BLAST RESISTANCE OF CLAMPED SANDWICH BEAMS

Vikram S. Deshpande*, Norman A. Fleck*

Cambridge University, Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, UK.

Summary   A systematic design procedure has been developed for analysing the blast resistance of clamped sandwich beams. The structural response of the sandwich beam is split into 3 sequential steps: stage I is the 1D fluid-structure interaction problem during the blast loading event, and results in a uniform velocity of the outer face sheet; during stage II the core crushes and the velocities of the faces and core become equalised by momentum sharing; stage III is the retardation phase over which the beam is brought to rest by plastic bending and stretching. The 3-stage analytical procedure is used to obtain the dynamic response of a clamped sandwich beam to an imposed impulse. Performance charts for a wide range of sandwich core topologies are constructed for both air and water blast, with the monolithic beam taken as the reference case. These performance charts are used to determine the optimal geometry to maximise blast resistance for a given mass of sandwich beam. For the case of water blast, an order of magnitude improvement in blast resistance is achieved by employing sandwich construction, with the diamond-celled core providing the best blast performance. However, in air blast, sandwich construction gives only a moderate gain in blast resistance compared to monolithic construction.

AN ANALYTICAL MODEL FOR THE BLAST RESISTANCE OF SANDWICH BEAMS

Consider a clamped sandwich beam, with identical face sheets of thickness h and core thickness c. The core is modelled as a compressible material: in uniaxial compression the core is assumed to deform at a constant stress with no lateral expansion up to a densification strain; beyond densification no further deformation is assumed to occur. The response of the sandwich beam is split into three stages:

  (i) Stage I - fluid-structure interaction phase.

 (ii) Stage II - core compression phase,

(iii) Stage III - beam bending and stretching phase.

Stage I - The initial fluid-structure interaction phase

G.I.Taylor [1] developed the solution for a one-dimensional exponentially decaying wave (decay constant θ) impinging a free-standing plate and thus computed the momentum transmitted to the plate by the blast. We follow this approach and similarly compute the momentum transmitted to the sandwich beam by treating the outer face of the sandwich beam as a free-standing plate. When the blast wave (with maximum impulse I and wave speed c_w) strikes a free-standing plate of thickness h made from a material of density ρ_f, it sets the plate in motion and is partly reflected. At the instant the plate achieves its maximum velocity, the pressure at the interface between the plate and the fluid is zero and cavitation sets in shortly thereafter. The momentum per unit area I_{trans} transmitted into the structure is then given by

$$I_{\text{trans}} = \psi^{\psi/(1-\psi)} I, \tag{1}$$

where $\psi \equiv \rho_w c_w \theta / (\rho_f h)$. Since ψ is much larger for the sandwich beam compared to a monolithic beam of the same mass, it is expected that a smaller impulse is transmitted into the sandwich beam compared to the monolithic beam.

Stage II - Core compression phase

The impulse I_{trans} per unit area imparts a velocity $v_o = I_{\text{trans}}/(\rho_f h)$ to the outer face. The outer face compresses the core, decelerating the outer face while simultaneously accelerating the inner face. The final common velocity of the faces and the core is dictated by momentum conservation and thus also gives the loss in kinetic energy in this phase. Equating this loss in kinetic energy to the plastic dissipation in compressing gives the core compression strain. Typically, the core compression time is small compared to the structural response time, and thus the transverse deflection of the inner face of the sandwich beam in this stage can be neglected.

Stage III - Beam bending and stretching phase

At the end of Stage II, the sandwich beam has a uniform velocity except for a boundary layer near the supports. The beam is brought to rest by plastic bending and stretching. This problem has been investigated by a number of researchers and here an analyses valid for both small and large deflections was performed. The analyses gives the deflection w and response time T of the beam as a function of the beam geometry and impulse I.

The above analysis has been shown to compare well with 3D Finite Element calculations performed in a parallel study [2].

OPTIMAL DESIGN OF SANDWICH BEAMS FOR BLAST RESISTANCE

The analysis detailed above is used to investigate the relative response of monolithic and sandwich beams to blast loading. In a typical design scenario, the solid material and length of the structural element are dictated by design constraints such

as corrosion resistance and bulkhead spacing, thus leaving the sandwich panel geometry, viz. the face sheet and core thickness, and core relative density and topology, as the free design variables. Here we optimise with respect to these variables while keeping the span $2L$ of the beam fixed.

