Journal of Constructional Steel Research 65 (2009) 1721–1730

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

journal homepage: www.elsevier.com/locate/jcsr

Web crippling strength of a steel sandwich panel with V-shaped webs

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ARTICLE INFO

Article history:
Received 8 October 2008
Accepted 10 March 2009

Keywords:
Cold-formed steel
Web crippling
Multi-web deck section
End one-flange loading

ABSTRACT

Steel sandwich panels with V-shaped web flutes (V-core panels) serve the structural functions of a proposed energy-efficient roof system for residential construction. Due to its intended use as a flexural member spanning between a ridge beam and a structural wall, and required slender webs for weight considerations, web crippling under end one-flange loading is a critical strength limit state for the V-core panels. Although the *2001 North American Specification for the Design of Cold-Formed Steel Structural Members* provides a design procedure to address web crippling, those design rules were developed for members whose cross sections are different from that of V-core panels. Consequently, nine specimens were tested to collect data on V-core panels subjected to end one-flange loading. Test observations suggested that V-core panels behave very similarly to multi-web decks that are strapped and unfastened to the supports. Experimental data reported in the literature was used to modify the web crippling strength equation in the *Specification* to reflect these particular conditions. The modified equation was found to adequately predict the measured web crippling strength of V-core panels.

1. Introduction

The University of Minnesota and industry partners developed a new panelized roof system for residential construction that optimizes efficiency in energy, durability, labor, and cost [1–3]. The roof system replaces conventional timber roof trusses by manufactured panels that span between the ridge beam and exterior wall without intermediate support. Fig. 1(a) shows the schematics of the roof system, while Fig. 1(b) shows the composition of the roof panel. Each panel comprises a steel sandwich panel, designated as a V-core panel, a polyurethane foam insulation layer, and integral metal roof finish. The foam is placed outside of the V-core panel for better thermal performance. The panels may be manufactured in a factory, and assembled on site using specially designed connectors at the ridge, soffit, and panel to panel edges [1]. The panelized roof system offers a number of performance advantages over conventional roof construction. These include factory quality production that yields superior thermal and moisture performance, the ease of placing HVAC equipment in a conditioned attic, the possibility of converting the attic to occupied space at reduced cost compared to a home with trusses, and the option for factory installed solar PV and solar thermal modules, and reduced construction cycle time, particularly in solar homes.

V-core panels combine slender flange and web elements to reduce the weight of the roof system. Fig. 2 shows prototype V-core panels that were tested in this study. The prototype panels consisted of top and bottom face sheets and V-shaped web flutes connecting the face sheets. The four bends of the web flutes, each with an inside radius of 2.4 mm, were made by a cold-press procedure. Adjacent to the bends, the web was connected to a face sheet by a continuous, longitudinal laser weld. The top face sheet was either 1.5 or 2.0-mm thick. The stiffened segment in the middle of the top face sheet had a slenderness ratio of 195 or 146. A steel plate of 0.75 or 1.0-mm thick was used for the bottom face sheet and web flutes. The stiffened segment in the middle of the bottom face sheet had a slenderness ratio of 610 or 457. The slenderness ratio of the web was 204 or 153. The prototype panels were 5-m long.

The V-core panel is intended to be used as a flexural member that is simply supported by a ridge beam and a structural wall. Four-point bending tests and distributed load tests by Di Muoio [3] and Siljenberg [4] demonstrated that the prototype V-core panels can safely develop the flexural strength required by the design loads. However, the tests also indicated that the slender webs make the V-core panels susceptible to local failure at the supports. The local condition at the supports is referred to in the literature as end one-flange (EOF) loading. Although the *2001 North American Specification for the Design of Cold-Formed Steel Structural Members* [5] (hereinafter referred to as the *2001 Specification*) provides a design procedure to address web crippling, those design

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0143-974X/$ – see front matter
doi:10.1016/j.jcsr.2009.03.008

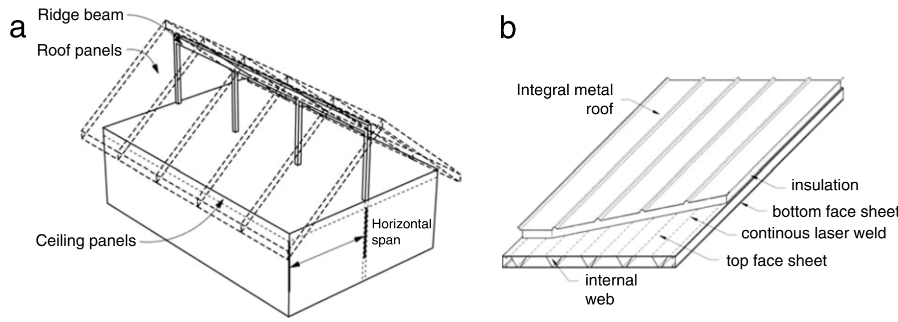


Fig. 1. Panelized roof system: (a) panelized roof with supports; and (b) composition of roof panel.

