Towards the design of cold-formed steel foam sandwich columns

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Abstract

In this paper a design method for the compressive capacity of sandwich panels comprised of steel face sheets and foamed steel cores is derived and verified. Foamed steel, literally steel with internal voids, provides the potential to mitigate many local stability issues through increasing the effective width-to-thickness of the component for the same amount of material. Winter's classical effective width expression was generalized to the case of steel foam sandwich panels. The provided analytical expressions are verified with finite element simulations employing brick elements that explicitly model the steel face sheets and steel foam cores. The closed-form design expressions are employed to conduct parametric studies of steel foam sandwich panels with various face sheet and steel foamed core configurations. The studies show the significant strength improvements possible with steel foam sandwich panels when compared with plain steel sheet/plate.

Introduction

Foamed steel intentionally introduces internal voids in steel, e.g. Figure 1. A variety of manufacturing methods are used to introduce the voids from powder metallurgy and sintering of hollow spheres to gasification (Ashby et al. 2000). Steel foams are largely still under development, e.g. Kremer et al. (2004); however steel foam sandwich panels have been utilized in a demonstration project as a parking garage slab (Hipke 2011) while mass production of

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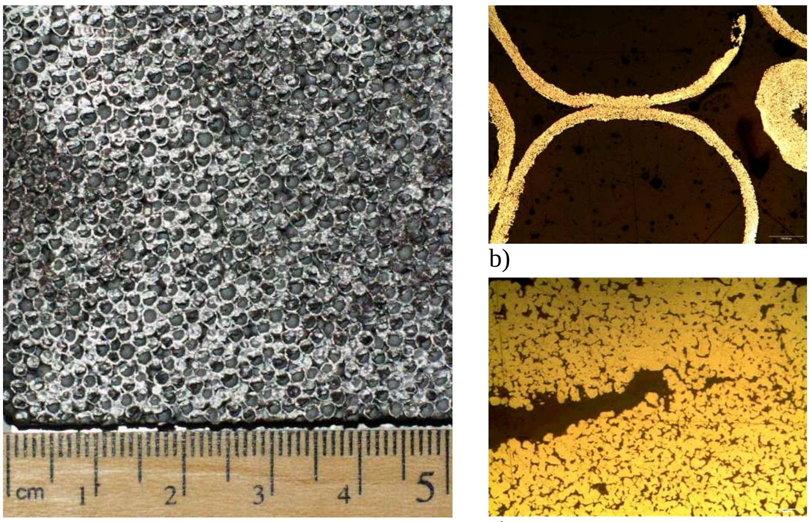
aluminum foam sandwich panels already exists (Figure 2, Banhart and Seeliger, 2008). In general, metal foams have high effective bending stiffness and energy absorption. In addition, metal foams have improved thermal conductivity (Neugebauer et al. 2005), enhanced fire resistance (Coquard et al. 2010), better noise attenuation (Ashby et al. 2000; Bao and Han 2009) , and provide improved electromagnetic and radiation shielding (Losito et al. 2010; Xu et al. 2010) when compared with solid metals.



a) b) c)

Figure 1: Steel hollow sphere foam 18% relative density: a) interior foam morphology, b) contact between spheres, c) sphere walls are not fully dense.

The overall objective of this study is to develop a design method for the determination of the in-plane compressive strength of steel foam sandwich panels comprised of solid steel face sheets and foamed steel cores. The design method development requires: (a) determination of the effective bending rigidity, including shear deformations, and the resulting local buckling stress, (b) determination of the yield strength for the composite (solid and foamed steel) panel, and (c) application and verification/calibration of Winter’s (1947) effective width expression suitably modified by (a) and (b).

a) b)

Figure 2: Aluminum foam sandwich panels a) on pallet, b) in section
Photo credit: Banhart and Seeliger (2008)

Basic steel foam material properties

A typical compressive stress-strain curve for the steel foam of Figure 1 is provided in Figure 3. This commercially available steel foam, manufactured by the Fraunhofer Institute in Germany, employs sintered hollow steel spheres and has a relative density ρ=0.18. For a typical sample the initial compression modulus, E_{fc} is approximately 3150 MPa, the yield stress in compression f_{yf} is approximately 6 MPa, and the compressive strain before the compaction of the steel foam walls is nearly 90%. In tension the initial modulus and yield stress are similar but tensile strain capacity is only on the order of 4%.

