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Load–deflection behaviour of thin-walled bolted plates in shear at elevated temperatures

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ABSTRACT

This paper presents the results of a numerical and analytical study of the load–deflection behaviour of thin-walled bolted plates under bolt shear at elevated temperatures. This paper first presents validation of the numerical simulation results against the high temperature tests carried out by Hirashima and Uesugi. The validated numerical model was then used to conduct an extensive series of parametric studies, in which the connection temperatures, material properties, geometries were changed, to generate a database of results to check the applicability of an analytical model previously developed by the authors for evaluating the load–deflection behaviour of this type of connection at ambient temperature. The results of this comparison indicate that the ambient temperature model can be applied to the elevated temperature condition if the ambient temperature mechanical properties of steel (Young's modulus, yield stress, elongation) are replaced by those at elevated temperatures.

1. Introduction

Cold formed thin-walled steel structures are becoming increasingly used in building construction. Bolted connection, in which the bolts are under shear, is commonly used in such structures. When dealing with structural robustness, the full load–deflection behaviour of such connections is required. However, such data is not available from the existing literature, in particular the maximum displacement. Kim et al. [1–3] performed a series of tests and FE simulations on thin-walled bolted connections in shear, mainly focusing on determining the ultimate capacity of the plates under plate curling; Rogers and Hancock [4–6] conducted a series of bolted connection in shear tests using G300 and G550 steel sheets, their main interest being in developing methods to calculate the ultimate capacity and the failure mode; Rex and Easterling [7] proposed an analytical model, based on non-linear regression curve-fit method, to predict the load–deformation behaviour of bolted hot-rolled thick plates in shear based on a series of relevant tests. Sarraj [8] further developed Rex and Easterling's model for predicting the stiffness and load carrying capacity of bolted hot-rolled plates in shear at elevated temperatures. In all the above studies, none investigated the maximum deformation of the connection. Hirashima and Uesugi [9] appear to be the only one to have provided some experimental data for the maximum deformation, based on a series of tests for hot-rolled bolted plates in shear at elevated temperatures.

In the authors' previous research studies [10,11], an analytical model was proposed to predict the full range load–deflection behaviour), including the maximum deformation, of thin-walled bolted connections in shear at ambient temperature. This paper assesses the applicability of extending the authors' analytical methods to elevated temperatures that are generated under fire conditions.

2. Simulations of the tests of Hirashima and Uesugi [9]

Hirashima and Uesugi's [9] fire tests were conducted on high strength friction grip (HSFG) bolted hot-rolled steel plates. Fig. 1 shows the set-up and dimensions of the test connections.

In total, 21 steady state tests were conducted at temperatures ranging from 20 °C to 650 °C. Table 1 gives detail of these tests.

All tests were steady state: Temperature was first increased to the desired value before load was applied.

2.1. Elevated temperature material properties

2.1.1. Steel plates

Hirashima and Uesugi [9] did not carry out any coupon test to measure the steel mechanical properties. The steel grade used in

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Nomenclature

A_n	net cross-section area
d	bolt-hole diameter
D_{ana}	analytical calculation maximum displacement
D_{FE}	finite element simulation maximum displacement
D_{test}	recorded displacement (slip displacement removed)
e_1	end distance
e_2	edge distance
$E_{a,\theta}$	slope of the linear elastic range at temperature Θ
$f_{p,\theta}$	proportional limit
f_u	ultimate tensile stress of material
f_y	yield strength of material
$f_{y,\theta}$	effective yield strength
F_{ana}	analytical calculation failure load
$F_{b,Rd}$	bearing failure load
F_{FE}	finite element simulation failure load
F_p	assumed proportional limit strength of the connection
F_s	end pull-out failure load
F_t	net-section failure load
F_{test}	test maximum load
F_u	ultimate strength of the connection
k	initial stiffness
k_0	initial stiffness from test result
k_{ana}	initial stiffness from proposed calculation
$k_{E,\theta}$	reduction factor (relative to E_a) for the slope of the linear elastic range
k_{FE}	initial stiffness from FE simulation
$k_{p,\theta}$	reduction factor (relative to f_y) for proportional limit
$k_{y,\theta}$	reduction factor (relative to f_y) for effective yield strength
m	number of bolt-hole in vertical direction
n	number of bolt-hole in horizontal direction
p_1	bolt-hole spacing in horizontal direction
p_2	bolt-hole spacing in vertical direction
t	plate thickness
w	the width of the plate
$\varepsilon_{p,\theta}$	strain at the proportional limit at temperature Θ
$\varepsilon_{y,\theta}$	yield strain at temperature Θ
$\varepsilon_{t,\theta}$	limiting strain for yield strength at temperature Θ
$\varepsilon_{u,\theta}$	ultimate strain at temperature Θ
Θ_a	steel temperature

