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Structural performance of cold-formed lean duplex stainless steel beams at elevated temperatures

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ABSTRACT

The structural performance of cold-formed lean duplex stainless steel beams at elevated temperatures ranging from 24 to 900 °C was investigated in this study. A finite element model was developed. The numerical analysis covered the specimens of square and rectangular hollow sections. The material properties obtained from tensile coupon tests on lean duplex stainless steel at elevated temperatures were used in the finite element model. A total of 125 numerical flexural strengths were obtained from the finite element analysis. The numerical results were compared with the design values calculated by the existing design rules, including the American Specification, Australian/New Zealand Standard, European Code, direct strength method and continuous strength method. The suitability of these design rules for lean duplex stainless steel beams at elevated temperatures was assessed using reliability analysis. It was shown that the existing design rules are generally quite conservative in predicting the flexural strengths at elevated temperatures, except that the modified direct strength method provides accurate and reliable predictions. Therefore, it is recommended that the modified direct strength method be used for cold-formed lean duplex stainless steel beams at elevated temperatures.

1. Introduction

A relatively new type of cold-formed lean duplex stainless steel is becoming an attractive choice as a construction material. Lean duplex stainless steel is characterized by a low nickel content of around 1.5%. Thus, lean duplex stainless steel has economic advantages over the other types of stainless steel. In addition, it is regarded as a high strength material with the nominal yield strength (0.2% proof stress) of 450 MPa [1]. However, there has been limited research on the structural performance and design of lean duplex stainless steel members, especially at elevated temperatures. Therefore, research on the lean duplex stainless steel material and structural members is required.

Lean duplex stainless steel is a relative new construction material. The previous research on lean duplex stainless steel focused mainly on the material properties and design of structural members at room temperature. Huang and Young [2], as well as Theofanous and Gardner [3], conducted tensile coupon tests and stub column tests to investigate the mechanical and section properties of cold-formed lean duplex stainless steel rectangular and square hollow sections. Experimental and numerical investigations were carried out on cold-formed lean duplex stainless steel columns [3–6], and the test and numerical data were compared with the predicted column strengths calculated by the existing design rules. It was shown that the existing design rules, including design rules in the European Code, explicit approach in the Australian/New Zealand Standard and the direct strength method, are quite conservative for the lean duplex stainless steel. The implicit approach for column design in the American Specification and Australian/New Zealand Standard provides accurate predictions, but the iterative calculation procedure is tedious. Therefore, modified design rules have been proposed for better prediction of lean duplex stainless steel structural strengths. Some research has also been conducted for cold-formed lean duplex stainless steel beams [7–10]. This research indicated that the existing European Code and direct strength method are quite conservative for lean duplex stainless steel flexural members, while the continuous strength method provides a better prediction. The European Code and direct strength method were found to be suitable for the shear design of lean duplex stainless steel rectangular hollow beams. The existing design rules in the European Code and the Australian/New Zealand Standard are generally quite conservative for lean duplex stainless steel beam-column members [11,12]. The mechanical properties of cold-formed lean duplex stainless steel at elevated temperatures have been investigated in previous research [13,14]. Huang and Young [13] conducted tensile coupon tests on lean duplex stainless steel in both steady and transient states. The existing design rules for