Local buckling of foamed steel sandwich panels

For the foamed steel sandwich panel the in-plane elastic local plate buckling stress, f_{cr}, is proportional to the plate bending rigidity (Allen 1969):

$$f_{cr} = k_p \ \frac{\pi^2 D_p}{b^2(t_c + 2t_s)} \tag{1}$$

where k_p is the plate buckling coefficient, b is the plate width, t_c, t_s are core and face sheet thickness, D_p is a panel bending rigidity.

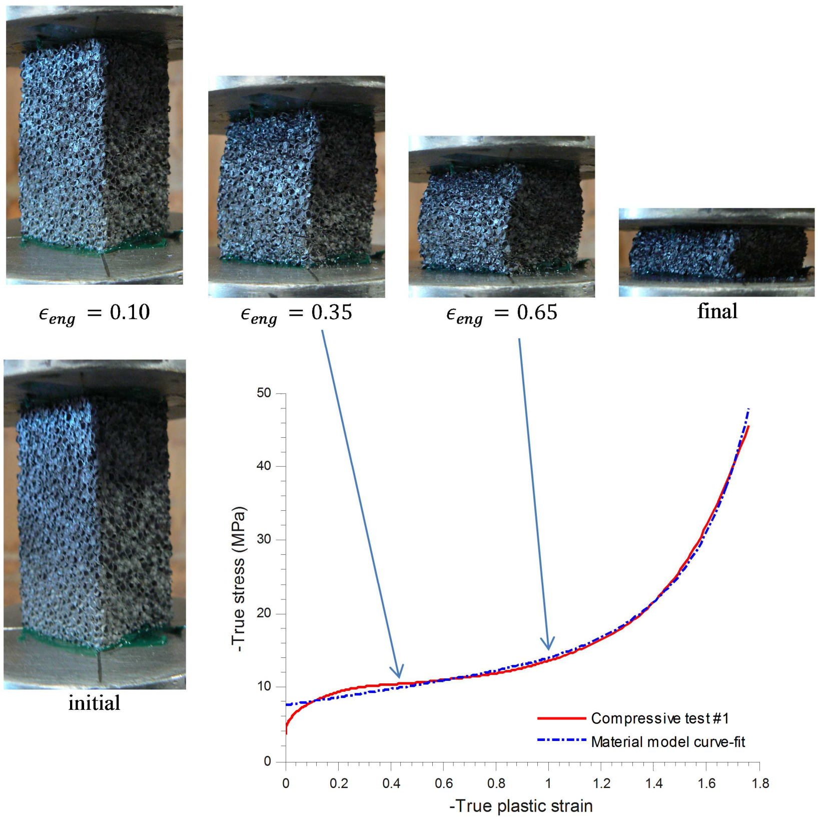


Figure 3: Uniaxial compression test for calibration of steel foam plasticity

The approach of Allen, for incorporation of shear and face sheet bending, is to (a) simplify the bending rigidity, and (b) smear the rest of the effects into the plate buckling coefficient, *k*. The plate bending rigidity, D_p, is reduced (and simplified) by ignoring the stiffness of the core, resulting in:

$$D_p = \frac{E_f t_s (t_c + t_s)^2}{2(1 - \nu_f^2)} \quad (2)$$

For a simply supported plate of length *a*, width *b*, uniformly compressed on the sides with width *b*, the plate buckling coefficient, *k*, of Allen, including shear deformation is as follows:

$$k_p = \left(\frac{mb}{a} + \frac{n^2 a}{mb}\right)^2 \left\{\frac{1}{1 + r\left(\frac{m^2 b^2}{a^2} + n^2\right)} + \frac{{t_s}^2}{3(t_c + t_s)^2}\right\} \tag{3}$$

where the first term in the parentheses is the classic isotropic plate solution (and converges to k=4 as $a/b \rightarrow \infty$), m is the number of transverse buckling half-waves, n is the number of longitudinal (in the direction of loading) buckling half-waves, and r accounts for shear deformation as given by:

$$r = \frac{\pi^2}{b^2} \frac{D_p}{G_c(t_c + t_s)^2/t_c} = \frac{\pi^2}{2(1 - {\nu_c}^2)} \frac{E_s}{G_c} \frac{t_s t_c}{b^2} \tag{4}$$

Note, if the core is isotropic unfoamed steel r depends on ν and the ratio of $t_s t_c/b^2$, and for typical b/t, r is less than 0.1. If the core is completely rigid in shear r=0. Note, even for r=0 Equation 3 still predicts a reduction in the plate buckling coefficient (note the last term) as Allen's method accounts for both face sheet bending and overall shear deformations.

