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Computational evaluation of limit states of thin-walled channels made from steel foam

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ABSTRACT

The objective of this paper is to explore the potential strength and serviceability implications of metallic foams, specifically steel foam, utilized as a thin-walled channel structural member. A typical advantage sought in the selection of a thin-walled member is minimal weight. However, the stability of the thin walls and the related limit states constrains the extent to which weight minimization may be utilized. As a material, steel foam (literally creating air voids in the steel microstructure) offers the potential to provide increased plate stiffness for a given weight and thus create even lighter thin-walled members and structures. In this work analytical material relationships are used to explore the structural potential for steel foam. First, the local buckling and yielding of an isolated steel foam plate is explored. Second, the local, distortional, and global buckling of a prototypical cold-formed steel channel using steel foam is examined. Finally, the strength and governing limit state of the channel as a function of relative density (i.e., the degree to which the material is foamed) is explored. The results show the key tradeoff made when foaming–stiffness per weight is increased, including stiffness related to member buckling modes; however, yield strength per weight decreases. Depending on the slenderness (in local, distortional, and global modes) of the member this tradeoff can be beneficial or detrimental.

1. Introduction

Thin-walled cold-formed steel lipped channels are commonly used in a variety of structural applications such as load-bearing and non-load bearing wall studs, floor joists, purlins, and girts. A key advantage of these structural members is that they are lightweight and easy to work with during field assembly. To achieve such lightness the walls of the folded member are thin, typically less than 2 mm, and as a result of this thinness plate instability is a common limit state.

In this study, we explore the possibility of lipped channels in which the member is formed from steel foam, rather than thin solid steel sheet. Steel foam has been developed over approximately the past 20 years and is now a mature material at laboratory production scales [1–3]. The material shares many similarities in microstructure and material properties with foams using metals such as aluminum and titanium as a base metal. These similarities include the possibility of open or closed cell microstructures, high elastic modulus to weight ratios, and stress–strain curves exhibiting a well defined yield point and long compressive plateau [15]. Because the microstructure of steel foam is similar to that of other metal foams, analytical equations linking the relative density and elastic modulus/yield stress [5] can be applied to steel foams. This is supported by the findings of a recent review paper on steel foam microstructure and mechanical properties [15]. By virtue of using steel as the base metal, steel foams promise greater eventual economy of scales and easier integration into civil structures due to the manufacturing and design infrastructure already in place for the use of steel. The steel foam lipped channels described here represent the first such candidate application.

This study examines, by analytical and empirical equations and numerical simulation, the behavior of two types of structural members made of steel foam: flat plates and thin-walled lipped channels. In both cases steel foams with relative density ranging from 1.0 (solid steel) to 0.05 (a very light steel foam) are examined, and the thickness of the steel foam plates or sections is chosen such that the unit weight is the same as for an equivalent solid steel plate or section.

To investigate the behavior of steel foam plates, exact expressions for the plate bending rigidity, elastic buckling capacity, and

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crush loads are used. Winter's equation [16], a semi-empirical expression, is used to combine the elastic buckling capacity and crush loads into the plate strength. Although Winter's equation is semi-empirical, not exact, it is widely used in design to evaluate the capacity of plates loaded in-plane, and it is used here to show that steel foam plates provide advantages in a structural engineering design context.

For thin-walled lipped channels, the finite strip method is used to evaluate the elastic buckling capacity of steel foam lipped channels and the Direct Strength Method is used to evaluate member strength. The finite strip method is a well established numerical technique for the instability analysis of thin-walled sections. The method is accepted for design by the specification of the American Iron and Steel Institute (AISI), and gives results equal to those obtained by the finite element method while consuming far fewer computational resources. The semi-empirical Direct Strength Method is encoded in the AISI specification, and is essentially a method of strength calculation for thin-walled members that is parallel in theoretical support and structure to Winter's equation [17].

2. Material and geometrical properties of the steel foam sections

To hold the weight per unit length of the cross section constant, while reducing the relative density of the walls (i.e. replacing the solid steel walls with steel foam walls), the thickness of the cross section has to be increased. The weight per unit length and per unit width of the solid steel and steel foam walls are $t_f\rho_f$ and $t_s\rho_s$ respectively, where t_f and t_s are the steel foam and solid steel wall thickness, and ρ_f and ρ_s are the steel foam and solid steel weight densities. The constraint on the weight per unit length of the member can then be expressed as $t_f\rho_f = t_s\rho_s$. By replacing the ratio ρ_f/ρ_s by ρ, the relative density of the foam, we find that

$$t_f = \frac{t_s}{\rho} \tag{1}$$

which relates the thickness of the steel foam walls to the thickness of the solid steel walls.

