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Shock loading response of sandwich panels with 3-D woven E-glass composite skins and stitched foam core

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ABSTRACT

Sandwich composite are used in numerous structural applications, with demonstrated weight savings over conventional metals and solid composite materials. The increasing use of sandwich composites in defense structures, particularly those which may be exposed to shock loading, demands for a thorough understanding of their response to suc highly transient loadings. In order to fully utilize their potential in such extreme conditions, design optimization of the skin and core materials are desirable. The present study is performed for a novel type of sandwich material, TRANSONITE® made by pultrusion of 3-D woven 3WEAVE® E-glass fiber composites skin preforms integrally stitched to polyisocyanurate TRYMER™ 200L foam core. The effect of core stitching density on the transient response of three simply supported sandwich panels loaded in a shock tube is experimentally studied in this work. The experimental program is focused on recording dynamic transient response by high-speed camera and post-mortem evaluation of imparted damage. The obtained experimental results reveal new important features of the transient deformation, damage initiation and progression and final failure of sandwich composites with unstitched and stitched foam cores. The theoretical study includes full 3-D dynamic transient analysis of displacement, strain and stress fields under experimentally recorded surface shock pressure, performed with the use of 3-D MOSAIC analysis approach. The obtained theoretical and experimental results for the transient central deflections in unstitched and two stitched foam core sandwiches are mutually compared. The comparison results reveal large discrepancies in the case of unstitched sandwich, much smaller discrepancies in the case of intermediate stitching density, and excellent agreement between theoretical and experimental results for the sandwich with the highest stitching density. The general conclusion is that further comprehensive experimental and theoretical studies are required in order to get a thorough understanding of a very complex behavior of composite sandwiches under shock wave loading.

1. Introduction

Sandwich materials are utilized in the naval and aerospace industry for their weight saving and high specific strength advantages. The mechanical behavior and structural response of sandwich materials under quasi-static loadings were studied in earlier publications, see [1–3] among few references. Often, such sandwich structures are subjected to highly transient shock loading conditions, with the surface pressure spread over the entire structure or over a certain area. In the recent times, experimental studies of response of sandwich structures to such dynamic loadings have been reported in [4,5].

The overall dynamic response of the sandwich is dependent, among several other factors, on the construction of the skin, compressive and shear moduli and strengths of the core, and the interface bonding strength between the skin and core. Due to the inherent nature of its construction, the strength of the whole sandwich structure is often limited by the strength of the core material. The skin may also appear the weakest link, then its thickness may be increased, but if increased beyond certain limit, it would negate the weight advantage of sandwich structures. Thus, maximizing the strength of core, skin and the interface between them vs. simply increasing thickness (and, consequently, weight) of the skin and core, is a much better alternative.

In lieu of these considerations and with the aim of obtaining better dynamic performance under shock loading, several design advancements have been sought after. These include better choice of core material, introduction of soft inter-layers (e.g. polyurea layer) between the core and the skin, etc. Also, *Z*-directional pins have been utilized in [6] to modify the core and improve overall response of the sandwich to high strain rate impact loading. Authors of [7] studied failure modes of carbon fiber based sandwich beams reinforced with *Z*-directional pins under three-point bending.

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The present study (it was initially reported in [5]) is focused on two new structural improvements of sandwich materials, namely, (1) superior skin construction by using 3-D woven fabric preforms for composites skins and (2) stiffening and strengthening the core and increasing its binding to the skins by through-thickness integral stitching of the skin preforms and foam core before resin infusion. This novel type of composite sandwich materials, named TRANSONITE®, is presently manufactured by Martin Marietta Composites by pultrusion method. One of its particular cases utilizes 3WEAVE® (three-dimensional orthogonal woven fabrics) manufactured by 3TEX for the skin reinforcement and TRYMER™ 200L foam as the core material. This type of sandwich has great potential for the applications where it is required to combine light-weight, high structural load-bearing capability, efficient blast mitigation ability, high damage tolerance and general survivability.

In the sandwich constructions used here, the 3-D woven skin preforms, made of E-glass roving, and the core were stitched together by a similar E-glass roving. The stitching pattern can be varied. Using higher stitching density results, firstly, in reduced through-thickness deformability of the core which, in turn, dramatically alternates the whole sandwich transient deformation mechanism. Secondly, through-thickness stitching of the skin preforms with the core substantially increases their interface strength and overall integrity of the sandwich structure, resulting in enhanced fracture toughness and damage tolerance. Thirdly, introducing transverse stitches to the core makes significant effect on its local stress–strain fields under transient loading.

