A novel lightweight sandwich panel with substantial resistance to ballistic penetration

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Abstract

The goal of this study was to develop a lightweight structural panel that also provided substantial resistance to ballistic penetration. Conventional sandwich structures consist of a low density core laminated between thin stiff facing sheets. Their specific flexural stiffness can be very high but their out-of-plane impact strength is typically so low as to barely slow a high-energy projectile. In a new configuration examined here, the standard core has been replaced by a novel hybrid structure that can redirect or dissipate most of the incoming projectile's energy. This new core consists of woven Aramid textile loosely anchored to the facing sheets by slender sacrificial pins. A numerical model of this structure was evaluated using Abaqus Explicit Nonlinear software. The initial phase of parameter study focused on the combined effects of pin modulus and strength. Various metrics were used to assess the simulated efficacy of armour test panels struck by a 5.66 mm (0.233 calibre) bullet travelling at 300 to 900 m/s (1000 to 3000 ft per s). The salient result was that the optimal choice of pin properties varied according to the chosen metric. For example, stiff weak pins maximized energy dissipation but stronger pins minimized backface deflection and softer pins minimized peak fabric stress. The overall pattern indicated that a pinned ballistic fabric core could, when suitably scaled, provide far better ballistic protection than standard core materials, with minimal weight or cost penalties.
Keywords: ultralight armour, sandwich structure, ballistic impact, finite element modelling, Abaqus, hybrid core, plain weave, sacrificial pins.

1 Introduction

The objective of this research was to develop a lightweight composite structure that could also provide substantial resistance to ballistic penetration. The initial

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goal was to perform a model-based assessment of the new structure's potential. Recall that a conventional sandwich structure consists of a low-density core laminated between two thin strong facing sheets. The crucial advantage of separating the facing sheets is to move them away from the neutral surface and to thereby obtain higher flexural stiffness, and strength, than a fully dense laminate of the same weight [1]. Detracting from these desirable attributes, most sandwich structures have very poor out-of-plane impact strength and often provide less resistance to a high speed projectile than two unbonded facing sheets [2, 3].

A great deal of research has been done on composite armour [4–7] and many of the tradeoffs associated with different approaches to military armour design are well understood. For example, the decision to armour a lightweight vehicle fuel tank must also consider the effect of added weight on payload, mobility, and range. In most cases, unarmoured sandwich structures are totally unsuitable for applications that cannot tolerate panel perforation.

When a projectile strikes a typical sandwich panel it crushes the core material below the point of initial contact [8]. This produces very high bending stresses in the front facing sheet, which can allow a relatively low energy projectile to break into the core region. Here, the impact force may be spread over a broader area of the rear facing sheet but the threshold for total penetration is still very low [8]. Adding a rigid front surface is beneficial because it helps spread the impact forces over a broader area while blunting and slowing the projectile. For example, a hard ceramic plate-like structure plus one or more compliant intermediate layers can be laminated to the front facing sheet [9, 10]. In applications that can tolerate panel perforation, anti-spall liners can also be secured to the rear facing sheet to capture and retain penetrating fragments or spalled chips. In this context, the effectiveness of woven Aramid and/or coated polyethylene fiber is well documented [11, 12].

All of the above approaches can be effective but each implies increased structural volume and weight. Replacement of standard core materials with dissipative structures is also possible. For example, pyramidal or truss-shaped structures can absorb far more energy than a conventional honeycomb [13]. Due to recent conflict in the Middle East, the ever-present need for effective armor has been compounded by limits on the supply of certain materials. Of particular relevance, armour systems incorporating ballistic fabrics must preserve and make optimal use of their intrinsic material strength.

2 Methods

The methods used to evaluate a new structural armour design are described in two sections. The first explains the motivation for its physical layout and the second describes the specific procedure used to conduct the impact simulations.

2.1 Physical characteristics

The energy-dissipating hybrid core is used between conventional fibre reinforced facing sheets. In Figure 1, it has a) two regions occupied by a compliant space filler, b) an intermediate region occupied by layers of ballistic fabric, and c) a regular array of Z-pins secured to both facing sheets and passing through the fabric weave. Stitching and pinning are typically used to delay core shear and delamination in foam core structures [14]. Their use here in conjunction with ballistic cloth is motivated by rather different factors.

The usual role of a sandwich core is to transfer shear loads between the two facing sheets and to offset them from the neutral surface. In the new hybrid core, the pin array serves to transfer the shear loads and any number of materials can perform the space filling function. None of these needs to be bonded to the facing sheets or to the ballistic fabric. The only critical requirement is to locate the other components during assembly and then to exert minimal effect on the fabric motion during impact. It might even be possible to extract or dissolve the space filler prior to service as a weight savings measure.