Notations

C, C_R, C_N, and C_h	coefficients in the unified web crippling strength equation.
F_y	yield strength of steel member, MPa.
P_n	nominal web crippling strength of one web, kN.
P_t	measured web crippling strength of one web, kN.
R	inside bend radius, mm.
N	bearing length, mm.
h	length of flat segment of the web, mm.
t	web thickness, mm.
t_1	thickness of top flange plate of specimen, mm.
t_2	thickness of bottom flange plate and web of specimen, mm.
x	clear distance between loading pad and reaction pad, mm.
Ω	factor of safety for US codes and specifications.
ϕ	resistance factor for US codes and specifications.
θ	angle between the plane of the web and plane of the bearing surface, rad.

rules were developed for members whose cross section is different from that of V-core panels.

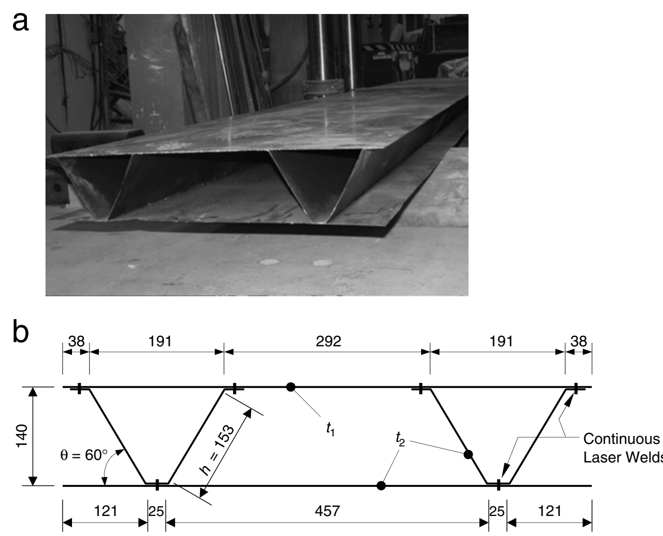
Consequently, a study was performed to evaluate the web crippling strength of V-core panels. A series of tests were conducted on V-core panels to examine their web crippling behavior and to measure their web crippling strength. Based on experimental data on multi-web deck sections reported in the literature, a modified web crippling strength equation was established for V-core panels. The modified equation is consistent with the design equation prescribed in the *2001 Specification*, but uses a set of newly calibrated coefficients that reflect the unique geometric features of V-core panels. The web crippling strength predicted by the modified equation was compared against the strength measured from the tests.

An overview of the study and key findings are discussed in this paper. The full detail of the study is provided by Siljenberg [4]. Other aspects of the broader research project, which spanned from the thermal, architectural, and constructability considerations for the V-core panel, to the overall development of the energy-efficient roof system, are reported by Mantell et al. [1], Davidson [2], and Di Muoio [3].

2. Web crippling strength

2.1. The 2001 Specification

According to the Commentary to the *2001 Specifications*, web crippling refers to a family of local web failures caused by concentrated load(s) or reaction(s). Web crippling in cold-formed steel sections is a complex phenomena affected by elastic stability, local yielding, geometric imperfection, uneven loading between adjacent webs, and interaction with the flange plates, among other factors. Therefore, international design codes [5,6] account for web crippling by empirical equations calibrated against experimental data. With modification, the web crippling strength specified in the *2001 Specification* might be applied to the V-core panel. The *2001 Specification* uses the following equation, referred to as the unified equation, to define the nominal web crippling strength of various sections:



Prototype	t_1 (mm)	t_2 (mm)
A	2.00	0.75
B	1.50	0.75
C	2.00	1.00

Fig. 2. V-core panel: (a) overall view; and (b) cross-sectional dimensions. (Units in mm).

$$P_n = Ct^2F_y \sin\theta \left(1 - C_R\sqrt{\frac{R}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\sqrt{\frac{h}{t}}\right) \quad (1)$$

where P_n is the nominal web crippling strength of one web, t is the web thickness, F_y is the design yield strength of the web material, R is the inside bend radius, N is the bearing length, θ is the angle between the plane of the web and plane of the bearing surface, and h is the length of the flat segment of the web. The *2001 Specification* states that the unified equation is valid within limits of $h/t \le 200$, $N/t \le 210$, $N/h \le 3$, and $45^\circ \le \theta \le 90^\circ$. Any consistent set of force and dimension units may be used for the variables. The four non-dimensional coefficients, C, C_R, C_N, and C_h, are specified depending on the cross section (five types), loading condition (four conditions), and the connection between the panel and the support