As illustrated in Figure 4a, in classic isotropic theory the minimum k occurs at a/b = integer and converge to 4 as $a/b \rightarrow \infty$. However, for k of Equation 3 the minima no longer occur at integer values and instead occur at $a/b = \chi_{min}$ where χ_{min} is a function of r and $t_s/(t_c + t_s)$. Allen proposed that iteration be used, i.e. for a given a/b iterate on m and n until the minimal k is determined. Eigenbuckling analysis was performed on the developed finite element model to explore the accuracy of Allen's elastic buckling solution. For the eigenbuckling models, based on a $t_{ini} = 1\ mm$, 30% of the solid sheet was foamed to 18% relative density (i.e. the foam of Figure 1) resulting in $t_s = 0.35\ mm$ and $t_c = 1.67\ mm$. Panel width b was varied from 50 to 200 to explore a wide range of b/t ratios. Figure 4b shows that Allen's elastic buckling solution works well for steel foam sandwich panels over a large variation in b/t ratios (and shear deformation ratio, r).

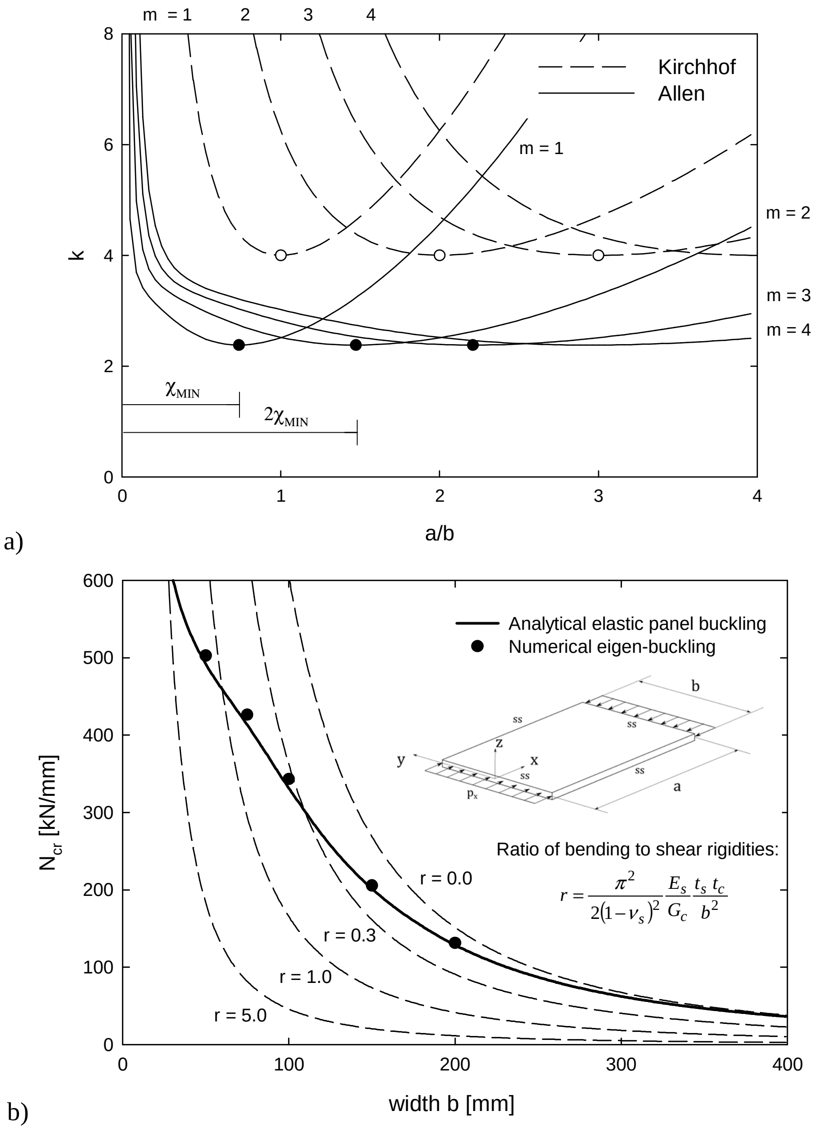


Figure 4: a) Plate buckling coefficient, k, as a function of plate aspect ratio (a/b) for $r = 0.3$ and $t_s/(t_c + t_s) = 0.1$; b) Comparison of Allen's elastic buckling solution with numerical plate buckling model

Strength of in-plane loaded sandwich panels

The squash load is the compressive load at which the section is fully yielded. In the case of steel foam sandwich panels this is modified to the compressive load at which the steel face sheets are fully yielded. The equivalent yield stress for the sandwich panel, f_{yp}, may then be found from simple force balance:

$$f_{yp} = \frac{2\, t_s f_{ys} + t_c \cdot min\left(f_{yc}, E_c \frac{f_{ys}}{E_s}\right)}{2t_s + t_c} \quad (5)$$

where the yield stress of the face sheets, f_y, is explicitly denoted here as f_{ys}, and the yield stress and modulus in the foamed core are denoted as f_{yc} and E_c. Typically, the core is still elastic when the face sheets yield, thus the second term of the minimum in Equation 5 usually controls.