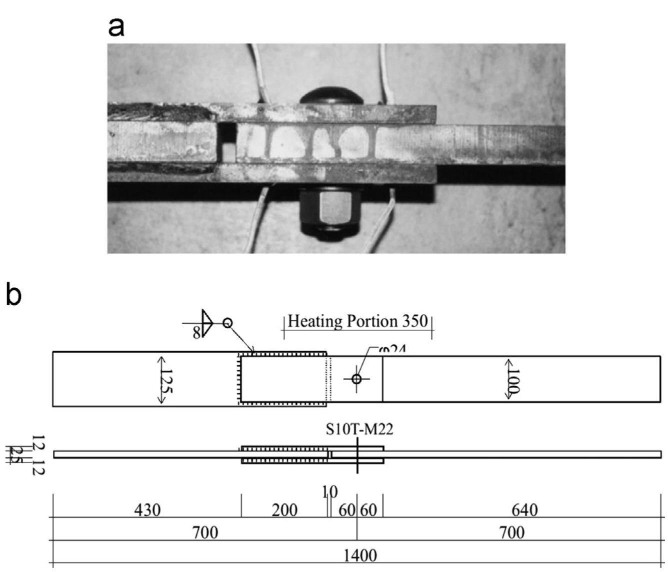

Fig. 1. Dimensions of high temperature test specimens of Hirashima and Uesugi [9].

Table 1
Details of the tests of Hirashima and Uesugi [9].

Test temperature (°C)	20	100	200	300	400	500	550	600	650
Number of tests	3	3	2	2	3	3	3	3	2
Bolt diameter d (mm)	22								
End distance (mm)	60								
Edge distance (mm)	50								
Plate thickness (mm)	25								
Ultimate strain of plates	0.3								

the tests was known as carbon steel grade SM490A with a nominal yield stress at ambient temperature of 400 N/mm^2.

The detailed material properties of SM490A were taken from the Japanese design guide for fire-resistive performance of structural materials [12]. They are given in Table 2.

The mechanical properties of the steel were modified by applying the strength and stiffness reduction factors in Eurocode 3 Part 1.2 [13], as shown in Table 3.

Table 2
Mechanical properties of SM490A [12].

Steel grade	Young's modulus (N/mm^2)	0.2% Proof stress (N/mm^2)	Ultimate stress (N/mm^2)	Limiting strain for yield stress (%)	Ultimate strain (%)
SM490A	210,000	400	540	0.3	0.35

Table 3
Reduction factors for carbon steel at elevated temperature according to EN 1993-1-2 [13].

Steel temperature θ_a (°C)	Reduction factors at temperature θ_a relative to the value of f_y or E_a at 20 °C		
	Reduction factor for effective yield strength $k_{y,\theta}=f_{y,\theta}/f_y$	Reduction factor for proportional limit $k_{p,\theta}=f_{p,\theta}/f_y$	Reduction factor for the slope of the linear elastic range $k_{E,\theta}=E_{a,\theta}/E_a$
20	1.000	1.000	1.000
100	1.000	1.000	1.000
200	1.000	0.807	0.900
300	1.000	0.613	0.800
400	1.000	0.420	0.700
500	0.780	0.360	0.600
600	0.470	0.180	0.310
700	0.230	0.075	0.130
800	0.110	0.050	0.090

Note: for intermediate values of the steel temperature, linear interpolation may be used.

The engineering stress–strain curves at elevated temperatures were constructed following the method in Eurocode 3 Part 1.2 [13], as shown in Fig. 2. The resulting engineering stress–strain curves for SM490A at different elevated temperatures are shown in Fig. 3. For ABAQUS simulations, the engineering stress–strain curve was converted to the true stress–strain curve using Eqs. (1) and (2).

$$\sigma_t = \sigma_n(1+\varepsilon_t) \quad (1)$$

$$\varepsilon_t = \ln(1+\varepsilon_n) \quad (2)$$

It should be pointed out that the limiting strain at the maximum stress and the ultimate strain at fracture of the steel used in