Steel foam mitigates instability in structural members

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1 Introduction

The advent of the manufacture of metal foams made with steel as the base metal [1,2,3] should open the door to utilization of metal foams in civil structural applications, yet metal foams have not so far been used in civil structural applications because of their cost and because steel foams are not yet manufactured on a commercial scale compatible with the construction industry. The development of steel foams and their implementation in structures has been caught in a classic "catch-22" in which commercialization of the impressive work of materials scientists and metallurgists is hampered by the lack of a marketplace for steel foams, and the development of structural applications is hampered by the lack of inexpensive versions of the material available in industrial quantities.

In this paper, we seek to begin to break this impasse by demonstrating how steel foams may be used to mitigate against structural instability in members such as thin plates and thin-walled columns without increasing the overall weight of the structural member. One feature of the utilization of steel foams in civil structures is that it is likely that significant strength and tensile ductility will need to be retained by the material, in addition to the large stiffness-to-weight ratio and compressive ductility exhibited by most current, low density, metal foams. Therefore, our investigations cover a range of potential steel foam relative densities from 1.0 (solid steel) to 0.15 (a light steel foam, although one substantially denser than may commercially produced metal foams). The investigations in this paper are hypothetical in that we have not performed physical testing of the proposed structural elements, and in that the range of relative densities considered extends beyond that produced by current manufacturing methods. Nevertheless, given the demonstration over the past decade of the possibility of manufacturing steel foams with desirable properties, this work should provide further impetus to the development of steel foams suitable for use in civil structures, and the continued development of novel structural applications of steel foams.

This paper presents two candidate applications of steel foams to mitigate against elastic instability in structural members: (1) thin steel foam plates loaded in-plane in compression; (2) thin-walled lipped C-channels loaded in axial compression. In both cases the steel foam is assumed to use a material such as ASTM A572 Gr. 50 steel (elastic modulus E_s = 200 GPa) as the base metal and to have elastic properties that depend entirely on the relative density of the foam and the elastic properties of the base metal. The elastic buckling load of the plates is calculated using exact analytical methods, whereas eigenvalue analysis is used to numerically calculate the elastic buckling load of the channels. The eigenvalue analysis is carried out in the Finite Strip (FS) analysis context using the software package CUFSM [4] developed by one of the authors (Schafer).

2 Material and section properties of steel foam members

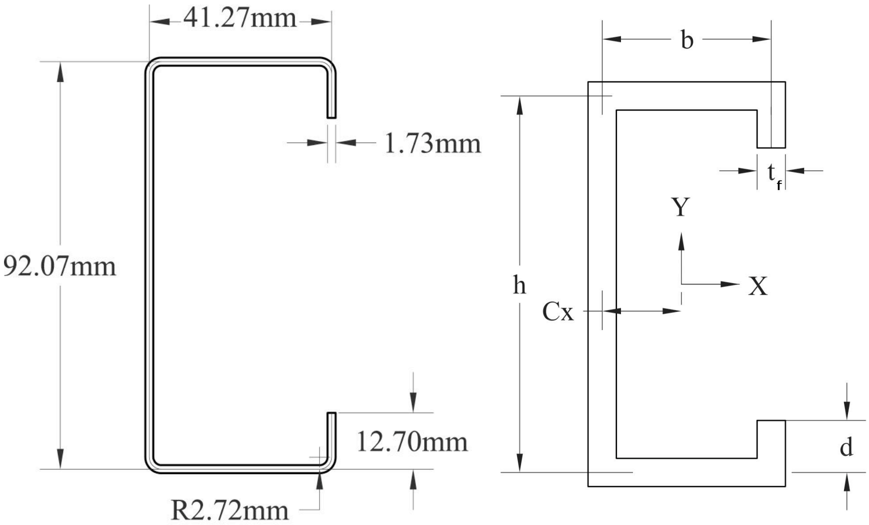
Gibson & Ashby [5] have established that, to a very good approximation, the effective elastic properties of foams depend only on the relative density ρ of the foam and the elastic properties of the base material. They have proposed that the relationship between the effective elastic modulus of the foam E_f and the elastic modulus of the base material E_s is

$$E_f = E_s\rho^2. \tag{1}$$

This expression agrees well with experiments conducted on polymer and metal foams and is adopted here to define the effective elastic modulus of the hypothetical steel foam.