The usual role of ballistic fabric in flexible armour is to redistribute and dissipate the focused kinetic energy of an impacting projectile [11]. Other investigators have described these various mechanisms, which could remain active in the new configuration [11, 12]. However, the more critical function is now to capture projectile energy elastically, and then to transfer it in a progressive fashion into the sacrificial pin array.

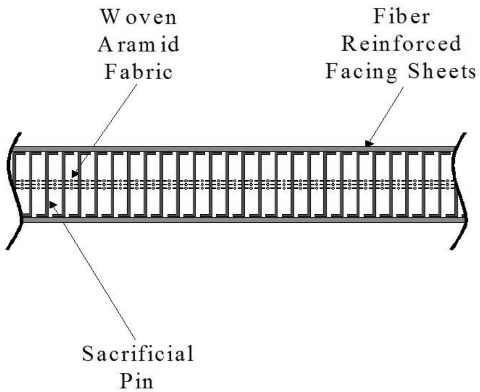

Figure 1: Structural armour with energy dissipating core.

Fabric based armour is most effective when its component yarns and layers are free to realign and shift during impact. Bar stitching between layers is often used but tends to diminish effectiveness. The original motivation for sandwich panel pinning was to control core delamination without any regard to its possibly negative effect on impact resistance. Initially, large pins or transverse screws were inserted into an assembled panel at right angles to its mid-plane. Increasingly, smaller pins are being inserted at oblique angles into foam carriers prior to face sheet assembly. For example, Aztex, Inc. has a patented ultrasonic insertion technology that uses multi-axis robotics to reinforce lightweight core material with small diameter pins (i.e., 0.25 mm=0.010”), often of pultruded carbon. In this process, various pin materials can be inserted into a foam carrier in uniform or spatially graded patterns. Oblique rather than orthogonal pining can alter the balance between compressive and shear stiffness. Usually, the pin ends are left to protrude from both sides of the foam carrier and are later pressed and cured into the facesheets. In other cases, the pin ends can be bent down against the foam carrier and later bonded to the inside of the facing sheet (as shown in Figure 1). To date, the intended function of such pins has been to stiffen and strengthen the other materials within the core.

In the new configuration, the pins serve a different role. When a projectile punches through the front facing sheet and approaches the ballistic fabric layers, a transverse wavefront moves laterally through the fabric and away from the point of impact. As this occurs, a large number of pins bend towards point of impact, as they resist the transverse motion of the fabric. Since each pin is anchored to the facing sheets, some of the energy extracted from the projectile by the fabric is then transformed into pin strain energy. At some critical threshold, the pins begin to break in a sequential manner, which can extend over a large area. A suitably scaled pin array can dissipate a large amount of energy, via a process that does not rely on the intrinsic dissipative capacity of ballistic fabric. Instead, the synergistic interaction between the fabric and the sacrificial pins forms the basis for a new tunable mechanism of impact energy dissipation. Having defined the basic design of the new hybrid core, the key question to be answered is how well can it perform in comparison to relevant baselines.

2.2 Numerical simulation

Many physical parameters affect the performance of a composite armour test panel. For a sandwich incorporating the new hybrid core, these include 1) the projectile's geometry, mass, and velocity, 2) the fabric's weave and material properties, and 3) the pin spacing, material, diameter, and alignment, as well as the panel's shape, dimension, and edge fixation. The goal here was to capture the essential nature of a rapidly unfolding process that begins when a high velocity projectile struck a panel of this general type, with a specific combination of these parameters. The impact simulations were obtained by solution of the equations of conservation of mass, momentum, and energy. With the advent of commercial finite element codes suitable for impact analysis, it has become technically feasible to develop true-scale literal models of any physical system. In the present case, this might entail the representation of every pin and yarn nestled between the two facing sheets. In fact, other investigators have developed such models, both for fabrics and for composites incorporating such fabrics, by accurate portrayal of every woven yarn, and by approximation of its interactions with other similar structures [9, 15]. When suitably benchmarked, models of this kind provide intricate detail about small-scale behaviours soon after and close to projectile impact. However, for broader ranging parameter study of larger scale behaviour, this approach can be unwieldy.

