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Bearing factors of cold-formed stainless steel double shear bolted connections at elevated temperatures

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ABSTRACT

A numerical investigation on double shear bolted connections of cold-formed stainless steel at elevated temperatures is described in this paper. A finite element model is developed in this study. The model was verified against stainless steel double shear bolted connection tests. It is shown that the finite element model is able to predict the test strengths and failure modes of the connections. Therefore, an extensive parametric study of 225 stainless steel double shear bolted connections at 5 different temperature levels was performed. Based on both the test and numerical results, bearing factors are proposed for the bearing strengths of stainless steel double shear bolted connections at elevated temperatures. Two sets of bearing factors are proposed based on the true plastic strains in the bolt hole and the bolt hole deformation. The connection bearing strengths obtained from the tests and finite element analysis were compared with the nominal strengths calculated using the current American, Australian/New Zealand and European specifications for stainless steel structures as well as the modified design rules in this study. In calculating the nominal strengths of the connections, the material properties of stainless steel obtained at elevated temperatures were used. It is shown that the modified design rules provided more accurate predictions compared to the current design predications for bearing strengths of stainless steel double shear bolted connections at elevated temperatures. The reliability of the current and modified design rules was evaluated using reliability analysis.

1. Introduction

The structural applications of stainless steel in construction industry are arising for its desirable characteristics as compared to currently used carbon steel, including the attractive appearance, corrosion resistance, excellent ductility, better fire resistance, life-cycle cost savings and so on [1]. Bolt connection is one of the most commonly used connection types in carbon steel and stainless steel structures. The design rules of stainless steel bolted connections are available in current specifications, such as the American Society of Civil Engineers Specification (ASCE) [2], Australian/New Zealand Standard (AS/NZS) [3] and European Code 3 Part 1.4 (EC3-1.4) [4]. However, the stainless steel bolted connection design rules in the current international specifications are mainly based on the rules of carbon steel with small modifications [5], despite fundamental differences between the mechanical behavior of stainless steel and carbon steel. Furthermore, the current design rules are applicable at room (ambient) temperature condition only and the application to elevated temperatures is questionable. Therefore, there is a need to investigate the cold-formed stainless steel bolted connections at elevated temperatures and propose design rules.

Finite element analysis (FEA) is an effect method to understand the stress distribution and the failure mechanism of structural connections throughout the loading history. Finite element analysis (FEA) has been successfully used in the numerical investigation of stainless steel bolted connections at room temperature. For examples, Kim and Kuwamura [6] developed a finite element model using ABAQUS program to investigate the curling behavior of single shear bolted connections with thin-walled stainless steel grade EN 1.4301 (AISI 304). A parametric study on the ultimate strengths of single shear four-bolted connections of stainless steel grade EN 1.4301 (AISI 304) with the influence of curling was investigated by Kim et al. [7]. Bouchaïr et al. [8] studied the influence of end distance on the resistance of stainless steel connections of grade EN 1.4306 (AISI 304L) using a numerical model that has been verified with the experimental results of bolted connections. Salih et al. [5,9] investigated the net section failure and bearing failure of bolted connections of austenitic stainless steel grade EN 1.4306 (AISI 304L) and ferritic stainless steel grade EN 1.4016 (AISI 430) by an extensive parametric study using ABAQUS program. It should be noted that these