In evaluating the elastic stability of structural elements the elastic modulus and the second moment of inertia of the element cross section, in addition to the loading condition, define the critical, or buckling, load. In structural elements that are composed of plate-like features the thickness of these features and their configuration determine the second moment of inertia. Here, we compare the buckling response of steel foam structural elements to elements made of solid steel (ρ = 1) with the same configuration of constituent plates and the same weight per unit length. Figure 1 shows a solid steel lipped C-channel (362S162-68) cross section with ρ = 1 and wall thickness t_s = 1.73 mm (Fig. 1a), and the equivalent channel with ρ < 1 and thickness t_f> t_s (Fig. 1b). Under the condition that the weight per unit length should remain constant, t_f is defined uniquely by ρ in terms of the thickness of the solid steel plate element according to

$$t_f = \frac{t_s}{\rho}. \tag{2}$$



(a) solid steel channel (b) steel foam channel

Figure 1. Change in wall thickness of thin-walled structural element when steel foam is substituted for solid steel and weight per unit length is constant. Coordinate system and nomenclature for cross section geometry.

3 Steel foam plates

The first steel foam structural element investigated is a plate loaded by in-plane axial compression. The plate is simply supported along all four edges. The buckling load of such a plate is

$$P_{cr} = \frac{4\pi^2 E_f t_f^3}{12\left(1-\nu^2\right)b} \tag{3}$$

in which E_f and t_f become E_s and t_s if $\rho = 1$ meaning that the section is made of solid steel. If Eqs. 1 and 2 are substituted into Eq. 3 to introduce the foam relative density, the buckling load of the plate becomes

$$P_{cr} = \frac{4\pi^2 E_s t_s^3}{12\left(1-\nu^2\right)b\rho} \tag{4}$$

demonstrating that, for fixed plate width b, and for a given initial thickness t_s the effect of replacing the solid steel of the plate with an equivalent mass of steel foam with $\rho < 1$ is to increase the elastic buckling load of the plate. This is readily explained by reference to equations 1 and 2 in which E_f is proportional to ρ^2 and the plate thickness is proportional to ρ^{-1}. Since the plate thickness appears to the third power in the plate buckling load, the increased thickness of the steel foam plate out-competes the simultaneous reduction in the elastic modulus of the steel foam compared to the elastic modulus of the solid steel. Note that this discussion of plate buckling capacity neglects the reduction in yield strength that accompanies a reduction in relative density, and also assumes that Poisson's ratio is invariant with respect to the relative density. Currently available expressions for the effective Poisson's ratio of metal foams apply only to low density foams ($\rho < 0.2$) with regular cell geometry. The Poisson's ratio of higher density foams is a subject of current investigation by the authors.

4 Steel foam channels

Thin-walled steel lipped C-channels are commonly used in a variety of structural applications such as wall studs and rack structures. Advantages of these structural members are that they are very lightweight and relatively easy to work with for the purposes of field assembly of structural systems. Their light weight arises from their very thin walls, typically less than 2 mm, and a result of this thinness is that elastic instability is a common limit state.

Elastic instability can occur in such channels in one of three fundamental modes, local, distortional, or global, or in modes which are combinations of the fundamental modes. The local mode is characterized by plate-like buckling of the web or flanges of the cross section and zero displacement of the nodes of the cross section. The global mode is characterized by rigid translation or rotation of the cross section without any change in the cross sectional geometry, and the distortional mode is characterized by plate-like buckling of the web accompanied by rigid rotation of the flanges and lips. The finite strip method [4] is a common numerical method for calculating the buckling modes and critical loads of thin-walled members. In the finite strip method, the cross section is discretized and is assumed to be extruded over a series of lengths, and at each length a numerical eigenvalue problem is solved for the modes (eigenvectors) and critical loads (eigenvectors).

Figure 2 shows the buckling curve obtained by the finite strip method as implemented in the software package CUFSM and the mode shapes obtained at the two local minima representing local and distortional buckling and the limiting lateral global buckling mode. The key features of this type of buckling curve are: (1) it clearly identifies the local, distortional, and global modes and critical loads, and (2) for any design half wavelength, which could correspond either to member length or to the unbraced length, the elastic buckling load can be read as the minimum point on the buckling curve at the design half wavelength or at any smaller half wavelength.