Winter's design method

For thin solid steel plates the most widely accepted engineering approach to predicting their in-plane compressive strength is Winter's effective width approach (Winter 1947) or some variant thereof. Ultimately, modern specifications (AISI 2007) have led to further small modifications. Winter's approach provides the reduced width of the plate, b_e, that is effective in carrying the maximum stress, f_y, per:

$$b_e = \begin{cases} b & if\ f_{cr} \geq 2.2\, f_y \\ b\left(1 - 0.22\sqrt{\frac{f_{cr}}{f_y}}\right)\sqrt{\frac{f_{cr}}{f_y}} & if\ \ f_{cr} < 2.2\, f_y \end{cases} \quad (6)$$

where b is the plate width, f_{cr} is the local plate buckling stress, and f_y is the plate material yield stress. The method results in a predicted compressive strength, P_n, for the plate of

$$P_n = b_e t f_y \quad (7)$$

Here we explore the generalization of this design approach where f_y is replaced with f_{yp} of Equation 5 and f_{cr} includes Allen's reductions for shear deformation and face sheet bending of Equations 1, 2, 3 and 4.

Sandwich panel collapse simulations

The LS-DYNA brick element model, employing J-2 plasticity for the face sheets and the triaxial stress dependent Deshpande and Fleck (2000) model for the foamed steel core is employed here to conduct material and geometric nonlinear collapse analysis of simply supported steel foam sandwich panels loaded under in-plane compression. Geometric imperfections in the shape of the first eigenmode with magnitudes of *0.1t* and *0.34t* (Vieira Jr. et al. 2011) where *t* is the total thickness, were employed. As in the eigenbuckling analysis: $t_{ini} = 1\,mm$, α= 30%, and ρ= 18% (i.e. the foam of Figure 1) which results in $t_s = 0.35\,mm$ and $t_c = 1.67\,mm$. Panel width b was varied from $50\ to\ 200\,mm$. The force at collapse in the models (normalized by the solid sheet squash load $P_y = bt_{ini}f_{ys}$) is provided as a function of the unfoamed solid plate width-to-thickness ratio in Figure 5.