The interaction between a projectile and ballistic fabric has also been studied using a different technique, which has been validated in several contexts [16–19]. The method is variously referred to as the trellis or cargo net approach. A homogenized representation of woven fabric is obtained using a network of larger yarns with the same material behaviour as the real yarns but a suitably rescaled cross section. Typically, an assembly of user defined bilinear elastic truss elements (e.g., linear in tension, buckling in compression) is used to obtain a coarse planar net. This overlooks the undulating nature of real fabric but can capture the essential character of its in-plane response. A further idealization made at this point is that the warp/weft cross-over points are tied by friction during impact. A cargo net has no initial shear stiffness and a limited ability to conform to a doubly curved surface (e.g., a bullet nose) but both of these challenges can be addressed. In the present study, various approaches were used to represent the yarn packing effect seen in loose woven fabric subjected to large shear strain [19]. In practice, consistent results were obtained by overlaying the net with an elastic membrane with shear properties based on experimental data [17, 19]. The hemispherical bullet nose was also flattened by 0.05 mm (~0.002") to control artefacts related to net distortion near the point of impact.

Nonlinear dynamic structural analysis was performed using Abaqus Explicit finite element analysis software operating on a 3.2 GHz Pentium IV processor. Abaqus was selected because its solution algorithm is well proven for impact [20], and because its user interface facilitates construction of the special pinned cargo net. The key challenge was solution noise (caused by the rapid propagation of sound through the net), which was overcome by limiting the maximum timestep to <4e-8 seconds and by artificial solution damping [21]. Run times of about 8 hours were required to simulate real time events lasting < 0.006 s.

The initial phase of parameter study focused on resolving the combined effects of pin elastic modulus and ultimate strength (or equivalently, failure strain). Both properties were varied to obtain a test matrix spanning a number of potentially suitable materials (e.g., cellulose; nylon; polyethylene; E-glass; aluminium; Kevlar 49 & 129; AS-4, P-55, & P-100 carbon, boron, SiC, etc). Many other parameters were simply assigned values consistent with current practice or technology. For example, all test panels had 1.0 mm (0.04") thick facing sheets, a total thickness of 14.7 mm (0.58"), a square area of 0.25 m x 0.25 m (10" x 10"), and were pinned along all four edges. Similarly, every projectile was a high velocity 5.66 mm diameter (0.223" calibre) round nose bullet striking the panel at right angles, represented as a rigid hemispherical surface with a mass of 3.56 g (55 grains) initially moving at 150 to 900 m/s (~500 to 3000 ft/s). (Note: the Abaqus contact algorithm updated the mesh contact forces after each time step.) In practice, most results were obtained for an initial velocity of 450 m/s (~1500 ft/s). The cargo net model consisted of a regular square grid of user-defined 0.42 mm (0.017") diameter truss elements spaced at 2.54 mm (0.10"), assigned the same properties as Dupont's Kevlar 129 [22], and representing a plain weave uncoated Aramid-like fabric with 0.010 diameter yarns spaced at 0.84 mm (0.033"). (Note: the ratio of the truss element diameter to that of the actual yarn was set equal to the inverse square root of their respective spacings.) The net was loosely anchored to the facing sheets by 0.5 mm (0.020") diameter by 12.7 mm (0.50") long beam elements halfway between each crossover point. (Note: the areal density of the pins was therefore 3.1%.)

Referring to Figure 1, the long leg of each pin was set perpendicular to the layered fabric, with its ends simply supported. (Note: its two short legs, the facing sheets, and the (possibly absent) space filler did not explicitly appear in the model.) The pin material was assumed to be linear elastic up to brittle failure and its Young's modulus was varied over the range of 70 to 490 GPa (~10 to 70 Msi). Similarly, the pin failure strain was varied over the range of 0.5 to 5.0%, implying ultimate strengths as low as 350 MPa (~50 Ksi) or as high as 2450 MPa (~ 3500 Ksi). To provide two baselines for comparison, simulations were also conducted for panels with `no pins' (fabric only) and with 'no pins, extra fabric' (i.e., fabric mass to balance missing pins).

3 Selected results and discussion

Any armour requires tradeoffs between competing constraints and requirements. By itself, inclusion of unpinned ballistic fabric in the core of an unarmoured sandwich panel should increase resistance to projectile penetration. The only motivation for then adding the sacrificial pins would be to further improve performance relative to the lower baseline defined by the 'no pins' panel, or hopefully, the higher level defined by the 'no pins, extra fabric' panel. Various metrics of performance were elaborated to quantify the efficacy of particular combinations of pin stiffness and strength. The salient finding was that the best choice of pin materials was not the same for each metric considered. For example, relatively stiff weak pins maximized energy dissipation but stronger pins could reduce backface deflection and softer pins could reduce peak yarn stress. Any presentation of quantitative results must therefore be prefaced by a brief explanation of the relevant metrics of armour performance.