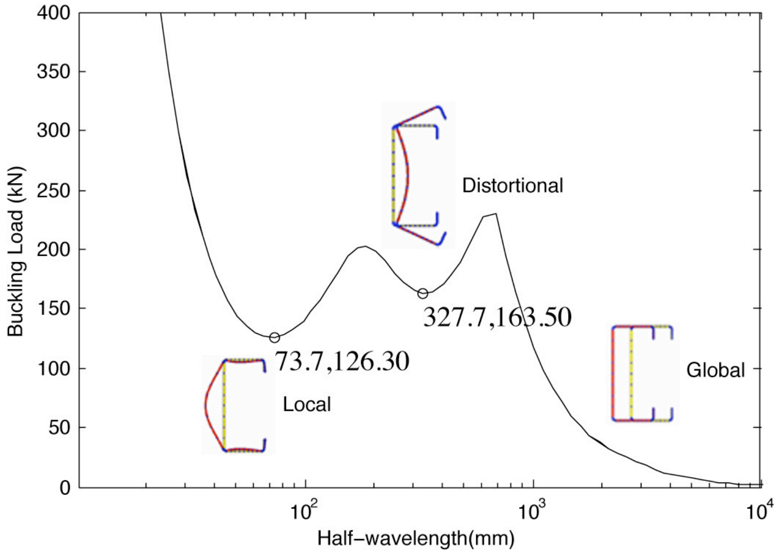


Figure 2. Elastic buckling curve for solid steel lipped C-channel of Fig. 1.

The local buckling strength of the channel is proportional to the plate bending stiffness coefficient $D = Et^3/12(1\text{-}\nu^2)$ of the web. If the cross section is made out of steel foam instead of solid steel the plate bending stiffness coefficient is $D_f = E_f t^3{}_f/12(1\text{-}\nu^2)$. Using Eqs. 1 and 2 we find that

$$P_{cr,local} \propto \rho^{-1} \tag{5}$$

just as is the buckling load of a simply supported plate given in Eq. 4. This is natural since local buckling of the channel is essentially a manifestation of plate buckling of the web. In the lateral global mode of a steel foam channel, on the other hand, the buckling strength is proportional to the weak axis bending stiffness $E_f I_{yy,f}$. The moment of inertia $I_{yy,f}$ can be approximated by

$$I_{yy} \approx \frac{2t_f b3}{12} + 2dt_f \bar{x}^2 + ht_f\left(b - \bar{x}\right)^2 + 2bt_f (b/2 - \bar{x})^2 \tag{6}$$

where $\bar{x}$ is the distance from the neutral axis of the section to the centerline of the lips. Since $I_{yy,f}$ is proportional to t_f which is in turn proportional to ρ^{-1}, and E_f is proportional to ρ^2, the lateral global mode buckling load obeys the proportionality

$$P_{cr,global} \propto \rho. \tag{7}$$

Equations 4 and 6 show that a steel foam channel is expected to exhibit greater local buckling capacity and less global buckling capacity than a solid steel channel with the same weight per unit length.

To fully investigate the effect of steel foam relative density on the buckling response of the thin-walled lipped channel of Fig. 1, CUFSM is used to calculate the buckling curve for channel relative densities ranging from 1.0 (solid steel) to 0.15 (light foam). We emphasize that the low relative densities are unlikely to generate practical structural shapes because the strength of low density foams is drastically compromised, and crushing of the cross section will begin to dominate the behavior, and furthermore acknowledge that the higher density foams are what many might refer to as a porous steel rather than a true foam material.