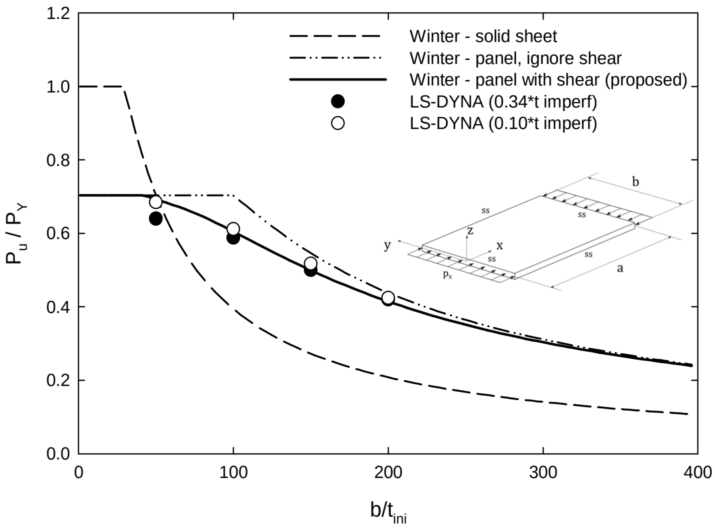


Figure 5: Comparison of FEA collapse simulations of steel foam sandwich panels with predicted strength based on modified version of Winter's method.

Three curves are provided for Winter's method: solid steel (unfoamed) sheet; sandwich panel - ignoring shear effects, and; sandwich panel - including shear effects. The results indicate that shear effects must be included in the solution, but if they are included (and the yield stress suitably modified to f_{yp}) Winter's method provides an accurate prediction of strength. Further, even granting the small loss in capacity due to shear deformations, the foamed panel outperforms the solid steel sheet for a large range of b/t ratios.

Steel foam sandwich panel optimization

To illustrate the performance that is possible with steel foam sandwich panels the strength predicted by the suitably modified and validated Winter's method is compared to a solid plate (thickness=t_{ini}) of the same weight for a variety of different foamed depths. The commercially available steel foam of Figure 1 (ρ=18%) is again used for the core density, and the depth of foaming, α, is varied from 0.1 to 0.6 (i.e. the initial portion of the plate that is foamed varies from 0.1t_{ini} to 0.6t_{ini}). The plate width is varied and the resulting strength prediction is provided in Figure 6. Fundamentally, foaming decreases f_y (to f_{yp} via Equation 5) and increases the local buckling stress f_{cr} (through an enhanced plate rigidity appropriately reduced for shear deformations and face bending Equations 1, 2, 3 and 4).

Thus, as shown in Figure 6 for stocky plates (low b/t_{ini}) the sandwich panel has a reduced capacity when compared to a solid plate of the same weight, but as slenderness increases the sandwich panel capacity exceeds that of the solid plate. In striking the balance between reduced f_y and enhanced f_{cr} it is shown that a foamed depth of 0.3t_{ini} (α=0.3) provides the biggest improvements over the solid plate, over the widest range of b/t_{ini}, In the studied case strength gains above the solid plate between 150% and 200% are realized for b/t_{in}>100.

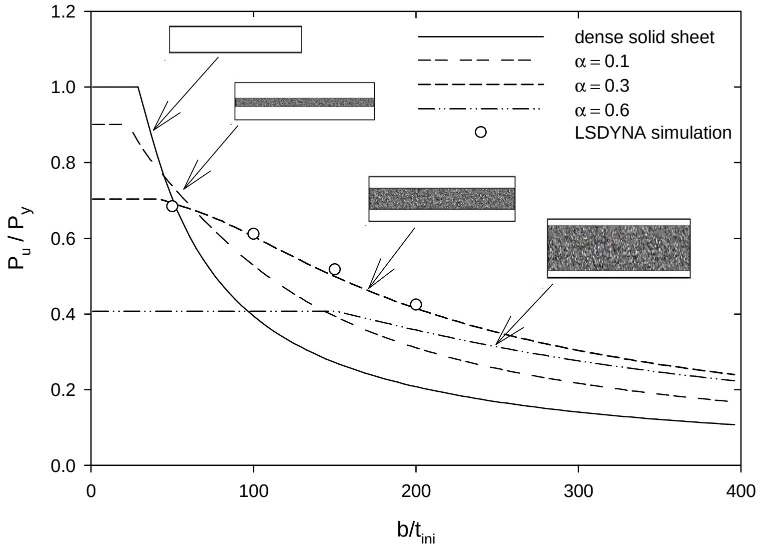


Figure 6: Strength of solid steel and sandwich panels of the same weight normalized to yield as a function of initial plate width-to-thickness, ρ=18% in the foam cores and depth of foaming varied

Design examples

In this section the traditional effective width design of a steel section is compared with the proposed procedure for sandwich panels. Calculations for the solid and foam sections are presented side by side to facilitate understanding of the proposed procedure for sandwich panels (Figure 7). Calculations pertaining to panels have '*p*' subscript to differentiate them from the solid steel section. The effective width method in the AISI specification (AISI, 2007) was employed to calculate the strength of the rectangular sections under concentric compression (Eq. C.4.1-1 in AISI 2007).