The National Institute of Justice provides guidelines for measuring the 'backface signature' of flexible body armour using a clay backing technique [23]. Most data suggests that the likelihood of severe trauma in the absence of projectile penetration is greatly increased by excessive backface deflection [23]. By analogy, the structural armour sandwich also experienced the largest out-of-plane displacement of its fabric directly beneath the point of impact. Below some critical velocity, the projectile was simply captured by the hybrid core and never reached the rear facing sheet. However, since the panel thickness was three times less than the NIJ limit for body armour, the model did allow the fabric to break through the rear facing sheet if the panel was struck by a more energetic projectile. In this context, the *maximum backface deflection* is the most useful measure of relative risk to the protected space.

Ballistic fabric experiences the highest yarn stresses near the point of projectile impact, and these stresses are attenuated as the deformation wavefront moves outwards. In the model, the elastic trellis elements were made infinitely strong to prevent the projectile from passing through the coarse net. In reality, Aramid exhibits a rate dependent finite strength that limits the maximum permissible yarn strain. Since the model allowed the trellis element strains to exceed this limit, more than one layer of fabric was required to carry the imposed loads. Given that these issues were correctly addressed, the *peak yarn stress* is the most useful measure of relative risk of fabric perforation.

The amount of energy dissipated by a single pin failure was always small, regardless of its specific properties. In fact, the optimal situation occurs when the material of each pin is stiff and strong enough to ensure that it and every one of its fellows in the panel can only just fail. In any event, the only way to dissipate a large fraction of the projectile's impact energy was to break a large number of pins. When all pins in a given panel are the same, the *total energy dissipated* by pin failure provides an integrated measure of the benefit of pinning.

The clamped `no pins' panel underwent a maximum backface deflection of 79 mm (3.11") when struck by a projectile travelling at 450 m/s (1500 ft/s). This value was nearly twice the 44 mm (1.73") limit for flexible body armor [23]. However, with the addition of pins weighing ~0.067 N/m2 (0.169 lbs/ft^2), this maximum could be reduced to 40 mm (1.57") or less. In Table 1, no data was obtained for cells denoted N/R (not realistic) due to excessive trellis distortion. However, for any of the shaded combinations, the maximum backface deflection was reduced below the acceptable level (i.e., 44/79=0.56). Note that the `no pins, extra fabric' panel still exceeded the NIJ limit by more than 20%. As a rule, stiffer stronger pins produced a larger reduction in backface deflection but also increased the peak stress in the trellis elements.

Table 1: Maximum backface deflection normalized by 'no pins' value.

		Pin failure strain (%)					
		1.00	**1.25**	**1.50**	**2.50**	**3.75**	**5.00**
Pin Young's modulus (Msi)	**10**	0.81	0.75	0.71	0.58	0.54	0.53
	20	0.70	0.64	0.59	0.53	0.54	0.54
	30	0.64	0.59	0.55	0.50	0.54	0.53
	40	0.60	0.55	0.53	0.50	0.54	0.53
	50	0.57	0.52	0.53	0.54	0.53	0.52
	60	0.55	0.53	0.53	N/R	N/R	N/R
	70	0.53	0.54	0.55	N/R	N/R	N/R
No pins							1.00
No pins, extra fabric							0.67

Table 2 shows the maximum trellis strain (normalized by the 'no pins' value) after 450 m/s (1500 ft/s) impact. If the peak fabric stress can be assumed to be proportional to trellis strain, these results imply that the peak yarn stress was increased up to 1.7 x by relatively stiff strong pins (lower right) but could be reduced 2.0 x by softer weaker pins (upper left). However, none of the pinned panels could reduce the peak yarn stress below the 'no pins, extra fabric' level.

In the model, the trellis element strain was allowed to exceed the range of values that could be endured by a single straight Aramid fiber. The rationale was that a stack of loosely woven uncoated fabric could undergo much larger strains prior to failure, due to the effects of internal shifting, uncrimping, and slippage. It can then be illustrative to assume that the required number of fabric layers must equal or exceed the ratio of the trellis strain to the maximum allowable strain in a single layer. For example, the values in Table 3 were obtained by assuming that the strain in a single layer could not exceed 20%.

Table 2: Maximum trellis element strain normalized by 'no pins' value.

