate strength. Based on the research accomplishment with respect to thin-walled stainless steel structures presented above, Stainless Steel Building Association of Japan (SSBA) published "design manual of light-weight stainless steel structures" (2001) [16]. However, when thinner plates (1.5 and 3.0 mm thickness) of single-shear connections or the outside plate of double shear connections with a long end distance (edge distance in the loading direction) curled out of plane, back toward the bolt, the reduction of the load-carrying capacity of bolted connections was observed. It was reported that the curling of ends of plates was not sufficiently considered, and thus, the modified formulae overestimated the ultimate strength of connection with end curling.

Numerical simulation has become more and more popular in almost all research fields, especially, mechanical engineering or civil engineering. Therefore, in order to further investigate the ultimate behaviors such as failure mode and ultimate strength of thin-walled stainless steel bolted connections, in this study, finite element (FE) analysis for the previous test specimens [12] was preformed. Only single plate with free edges in single-shear bolted connections was modeled. Non-linear analysis was carried out in order to extend the range of variables applied in experimental data and investigate the stress/strain component of connection plate in which stress concentration is predicted [17]. Finally, the objective of this paper is to exhibit the test results of representative specimens with distinguished failure mode: net section fracture, end opening fracture and block shear rupture and prove the validation of FEM analysis in predicting the ultimate behaviors of thin-walled stainless steel bolted connections. Parametric studies such as analysis element type, mesh size, loading method, and connection model length were preformed in order to establish the FE analysis model, and FE results showed a good correlation with test results. Furthermore, three failure criteria (FC)which is usually applied in estimating the failure mode of bolted connections were discussed.

2. Reference test results preformed by Kuwamura et al

Experimental research regarding two types of bolted connections: single shear and double shear connections, fabricated from thin-walled stainless steel (austenitic stainless steel type; SUS304) using 1.5 or 3.0 mm thick plate and 12 mm/15 mm diameter bolt (A2-50; SUS common bolt or 10T-SUS; SUS high tensioned bolt) were carried out by Kuwamura et al. (2001) [11,12]. Figs. 1 and 2 display geometry of test specimens and test set-up of specimen (series SA). The both ends of test specimens were gripped through chucks onto a tensile test machine (Amsler typed Universal Testing Machine) by which a tensile force was applied gradually to the test specimen in monotonic displacement control. It should be noted that the experimental data are very important since they can be used for calibration and implementation of numerical analysis. In this FE analysis, Only the thinner plate (1.5 or 3.0 mm thick) out of single-shear connection with both test plates (1.5 or 3.0 mm thick) and rigid plate (6.0 mm thick) was

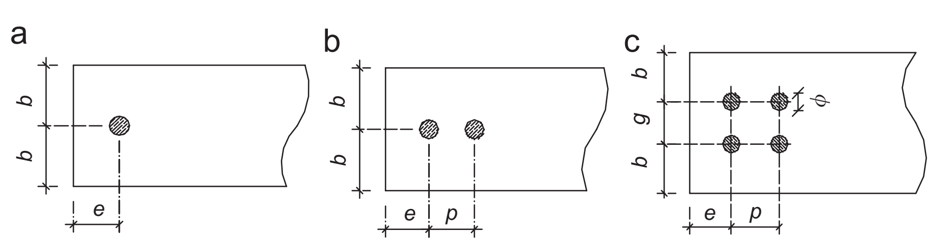

Fig. 1. Geometry of test specimen and notation. (a) Series SA, (b) Series SB, and (c) Series SC.