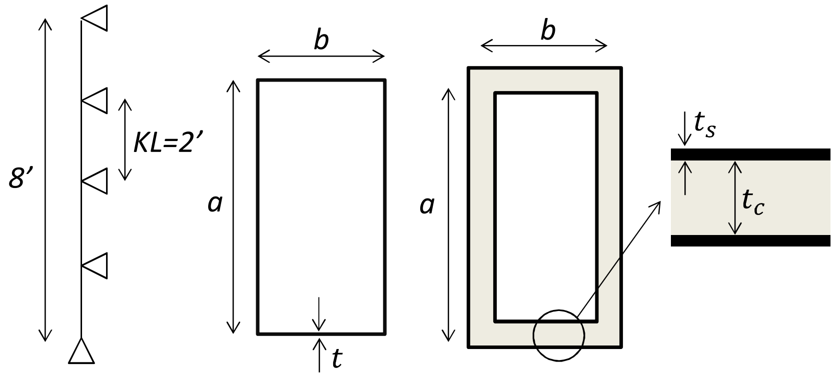


Figure 7: Cold-formed steel (left) and sandwich panel section (right). Both sections have the same weight.

The strength, P_n, of a concentrically loaded compression member may be calculated based on section C4 in AISI 2007 per Eq. C4.1-1:

$$P_n = A_e F_n \qquad\qquad P_{np} = A_{ep} F_{np} \tag{8}$$

The effective area, A_e, is calculated from the effective section based on section B2.1 in AISI 2007. The nominal buckling stress, F_n, is obtained from AISI 2007 section C4.1.

$$F_n = \begin{cases} 0.658^{\lambda_c{}^2} F_y & \text{if } \lambda_c \leq 1.5 \\ \dfrac{0.877}{\lambda_c{}^2} F_y & \text{if } \lambda_c > 1.5 \end{cases} \qquad F_{np} = \begin{cases} 0.658^{\lambda_{cp}{}^2} F_{yp} & \text{if } \lambda_{cp} \leq 1.5 \\ \dfrac{0.877}{\lambda_{cp}{}^2} F_{yp} & \text{if } \lambda_{cp} > 1.5 \end{cases} \tag{9}$$

where the global slenderness factor, λ_c, is obtained per AISI 2007 Eq. C4.1-4.

$$\lambda_c = \sqrt{\frac{F_y}{F_e}} \qquad\qquad \lambda_{cp} = \sqrt{\frac{F_{yp}}{F_{ep}}} \tag{10}$$

where F_e, or F_{ep} is the least of flexural, torsional, flexural-torsional buckling stresses and in this case:

$$F_e = \frac{P_{cr}}{A} = \frac{\pi^2 EI}{(KL)^2 A} \qquad F_{ep} = \frac{P_{crp}}{A_p} = \frac{\pi^2 (E_s I_{s1} + E_c I_c + E_s I_{s2})}{(KL)^2 (A_{s1} + A_c + A_{s2})} \tag{11}$$

where K is the effective length factor and I is the moment of inertia and A is the area of the cross-section. The panel flexural buckling load (P_{crp}) of the equivalent cross section is used, where I_{s1} and A_{s1} are the moment of inertia and area of the inner face steel sheet and I_{s2} and A_{s2} correspond to the outer face sheet. The steel foam core is characterized with I_c and A_c. The yield stress, F_y, is

$$f_y = f_{ys} \qquad f_{yp} = \frac{2\, t_s f_{ys} + t_c \cdot min\left(f_{yc}, E_c \frac{f_{ys}}{E_s}\right)}{2t_s + t_c} \qquad (12)$$

The effective section is composed of corner portions of the section plus the effective width, *b*, of the flat parts, *w*, of the elements. The effective width of each element of the cross section is determined according to Section B2.1 of AISI 2007.