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Notation

A_0	original cross-sectional area of coupon
A_f	smallest cross-sectional area after fracture
C	bearing factor
DL	dead load
d	nominal diameter of bolt
d_0	nominal diameter of bolt hole
E	initial Young's modulus of engineering stress–strain curve
E_N	elastic modulus at room (ambient) temperature
E_T	elastic modulus at elevated temperatures
e_1	end distance that is the end distance from the center of a bolt hole to the adjacent end of any part in the direction of load transfer
e_2	edge distance that is the edge distance from the center of a bolt hole to the adjacent edge of any part that measured at right angles to the direction of load transfer
$f_{0.2}$	longitudinal 0.2% tensile proof stress
F_m	mean value of fabrication factor
$f_{0.2,N}$	longitudinal 0.2% tensile proof stress at room temperature
$f_{0.2,T}$	longitudinal 0.2% tensile proof stress at elevated temperatures
f_u	longitudinal tensile strength
$f_{u,b}$	ultimate tensile strength of the bolt
$f_{u,N}$	longitudinal tensile strength at room temperature
$f_{u,red}$	reduced ultimate tensile strength
$f_{u,T}$	longitudinal tensile strength at elevated temperatures
K	strength constant
LL	live load
l	length of specimen plate
l_o	original gauge length
l_f	final length after fracture
m	strain hardening exponent
P	bearing strength corresponding to critical end displacement predicted from FEA
P_{ASCE}	nominal strength of bolted connection based on ASCE specification
P_b	defined bearing strength predicted from FEA
$P_{FEA,bh}$	bolt hole deformation-based bearing strength of connection predicted from FEA
P_{EC}	nominal strength of bolted connection based on Eurocodes
$P_{FEA,sb}$	bolt hole strain-based bearing strength of connection predicted from FEA
P_m	mean value of variation of FEA and tested-to-predicted strength ratio
P_{max}	maximum connection strength of connection predicted from FEA
P_n	nominal bearing strength of bolted connection
P_{p1}	predicted bearing strength calculated using proposed bearing factor based on true plastic strains in the bolt hole
P_{p2}	predicted bearing strength calculated using proposed bearing factor with considering 3.0 mm bolt hole deformation
P_t	ultimate strength of connection obtained from test result
p_1	longitudinal spacing that is the spacing between centers of bolt holes inline with the direction of load transfer
p_2	transverse spacing that is the spacing measured perpendicular to the load transfer direction between centers of bolt holes
t	thickness of the connection plate
u_x	longitudinal displacement in axial X direction
u_y	longitudinal displacement in axial Y direction
u_z	longitudinal displacement in axial Z direction
u_{z1}	longitudinal displacement in axial Z direction of node 1 in the bolt hole
u_{z2}	longitudinal displacement in axial Z direction of node 2 in the bolt hole
w	nominal width of specimen plate
M_m	mean value of material factor
V_M	coefficient of variation of material factor
V_F	coefficient of variation of fabrication factor
V_P	coefficient of variation of FEA and tested-to-predicted strength ratio
α	reference element in the bolt hole of FEM
β	reliability index
β_1	reliability index determined using ϕ_1
β_2	reliability index determined using ϕ_2
Δ_{bh}	bolt hole deformation
ε	engineering strain
ε_{ep}	equivalent plastic strain of the element
$\varepsilon_{ep,max}$	maximum equivalent plastic strain of the element
$\varepsilon_{frac,elong}$	fracture true strain based on elongation of gauge length
$\varepsilon_{frac,red}$	fracture true strain based on reduced cross-section area
ε_{true}^{pl}	true plastic strain
$\varepsilon_{u,N}$	ultimate strain at room temperature
$\varepsilon_{u,T}$	ultimate strain at elevated temperatures
δ_{cr}	critical end displacement of bolted connection
δ_{max}	end displacement of bolted connection at ultimate strength predicted from FEA
σ	engineering stress
σ_{true}	true stress
$\sigma_{u,true}$	true ultimate stress
$\sigma_{frac,true}$	true stress at fracture strain
ϕ	resistance (capacity) factor
ϕ_1	resistance (capacity) factor specified in the current specifications
ϕ_2	resistance (capacity) factor specified in this study ($\phi_2=0.70$)
γ_{m2}	partial resistance (safety) factor in Eurocodes

investigations focused at room temperature. However, numerical study of cold-formed stainless steel bolted connections at elevated temperatures is not found in the literature.

Over two hundred double shear bolted connection specimens of cold-formed stainless steels were conducted at both room and elevated temperatures by Cai and Young [10,11], and steady state test method as well as transient state test method was used. It is found that the bolted connection strengths predicted by the current design rules generally underestimate the bearing strengths at elevated temperatures, despite using the reduced material properties of stainless steel due to elevated temperatures. In this study, the appropriateness of the current design rules for the bearing strengths of double shear bolted connections of cold-formed stainless steel at elevated temperatures is investigated. A finite element model (FEM)