Practical needs for 3-D dynamic structural analysis tools capable of accurately predicting the explosive blast effects on layered, composite, sandwich and other similar material types used in civil engineering, marine, ground vehicle, helicopter, aircraft, etc. structures, has grown tremendously in the last several years. In general, the required theoretical methods and analysis tools should address a number of specific practical problems. Among them are: (i) establishing relations between the "ideal" or "non-ideal" explosive characteristics on one side and the "field-free" blast pressure history on the other; (ii) correlating the field-free and the "true" pressure pulse acting on the structural elements like front wall, back wall, side wall, roof, ceiling, etc. Typical structural materials are highly vulnerable to blast overpressure even if exposed to a rather low-mass explosive charges at a relatively short standoff distances. Predecessors of total fracture and collapse of the structures exposed to blast overpressure are initiation and growth of cracks, their coalescence, followed by the material fragmentation, and spalling from the back surface. All of these phenomena occur during a very short, several millisecond time interval.

There are many analytical and computational approaches described in the literature, see [8–13] for example. They are aimed at solving the aforementioned scope of blast-related practical problems and range from rudimentary closed-form solutions to 3-D dynamic finite element packages like LS DYNA and ABAQUS. One quite simplistic finite element analysis approach, which is often used in blast response analysis of civil engineering structures is described in technical manual for Army [11]. It assumes that each building component responds as the equivalent single-degree-of-freedom system. This approach was also recommended in some of the later blast resistant structures design manuals [12,13].

In the above sources a blast pressure vs. time relationship is typically characterized by a peak pressure, impulse and shape. It is commonly assumed that the blast pressure rises instantaneously to its peak value, however under a more scrupulous look, the blast pressure rise stage may last for tens or even hundreds of microseconds. The second stage typically consists of a relatively long steady level pressure, followed by an even longer exponential decay to ambient pressure. Then there is a rather long time period when the pressure is below the ambient pressure. In the negative phase of the pressure history, the maximum pressure magnitude is typically small compared to the positive pressure magnitude and is commonly neglected in the analysis. Importantly, the so-called "reflected blast pressure" acting on the front wall may significantly exceed the peak field-free pressure. In the result of all these considerations, the incident pressure pulse can be reasonably represented by a "triangle-type" curve with the peak pressure multiplied by the "reflection factor" in the case of a front wall.

The above features of the blast pressure variation are well known and were mentioned here only with the aim to emphasize that in-depth understanding of the specifics of shock wave formation and adequate quantification of the entire pressure pulse history are crucial for a successful prediction of the respective transient structural response. Obviously, most sophisticated and accurate structural analysis tools would not provide useful results if the incident blast pressure is poorly defined. This statement also underscores how important it is to combine theoretical predictions of blast effects on practical structures with appropriate experimental studies. To these authors' best knowledge, first attempt to tie together theoretical and experimental studies of 3-D woven composites exposed to transient shock wave loading was made in [5], where theoretical results generated by 3TEX's in-house 3-D MOSAIC analysis tool were compared to some of experimental data presented in [14]. Experimental studies of the transient response of sandwich structures loaded in a shock wave tube [5] have not yet been tied to theoretical work. Such effort is undertaken in this paper.

The experimental method used here is similar to the method reported in [14], where several different 3-D woven fabric composites made of S-2 glass fiber and Derakane 8084 epoxy–vinyl ester resin were exposed to a highly transient dynamic loading in a shock tube. However, the object of present study is very different – instead of a one layer or two layer relatively thin solid composites we now have a thick sandwich panel with quite a complex construction and reinforcement architecture. Accordingly, the transient deformation, damage progression and failure phenomena are totally different than those observed in [14].

Regarding theoretical part of this work, the original 3TEX's in-house 3-D MOSAIC variational analysis approach and computer code are used here. The necessary mathematical details of this analysis approach and its various application examples can be found in [15–18]. The approach has totally different mathematical background than conventional 3-D hexahedral finite element and it provides significant analytical, algorithmical and computational advantages, see [15] for details. However, its objective is the same: to accurately predict 3-D static and dynamic stress–strain fields, damage, fracture and failure processes in complex composite material systems. The analysis approach is displacement-assumed; it employs Hamilton's variational principle with Bernstein approximation polynomials of an arbitrary degree used as the basis functions in all three coordinate directions. The displacement continuity is imposed between the layers. The interlaminar stress continuity conditions are satisfied with controlled accuracy as natural internal boundary conditions. Similarly, the external surface traction boundary conditions are satisfied in a "soft" variational sense with controlled accuracy.

In its dynamic version, see [16], 3-D MOSAIC analysis approach preserves all individual inertia terms without "lumping", thus allowing to study the whole variety of 3-D stress wave propagation processes. This may be especially important when analyzing those composites and sandwiches which contain very different constituent material densities (like foam core vs. E-glass composite) and geometric parameters (like skin thickness vs. core thickness). Damping (energy dissipation) factors can be also accounted in the analysis. Earlier applications of this analysis approach to the transient response predictions of thick layered panels composed