The material properties of metallic foams are different from those of solid metals and depend on base metal properties and relative density. Ashby and Gibson [10] developed the expressions

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

and

$$f_{yf} = f_{ys}\rho^{1.5} \tag{3}$$

Extending the preceding to steel foam: the elastic modulus and yield stress of steel foam is related to the elastic modulus and yield stress of solid steel and relative density [5]. In these equations subscripts s and f stand for solid steel and steel foam properties respectively. While a reduction in relative density results in lower elastic modulus and yield stress, the rates at which these two properties decrease differ. This difference plays a crucial role in determining how the relative density of the steel foam influences the buckling response of the thin plates and lipped channels.

3. Steel foam plate

Before investigating the behavior of the steel foam lipped channel, it is worthwhile to study the behavior of a simple steel foam plate since the walls of the lipped channel behave in many ways as thin plates. The web plate of the 362S162-68 lipped channel [6] has width and thickness equal to 92.08 mm (3.625 in) and 1.73 mm (0.068 in) respectively, and is chosen for this part of the study. Simply supported boundary conditions are assumed along the four plate edges. The steel elastic modulus and steel yield stress are chosen to be equal to $E_s = 2.03\times10^5$ MPa (29 500 ksi) and f_{ys}=345 MPa (50 ksi) respectively. The post-yielding behavior is assumed to be perfectly plastic.

3.1. Compression–moment failure interaction of steel foam plate

The plastic moment of a plate (M) (assuming simple one-dimensional behavior to develop basic relations for comparison) is a function of axial force (P), material property of the plate and geometry of the plate, and is given by

$$M = \left(\frac{t_f^2}{4} - \frac{P^2}{4b^2f_{yf}^2}\right)bf_{yf} \tag{4}$$

in which t_f is the plate thickness and f_{yf} is the material yield stress. By substituting plate thickness and plate yield stress (Eqs. (1) and (3)) into Eq. (4), the plate plastic moment can be written in terms of steel foam relative density. This expression is

$$M = \frac{bf_{ys}t_s^2}{4\sqrt{\rho}} - \frac{P^2}{4bf_{ys}\rho^{1.5}} \tag{5}$$

Two extreme cases of this interaction surface are the plastic moment (M_p) with no axial force, which is

$$M_p = \frac{bf_{ys}t_s^2}{4\sqrt{\rho}} \tag{6}$$

and the crushing load (P_{nf}) for zero moment, which is

$$P_{nf} = f_{ys}t_sb\sqrt{\rho} \tag{7}$$

Fig. 1 shows the compression–moment failure interaction surface for the steel foam plate. In part (a) of the figure, a section through

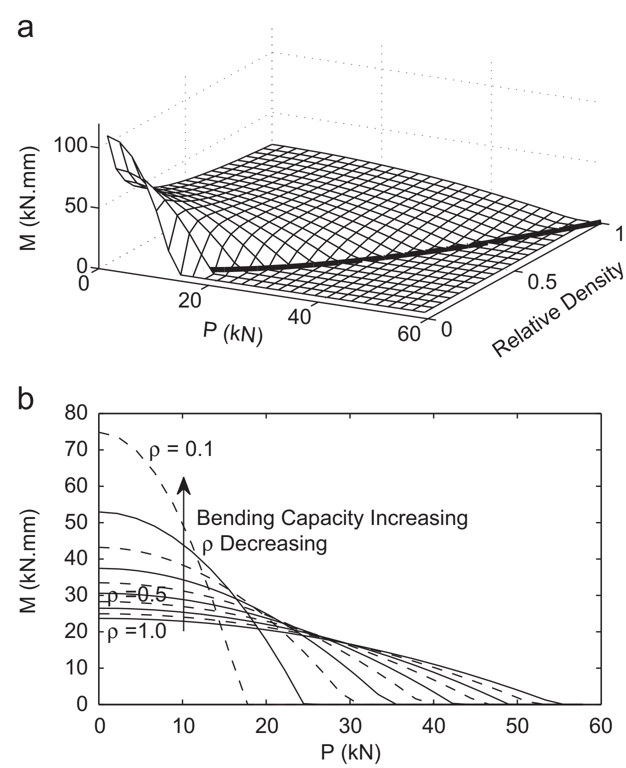

Fig. 1. Axial force–bending moment failure interaction surface of the steel foam plate (a) in 3D and (b) in 2D.