		Pin failure strain (%)					
		1.00	**1.25**	**1.50**	**2.50**	**3.75**	**5.00**
Pin Young's modulus (Msi)	**10**	0.48	0.53	0.58	1.02	1.36	1.48
	20	0.59	0.68	0.79	1.37	1.48	1.67
	30	0.57	0.74	1.12	1.43	1.67	1.67
	40	0.65	0.80	1.31	1.51	1.67	1.66
	50	0.72	0.88	1.44	1.68	1.67	1.65
	60	0.75	1.38	1.52	N/R	N/R	N/R
	70	0.89	1.50	1.69	N/R	N/R	N/R
No pins							1.00
No pins, extra fabric							0.28

Table 3: Number of Aramid layers required to stop projectile @ 1500 ft/s.

		Pin failure strain (%)					
		1.00	**1.25**	**1.50**	**2.50**	**3.75**	**5.00**
Pin Young's modulus (Msi)	**10**	4	5	5	9	12	64
	20	5	6	7	12	13	72
	30	5	7	10	12	14	72
	40	6	7	11	13	14	72
	50	6	8	12	14	14	72
	60	7	11	13	N/R	N/R	N/R
	70	8	13	14	N/R	N/R	N/R
No pins							9
No pins, extra fabric							3+1

In Table 3, note that softer weaker pins reduced the number of layers required to stop the bullet relative to the 'no pins' panel. Extrapolating beyond these results, the simulations suggested that a nominal 1/2"' structural armour sandwich panel, if pinned with a sufficiently soft and weak material, could weigh about the same as a conventional foam core panel while requiring no more ballistic fabric than the 'no pins, extra fabric' panel. By idealizing the trellis elements as perfectly elastic, the model neglected any intrinsic dissipation by Aramid, and provided a conservative bound on armouring capacity. In Table 4, note that the total energy dissipated by pin failure was greatest when the pins were relatively stiff but weak. In contrast, much less energy was dissipated by stronger pins of the same stiffness. However, much softer pins with reduced strength could still dissipate a substantial amount of energy while lowering peak yarn stress by up to a factor of two. Some of the elastic strain energy absorbed by the cargo net remained available to reaccelerate the bullet. The scaling was such that the rebound velocity was similar for either unpinned panel. Any of the better choices of pin material could reduce the rebound energy by a factor of two. As expected, the number of failed pins increased as the impact velocity increased, as the pin strength decreased, and as the pin modulus decreased. In a panel pinned with soft weak pins not unlike ductile aluminum, the rate of pin failure increased from as little as 7.4% @ 150 m/s to 64.0% @ 450 m/s to >95% for 900 m/s. The spatial distribution of pin failure exhibited a complex dependency on many factors. In absolute terms, the pin failures never dissipated more than 25-35% of the initial impact energy (~4000 in-lbs @ 1500 ft/s), because the test panels were relatively small and had clamped corners. The balance was either returned to the rebounding projectile or left behind in the moving elastic fabric. Even so, it was clear that the presence of the pins altered the basic kinetics of the projectile-structure interaction. In comparison to the 'no pins' baseline, the addition of stiff strong pins increased the fabric's initial resistance to deflection from its neutral position but created high yarn stresses around the point of impact. Thus, strong pinning had the undesirable effect of focusing impact energy on a very small area, increasing the risk of fabric perforation. In contrast, softer weaker pins were easily broken but did not inhibit the fabric's ability to gather energy from the projectile. In effect, weak pinning was much more effective because a much larger number of pins were able to extract energy from the fabric over a longer period. Interestingly, spectral analysis of the fabric motions indicated that pinning shifted power into higher frequency, shorter duration modes.

Table 4: Total energy dissipated by pin failures @ 1500 ft/s (lb-in).

		Pin failure strain (%)					
		1.00	**1.25**	**1.50**	**2.50**	**3.75**	**5.00**
Pin Young's modulus (Msi)	**10**	1,010	1,160	1,210	995	651	449
	20	1,170	1,210	1,180	559	375	46
	30	1,290	1,210	911	424	38	62
	40	1,330	1,290	710	314	45	82
	50	1,290	1,270	481	29	56	102
	60	1,330	580	419	N/R	N/R	N/R
	70	1,360	390	214	N/R	N/R	N/R

4 Summary

A sandwich panel with a pinned fabric core can potentially provide much better impact protection than a conventional foam core structure, with little increase in cost or weight. The optimal pin material varies with the specific armour requirements. If maximum energy dissipation is of primary importance, a stiff relatively weak material (e.g., pitch precursor carbon) may be the best choice. If backface deflection is of greater concern, a high strength material (e.g., boron or SiC) may be the better choice. However, if avoiding perforation is the overriding concern, a weak soft pinning material allows the hybrid core to make the most effective use of high strength ballistic fabric.

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