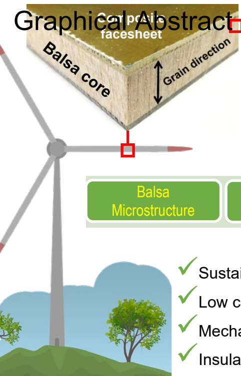
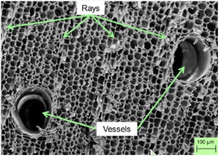
Graphical Abstract





Balsa Microstructure → Sandwich Processing → Properties & Performance

- ✓ Sustainable
- ✓ Low cost
- ✓ Mechanical props
- ✓ Insulating props

- ✗ Supply chain
- ✗ Part processing compatibility
- ✗ Impact, blast, fire

Highlights

- Benefits and limitations of balsa wood in sandwich structure construction are reviewed and summarised.
- Engineering material properties and mechanisms responsible for the benefits and limitations of balsa core sandwich structures are discussed.
- Benefits include environmental sustainability, low raw material cost, high specific mechanical properties, and thermal insulation properties.
- Limitations include limited applicability of part processing techniques, impact, blast and fire performance, as well as water durability.
- Topics for further research to advance balsa sandwich structures are discussed.

Response to reviewers: JMADE-D-22-01082R1

Review of balsa core sandwich composite structures

Joel Galos, Raj Das, Michael Sutcliffe and Adrian P. Mouritz

The authors thank the reviewers for their helpful and insightful comments which are addressed below and in the revised manuscript. The changes made to the manuscript are in blue text.

Reviewer 1

Comment 1: The manuscript cites 255 references. It is good but lacks references to 2022. There is only one publication dated 2022 ([223] Gargano A, Das R, Mouritz AP. Comparative experimental study into the explosive blast response of sandwich structures used in naval ships. Composites Communications. 2022;30:101072)

In this regard, I suggest the following references in the following sections/lines

To introduction: Book Name: Sandwich Composites, Fabrication and Characterization, Edited By Senthilkumar Krishnasamy, Chandrasekar Muthukumar, Senthil Muthu Kumar Thiagamani, Sanjay Mavinkere Rangappa, Suchart Siengchin, 1st Edition, Copyright Year 2022, ISBN 9780367697273, January 26, 2022, by CRC Press 406 Pages,

Please consider adding the following reference to (Page 16 line 46)… Sandwich structure design optimisation via analytical and finite element modelling is an important area of research [1, 96-99]....

A. Çetin, Ç. Uzay, N. Geren, M. Bayramoğlu & N. Tütüncü, (2022) A practical approach to predict the flexural properties of woven plain carbon fiber/epoxy laminates, Mechanics of Advanced Materials and Structures, DOI: 10.1080/15376494.2022.2044570

C. Uzay, D.C: Acer and N. Geren, (2022) "A method for the optimal design of low-density polymer foam core sandwiches using FEA and multiobjective optimization of design variables", Journal of Polymer Engineering, 42(1): 75–84, https://doi.org/10.1515/polyeng-2021-0181,

Response: We have carefully read the references suggested, however they are not relevant to the present review article. Therefore, the references are not included in the revision.

Comment 2: Please refer to the commercial software used for the construction of the following figures: Figures 10, 11, and 16. It seems that these are plotted using GRANTA Selector or CES materials selection software. Please refer to the software (CES etc.) if it is used. If not provide the references. In addition to that Blue and orange lines provided in Figures 11, a and b should also be indicated by different lines (dashed, dotted etc.) so these Figures in black and white printed documents can be read.

Response: A statement has been added to the relevant figure captions indicating that the plots were created using the tools in the Granta CES software. The lines in Figure 11 are already comprised of dotted/solid segments and are labelled individually to avoid confusion if printed in black and white.

Comment 3: Page 33, above Figure. 19, contains....”These results demonstrate the heat insulation effect of thick-section balsa core sandwich materials”…Is this correct or should it be “These results demonstrate the heat insulation effect of lower-density balsa core sandwich materials.”

Response: The existing wording is correct.

Comment 4: Page 40, line 17, …… “Vertical cracks can grow along the rays of the balsa when the grain direction in aligned in the through-thickness direction of the sandwich material, as shown for example in Figure 24 [198].” This is possibly corrected as “Vertical cracks can grow along with the rays of the balsa when the grain direction is aligned in the through-thickness direction of the sandwich material, as shown for example in Figure 24 [198].”

Response: Wording corrected.