$$b = \begin{cases} w & \text{if } \lambda \leq 0.673 \\ w \dfrac{1 - \frac{0.22}{\lambda}}{\lambda} & \text{if } \lambda > 0.673 \end{cases} \qquad b_p = \begin{cases} w_p & \text{if } \lambda_p \leq 0.673 \\ w_p \dfrac{1 - \frac{0.22}{\lambda_p}}{\lambda_p} & \text{if } \lambda_p > 0.673 \end{cases} \qquad (13)$$

where λ is the local slenderness factor of the element per AISI 2007, Eq. B2.1-4:

$$\lambda = \sqrt{\frac{f}{F_{cr}}} = \sqrt{\frac{F_n}{F_{cr}}} \qquad \lambda_p = \sqrt{\frac{f_p}{F_{cr}}} = \sqrt{\frac{F_{np}}{F_{cr}}} \qquad (14)$$

where $f = F_n$ for compressive members and F_{cr} is the plate elastic buckling stress for the flat portion of the element per AISI 2007 Eq. B2.1-5:

$$F_{cr} = k \frac{\pi^2 E_s}{12(1 - \nu_s{}^2)} \left(\frac{t}{w}\right)^2 \qquad F_{crp} = k_p \frac{\pi^2 D_p}{w_p{}^2 (t_c + 2t_s)} \qquad (15)$$

where *k* is the plate buckling coefficient and is equal to 4 for solid plate, *t* is the thickness of the steel panel, and E_s and ν_s are the Young's modulus and Poisson's ratio of steel. Sandwich panels with steel face sheets and a steel foam core may experience shear deformations in the core, and its local buckling critical stress is expressed in terms of core t_c and face sheet thickness t_s. Panel bending rigidity D_p and its buckling constant k_p are given in Eq. 2 and 3.

The effective area, A_e, for the box section is:

$$A_e = (2b_1 + 2b_2 + 2\pi r)t \qquad A_{ep} = (2b_{1p} + 2b_{2p} + 2\pi r)(2t_s + t_c) \qquad (16)$$

where b_1 and b_2 are the effective widths of the two sides of the box section (*a* and *b*) and *r* is the corner radius of the section.

A typical cold-formed steel box with thickness $t = 0.033\ in$ is considered. The box dimensions are selected based on approximating two channel section 600S162-33's connected together. Therefore, one side of the box is 6 *in* wide and the other side is 3.25 *in* wide. A corner radius of 0.185 *in* is assumed. The strength of the steel cross-section is compared with the steel foam sandwich column in Figure 7. The optimized panel is obtained by replacing 30% of the steel plate with the steel foam core, and the remaining 70% of the steel is divided between the two face sheets. Thus, the sandwich panel consists of two steel face sheets t_s and a foam core t_c:

$$t = 0.033\ in \qquad t_c = \frac{0.3}{\rho} t = 0.054\ in, \qquad t_s = \frac{0.7}{2} t = 0.012\ \ in \tag{17}$$

where $\rho = 0.18$ is the foam relative density, indicating that 18% of the volume is steel, and 82% is void space. Foam with $\rho = 0.18$ is approximately five times thicker than a steel sheet which has the same weight.

The calculation for the steel and sandwich panel section is given below.

$$F_e = 1010\ ksi \qquad\qquad F_{ep} = 314.7\ ksi \tag{18}$$

$$f_y = \ 50\ ksi \qquad\qquad f_{yp} = \ 15.6\ ksi \tag{19}$$

per AISI 2007 Eq. C4.1-4.

$$\lambda_c = \sqrt{\frac{50}{1010}} = 0.22 < 1.5 \qquad\qquad \lambda_{cp} = \sqrt{\frac{15.6}{314.7}} = 0.22 < 1.5 \tag{20}$$

The nominal buckling stress, F_n, is obtained from AISI 2007 section C4.1.

$$F_n = 0.658^{0.22^2} 50 = 48.97\ ksi \qquad F_{np} = 0.658^{0.22^2} 15.6 = 15.28\ ksi \tag{21}$$

The local buckling stress of the 6 in plate, per AISI 2007 Eq. B2.1-5:

$$F_{cr1} = \ k \frac{\pi^2 E_s}{12(1 - \nu_s{}^2)} \left(\frac{t}{w}\right)^2 = 3.66\ ksi \qquad\qquad F_{crp1} = k_p \ \frac{\pi^2 D_p}{w^2 (t_c + 2t_s)} = 12.3\ ksi \tag{22}$$

