Closure to "Discussion of 'The Resistance of Clamped Sandwich Beams to Shock Loading' " (2005, ASME J. Appl. Mech., 72, pp. 978–979)

N. A. Fleck
e-mail: naf1@eng.cam.ac.uk

V. S. Deshpande

Department of Engineering, Cambridge University,
Trumpington Street, Cambridge CB1 1PZ, UK

The authors, Fleck and Deshpande (FD), are grateful for the interest shown in their work [1] by Tan et al. [2].

The aim of the FD study [1] was to present a simple analytical framework in order to understand the sequence of deformation events in shock-loaded sandwich beams. The analytical framework, although limited in accuracy, provides physical insight and allows for the interpretation of full numerical simulations and experiments. We reply to the comments of Tan et al. [2] point by point.

Points 1 and 2: We agree with Tan et al. [2] that the Taylor [3] analysis is of limited accuracy for strong air shocks. However, the FD analysis can handle strong air shocks provided one takes the transmitted impulse as an input to the model. This was done in the paper.

Point 3: (i) A global energy balance is a possible assumption for the core compression phase, leading to an internally self-consistent theory. FD used it in order to obtain simple analytical expressions for the degree of core compression. Recently, the accuracy of this assumption in predicting the sandwich panel shock response has been assessed by Deshpande and Fleck [4] for the case of a foam core. For such a core, shock wave effects and rate effects are important. The simple energy balance then overpredicts the degree of core compression as it neglects additional mechanisms of dissipation (largely viscous we believe).

Recall that the FD model was developed for lattice cores such as the corrugated core. The application of shock theory to those cores remains in open topic and hence FD used a simple energy balance argument to develop an initial understanding of the sandwich beam response.

Point 3: (ii) Tan et al. [2] argue that large internal energy can accrue in a metallic foam made from a rate independent plastic solid material by a switch in the deformation mode from bending to stretching of the cell walls. It is difficult to see how this mechanism switch can explain increases in plastic work by an order of magnitude or more at high velocities. This can argued as follows. An ideal work calculation can be performed by equating the change in internal energy shown in the FE calculations of Tan et al. [2] to the degree of axial stretch of the cell walls of the foam in the extreme case of all the cell walls equally sharing this energy change. In the case of an impact velocity $v_o = 200\ \mathrm{ms}^{-1}$, each cell wall would need to undergo a nominal compressive strain of 0.99[1] or equivalently the cell walls thickening by more than a factor of 100. This is physically unrealistic and not borne out by experiment [5]. It is the opinion of FD that a major component to the internal work in the simulations of Tan et al. [2] (Figs. 1 and 2) is from the artificial viscosity inherent in the explicit FE simulations using ABAQUS.

Point 4: We agree that the dynamic strength of lattice cores can exceed the static strength. This can be due to rate sensitivity and/or inertial effects. The FD analysis neglects both effects. Despite these simplifications (not inconsistencies) the model is remarkably robust.

Comparison of the FD analysis with more sophisticated calculations and experiments remains an active research topic, and FD welcome such activity.

References

[1] Fleck, N. A., and Deshpande, V. S., 2004, "The Resistance of Clamped Sandwich Beams to Shock Loading," J. Appl. Mech., **71**(3), 386.
[2] Tan, P. J., Reid, S. R., and Harrigan, J. J., 2004, Discussion: "The Resistance of Clamped Sandwich Beams to Shock Loading" (Fleck, N.A., Deshpande, V.S., 2004, ASME J. Appl. Mech., **71**, pp. 386–401), this issue.
[3] Taylor, G. I., 1963, *The Scientific Papers of G. I. Taylor*, Cambridge University Press, Cambridge, Vol III, pp. 287–303.
[4] Deshpande, V. S., and Fleck, N. A., 2004, "One-Dimensional Shock Response of Sandwich Plates," submitted to J. Mech. Phys. Solids 2004.
[5] Radford, D. D., Deshpande, V. S., and Fleck, N. A., 2005, "The Use of Metal Foam Projectiles to Simulate Shock Loading on a Structure," Int. J. Impact Eng., **31**, 1152.

[1]Here we assumed a solid material yield strength of 70 MPa which is consistent with the choice $\sigma_u = 0.7$ MPa by Tan et al. [2].