Figure 3a shows the series of buckling curves that are generated for the channel over the full range of relative densities investigated. These buckling curves are arranged to form a buckling surface that gives the buckling load as a function of half wavelength and relative density. Recalling that the design buckling load at a given design half wavelength is the minimum buckling load at that and smaller half wavelengths, and assuming here an unbraced length of 305 mm, the bold line superimposed on the buckling surface represents the design buckling load over the range of relative densities. A key observation is that as the relative density is decreased the dominant buckling mode changes from local ($1 > \rho > 0.7$) to distortional ($0.7 > \rho > 0.23$) to global ($0.23 > \rho$). The change in buckling mode is caused by the tendency of reducing the relative density to increase the local buckling load but decrease the global buckling load (Eqs. 5 and 7). Figure 3b projects the solid line of Fig. 3a onto the relative density axis, and also shows how the minimum local, global, and distortional buckling loads change with relative density. The results shown in the figure agree with Eqs. 5 and 7, and show that the distortional buckling load also increases with decreasing relative density, although more slowly than does the local buckling load. The bold line in Fig. 4 is defined by the minimum of the local, distortional, and global buckling loads at 305 mm half wavelength or less and gives the buckling load for the channel. This figure clearly shows the transition between modes as the relative density is decreased.

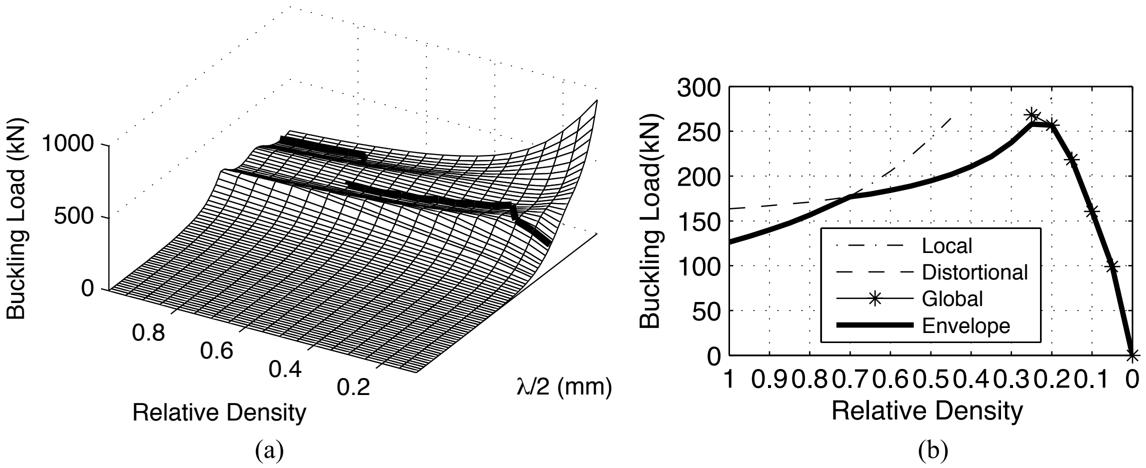


Figure 3. (a) Buckling surface showing relationship between buckling load, half wavelength (λ) and relative density. The solid line superimposed on the surface represents the buckling load for a 305 mm design half wavelength. (b) Buckling load as a function of relative density for a 305 mm design half wavelength. The critical mode transitions from local to distortional to global, and decreasing the relative density increases the buckling load until the relative density reaches approximately 0.23.

5 Conclusions

Steel foams are still a relatively new material, and have yet to find broad application in the field of structural engineering, a major user of structural steel. We present an example application of a hypothetical steel foam made of base metal similar to common structural steels and find that a thin plate loaded in-plane and simply supported along all four edges has a higher buckling load when made of a steel foam with relative density less than one. The buckling strength of the plate is inversely proportional to the steel foam relative density when the weight per unit length of the plate is held constant. Lipped C-channels are a more complicated structural member that are commonly made with very thin walls and are used in a variety of structural framing applications. By virtue of their thin walls the strength of such channels is often controlled by elastic instability in one of three modes, local, distortional, and global. The local buckling strength is inversely proportional to the relative density and the global buckling strength is directly proportional to the relative density so that a channel will have higher local and lower global buckling loads than a solid steel channel of equal weight per unit length. Numerical calculations show that for a design unbraced length of 305 mm decreasing the relative density of the steel foam channel increases the buckling capacity until the relative density reaches approximately 0.23, at which point the global mode becomes dominant and the buckling strength begins to decrease. A full treatment of the potential utility of steel foam thin-walled structural sections also requires consideration of member yield loads and stiffness, yet the results presented here give a strong indication that steel foam members are less susceptible to catastrophic buckling failure than equivalent solid steel sections.

6 References

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7 References

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