The local slenderness of the element per AISI 2007, Eq. B2.1-4:

$$\lambda_1 = \sqrt{\frac{F_n}{F_{cr1}}} = 3.65 > 0.673 \qquad \lambda_{p1} = \sqrt{\frac{15.6}{12.3}} = 1.11 > 0.673 \tag{23}$$

$$b_1 = (6 - 2 \cdot 0.185)\frac{1 - \frac{0.22}{3.65}}{3.65} = 1.45\ in \qquad b_{p1} = (6 - 2 \cdot 0.185)\frac{1 - \frac{0.22}{1.11}}{1.11} = 4.1\ in \tag{24}$$

The local buckling stress of the 3.25 $[in]$ plate, per AISI 2007 Eq. B2.1-5:

$$F_{cr2} = k\frac{\pi^2 E_s}{12(1 - {\nu_s}^2)}\left(\frac{t}{w}\right)^2 = 14.1\ ksi \qquad F_{crp2} = k_p\ \frac{\pi^2 D_p}{w^2(t_c + 2t_s)} = 39.5\ ksi \tag{25}$$

The local slenderness factor of the element per AISI 2007, Eq. B2.1-4:

$$\lambda_2 = \sqrt{\frac{F_n}{F_{cr1}}} = 1.86 > 0.673 \qquad \lambda_{p2} = \sqrt{\frac{15.6}{39.5}} = 0.62 < 0.673 \tag{26}$$

$$b_2 = (3.25 - 2 \cdot 0.185)\frac{1 - \frac{0.22}{1.86}}{1.86} = 1.36\ in \qquad b_{p2} = w_2 - 2r = 3.25 - 2 \cdot 0.185 = 2.88\ in \tag{27}$$

The effective area:

$$A_e = 0.22\ in^2 \qquad A_{ep} = 1.18\ in^2 \tag{28}$$

The column strength:

$$P_n = 0.22 \cdot 48.97 = 10.9\ kip \qquad P_{np} = 1.18 \cdot 15.28 = 18.0\ kip \tag{29}$$

The above example is repeated for thicknesses of 0.018 and 0.097 in. with the same box dimensions and a comparison of steel and sandwich panel sections as given in Table 1. Thinner (*t=0.033 in.)* and non-structural sections (*t=0.018 in.*) benefit greatly from the local buckling mitigation through the use of the steel foam sandwich panels. Locally slender ($b/t > 100$) sandwich columns are significantly stronger than traditional steel sections which have the same weight.

Table 1: Comparison of steel and sandwich panel columns (in, kip)

t_s *in*	P_n *kip*	$2t_s + t_c$ *in*	P_{np} *kip*	P_{np}/P_n
0.033	10.9	0.077	18.0	1.65
0.097	68.2	0.225	62.6	0.92
0.018	3.8	0.042	6.7	1.75

Conclusions

Steel foam is emerging as a new structural material with intriguing properties: high stiffness-to-weight ratio, high energy absorption, and other advantages. Foaming steel increases bending rigidity, but decreases the effective modulus and yield stress. A steel foam sandwich panel, consisting of solid steel faces and an interior of foamed steel further increases the bending rigidity, and limits the loss in effective modulus and yield stress. However, depending on the density of the foamed steel core, shear deformations and non-composite bending of the face sheets, must be accounted for in the behavior of steel foam sandwich panels. It is found that the approximation of Allen (1969) effectively captures these phenomena in the prediction of the elastic local buckling stress for a steel foam sandwich panel. This observation is verified, by detailed continuum finite element models of a steel foam sandwich panel with brick elements.

The ultimate strength of steel foam sandwich panels is explored with the detailed finite element model and it is found that Winter's classic effective width method suitably modified for the effective yield stress (derivations provided herein) and local buckling stress (based on Allen's method) is an excellent predictor of steel foam sandwich panels over a wide slenderness range. Further, exploration of the developed expressions utilizing commercially available steel foam demonstrates that foaming the middle 30% of a solid steel plate leads to optimal strength gains, which can be in excess of 170% of the strength of the solid steel section of the same mass.

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