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Notation

TB	overall width of cross-section of specimen
C_y	compression strain factor in American Specification and Australian/New Zealand Standard
c	flat width of specimen;
D	overall depth of cross-section of specimen
d_w	depth of the compressed portion of the web
f_y	yield strength (0.2% proof stress)
F_m	mean value of fabrication factor
$k_{FEA,T}$	curvature corresponding to the ultimate moment predicted by finite element analysis at elevated temperature
L	length of specimen
M_{crl}	critical elastic local buckling moment
$M_{CSM,T}$	unfactored design moment capacity predicted by the continuous strength method at elevated temperatures
$M_{DSM,T}$	unfactored design moment capacity predicted by the direct strength method at elevated temperatures
$M_{DSM,T}$	unfactored design moment capacity predicted by the direct strength method without considering the inelastic bending reserve at elevated temperatures
M_d	moment capacities predicted by design rules
M_{EC3}	unfactored design second-order elastic moment of beam-column for European Code at room temperature
$M_{EC3,T}$	unfactored design second-order elastic moment of beam-column for European Code at elevated temperatures
$M_{FEA,T}$	ultimate moment predicted by finite element analysis at elevated temperatures
$M_{G\&T,T}$	unfactored design moment capacity predicted by the modified European Code by Gardner and Theofanous at elevated temperatures
$M_{inelastic,T}$	unfactored design moment capacity predicted by the approach by inelastic reserve capacity in American Specification and Australian/New Zealand Standard at elevated temperatures
M_m	mean value of material factor
M_{nd}	nominal flexural strength for distortional buckling in direct strength method
M_{ne}	nominal flexural strength for lateral-torsional buckling in direct strength method
M_{nl}	nominal flexural strength for local buckling in direct strength method
M_u	experimental and numerical ultimate moments
M_y	yield moment
$M_{yielding,T}$	unfactored design moment capacity predicted by the approach by initiation of yielding in American Specification and Australian/New Zealand Standard at elevated temperatures
$M^{\#}_{DSM,T}$	unfactored design moment capacity predicted by the modified direct strength method at elevated temperatures
$M^{\#}_{EC3,T}$	unfactored design moment capacity predicted by the modified European Code at elevated temperatures
$M^{\#}_{inelastic,T}$	unfactored design moment capacity predicted by the modified approach by inelastic reserve capacity at elevated temperatures
$M\hat{}_{DSM,T}$	unfactored design moment capacity predicted by the direct strength method with considering the inelastic bending reserve at elevated temperatures
P_m	mean value of tested-to-predicted load ratio
S_e	effective section modulus
t	thickness of specimen
T	temperature in °C;
V_F	coefficient of variation of fabrication factor
V_m	coefficient of variation of material factor
V_p	coefficient of variation of test and finite element to design predictions
β_0	reliability index
β_1	reliability index
ε	material factor
ϕ_o	resistance factor
ϕ_1	resistance factor
λ_l	non-dimensional slenderness to determine P_{nl}
$\bar{\lambda}_p Z$	element slenderness

predicting the reduced material properties at elevated temperatures were assessed for lean duplex stainless steel. A modified design rule was proposed for lean duplex stainless steel material properties at elevated temperatures. Gardner et al. [14] summarized the results of tests on material properties of various stainless steel alloys at elevated temperatures, including the lean duplex stainless steel material reported by Outokumpu [15]. Reduction factors of strength and stiffness for lean duplex stainless steel were obtained according to the available data.

A search of the literature revealed a lack of research on cold-formed lean duplex stainless steel beams at elevated temperatures. Therefore, the objective of this study was to investigate the structural performance of cold-formed lean duplex stainless steel beams at elevated temperatures, ranging from 24 to 900 °C, using finite element analysis. The reduced mechanical properties at elevated temperatures were used in the FEM. A total number of 125 numerical flexural strengths were compared with the design values calculated from the existing design rules. The applicability of the existing design rules for the lean duplex stainless steel beams was assessed using reliability analysis. According to the comparison, recommendations for designing cold-formed lean duplex stainless steel flexural members at elevated temperatures are proposed based on this study.

2. Finite element model

The finite element model (FEM) for cold-formed lean duplex stainless steel flexural members was developed by Huang and Young [7] using the program ABAQUS version 6.11 [16]. The FEM has been verified with the test results of four-point bending tests at room temperature. The moment-curvature curves and the failure modes predicted by the FEM have been found to agree well with the test results. In this study, the FEM developed by Huang and Young [7] was used for the finite element analysis of flexural members at elevated temperatures, except that the materials properties at room temperature were replaced by the reduced material properties obtained from tensile coupon tests at elevated temperatures [13]. The mechanical properties of section 50 × 50 × 1.5 obtained from the tensile coupon tests at 24 °C, 300 °C, 500 °C, 700 °C and 900 °C using the steady-state test method were used in the FEM. ABAQUS allows for a multi-linear stress-strain curve to be used. Similar to the Huang and Young FEM [7], the first part of the curve represents the elastic part up to the proportional limit stress with the measured Young's modulus and Poisson's ratio taken as 0.3. In the plastic analysis, the static stress-strain curve obtained from tensile coupon tests was converted to true stress and logarithmic true plastic strain curve, as described by Huang and Young [7]. The material properties adopted in the FEM, including the modulus of elasticity, yield strength, and ultimate strength at high temperatures ranging from 24 to 900 °C, are summarized in Table 1. Similar to the FEM for beams at room temperature, the local imperfection of $t/10$ was incorporated into the FEM, where t is the thickness of the sections. The residual stresses in the sections were not included.