Water blast

The maximum blast impulse sustained by the sandwich beams with the five different topologies of the core subject to the constraint on the inner face deflection $w/L \leq 0.1$, are plotted in Fig. 1a as a function of the non-dimensional mass $\bar{M}$ of the beam. For comparison purposes, the blast impulse sustained by a monolithic beam subjected to the same constraints is also included in Fig. 1a. It is evident that sandwich beams all perform considerably better than the monolithic beam. This is mainly due to the fact that the sandwich beams have a thin outer face sheet which results in a small impulse transmitted into the structure whereas the relatively thick beams in monolithic design absorb a larger fraction of the blast impulse. A comparison of the various sandwich cores shows that sandwich beams with a metal foam and pyramidal core almost attain the performance of the hexagonal-honeycomb core. However, the diamond-celled core beams, which have high strength in both the through-thickness and longitudinal directions out-perform the other sandwich beams with a performance that approaches the "ideal" sandwich core limit.

Air blast

Due to the low acoustic impedance of air, the Taylor fluid-structure interaction parameter $\psi \approx 0$ for an air blast. The air blast performance of the optimised sandwich beams is compared to that of the monolithic beam in Fig. 1b. Specifically, the maximum sustainable impulse is plotted against the non-dimensional mass $\bar{M}$, with the deflection constraint $\bar{w} \leq 0.1$ imposed. In contrast to the case of water blast, the performance gain upon employing sandwich construction instead of monolithic beams is relatively small; at best the diamond-celled core sustains an impulse about 45 % greater than a monolithic beam of equal mass.
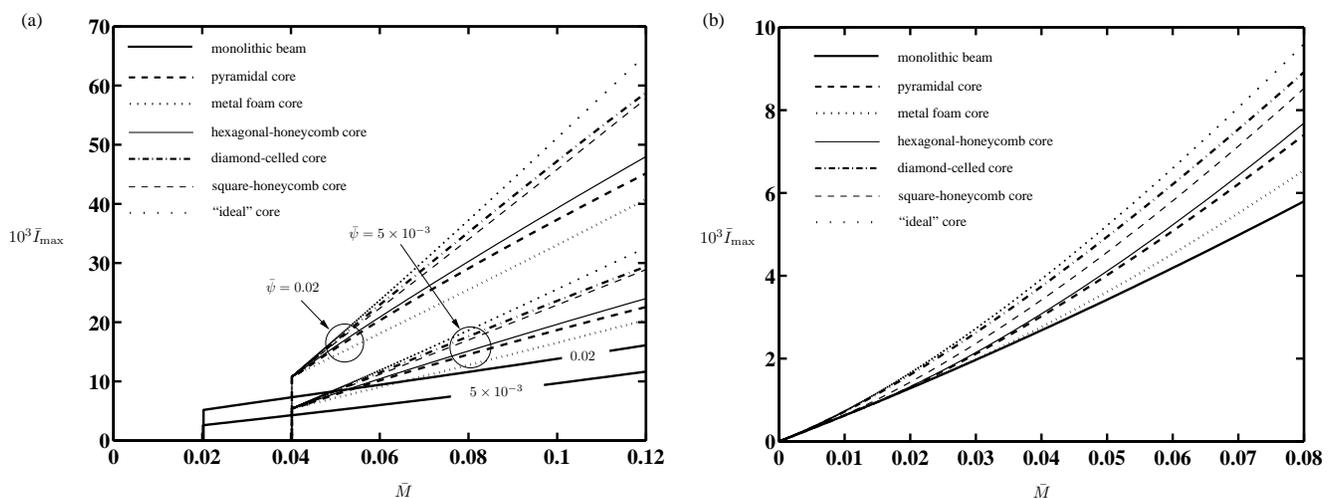

Figure 1. A comparison of the maximum blast impulse sustained by monolithic beams and by optimal designs of sandwich beams. (a) Water blast and (b) air blast.

CONCLUDING REMARKS

An analytical model has been developed to determine the response of both monolithic and sandwich beams subject to air and water borne blasts. For the case of water blast, an order of magnitude improvement in blast resistance is achieved by employing sandwich construction. This is mainly due to fluid-structure interaction: the reduced mass of the sandwich outer face leads to a reduction in the impulse transmitted to the structure from the water. In air, the impedance mismatch between air and the face sheet is comparable to that between air and a monolithic beam; consequently, the use of sandwich construction gives a more moderate gain in blast resistance compared to monolithic construction. For both air and water blast the diamond-celled core sandwich beam gives the best performance due to the longitudinal strength provided by the core.

References

[1] G I Taylor. *The scientific papers of G I Taylor, Vol III*, pages 287–303. Cambridge University Press, 1963, The pressure and impulse of submarine explosion waves on plates, 1941.
[2] Xue and J W Hutchinson. A comparative study of blast-resistant metal sandwich plates. To appear in *International Journal of Impact Engineering*, 2004.