Comment 5: Regional (Asia, Amerika etc) densities of balsa wood could have been provided.

Response: This is discussed in the introduction:

“Balsa (Ochroma pyramidale) is a tropical wood native to South America that is now grown in many countries, and is the lightest commercially available wood used in sandwich structures. Its density is low (typically between ~50 kg/m^3 and ~350 kg/m^3), which is determined by the age, condition and habitat of the source tree.”

Note that the density of balsa does not solely depend on the continent it is grown, rather the local climate. For this region, it is not possible (or correct) to provide regional densities of balsa wood. A comment to this effect has been added to the introduction.

Comment 6: Balsa wood used in sandwich structures as core usually have some small radius open surface channels (as shown in figure below) or to improve resin flow during Vacuum assisted resin infusion process. This should be better mentioned in the manufacturing section.

Response: This is described this in Section 3.1:

“Flexible balsa panels can be made by joining individual balsa cubes at one end only, enabling the core to flex in order to be used in curved sandwich structures.”

<u>Reviewer 2</u>

Comment 1: The authors detail well, in different sections, the applications, the microstructure, the mechanical properties of balsa, as well as its durability (thermal and fire performance, water durability, indentation, impact and blast response, etc.). The discussion is based on a rich bibliography and specific and relevant examples for readers who are experts or not in this type of material: balsa alone or balsa as a core material in sandwich composite structures. The references section is not exhaustive but already very complete. Such a review was lacking in the literature.

Response: Many thanks for the positive review of our work.

Reviewer 3

Comment 1: The review mostly covers materials aspects, including properties under different loading and environmental conditions. The structural aspects, e.g. how balsa core sandwich composite structures perform under different conditions, are not sufficient yet or not comparable to the materials aspects. The title with "structures" might not reflect well the content, given the lack of structural aspects at great length and depth.

Response:

We argue that the suggestions for changes are not appropriate given the scope of the paper and journal.

A significant part of the review (Section 6, 28 pages long) is devoted to ‘how balsa core sandwich composite structures perform under different conditions’. We believe the reviewer is using the term ‘structures’ in the context of geometric effects (rather than material effects), on the properties of balsa core sandwich structures.

The term “sandwich structure” is common throughout the literature to define a “sandwich material”, and is used to refer to the set of hybrid materials that consist of stiff, strong and thin facesheets joined to a relatively light and thick core. This definition is provided in the first line of the introduction for clarity. Moreover, the term “sandwich structure” is a keyword for the journal of Materials & Design. We believe our terminology is consistent with the literature and the journal.

Comment 2: The connections between materials and structural aspects need theoretical models and also numerical modelling/simulations. This part is either missing or very briefly addressed in this review article. To the reviewer this is the most interesting and also challenging part that would be very beneficial to the readers. At least a decent Section of the manuscript should be devoted to these connections, with in depth discussions and analysis.

Response:

The connections between material and structural aspects are discussed at length throughout Section 6 (28 pages in length). Moreover, the authors believe that we have cited all relevant papers relating to theoretical models and numerical modelling of balsa. Since the review article significantly long (57 pages, ~20,000 words, 25 figures), we omit detailed descriptions of modelling and numerical approaches for brevity. We have provided readers of the article with references to follow-up on specific details which are beyond the concise details provided. We believe providing an detailed and highly descriptive review of all the models adds little value to the article. Importantly, we have provided commentary throughout the article on what has been modelled and what has not yet been modelled for balsa core sandwich structures.

Review of balsa core sandwich composite structures

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Abstract

Renewed efforts towards greater use of environmentally sustainable materials have created new opportunities for balsa wood (*Ochroma pyramidale*) to replace non-renewable, petroleum-based cores such as polymer foams in a broad range of sandwich structures. This paper reviews published research into the applications, manufacturing, microstructure, mechanical properties and in-service performance of sandwich structures with balsa wood core. The benefits of balsa wood in sandwich structure construction are reviewed, including environmental sustainability, low raw material cost, excellent specific mechanical properties, and thermal insulation properties. The potential challenges of balsa cores in sandwich structures are also evaluated, including potential global supply chain issues, limited applicability of part processing techniques, impact, blast and fire performance, as well as water durability. Published research into the underlying properties and mechanisms responsible for the benefits and limitations of balsa core sandwich structures are reviewed. Topics for further research to advance the characterisation and applications of balsa structural sandwich materials are also discussed.

Keywords

Wood; mechanical properties; composites; sandwich; balsa; GFRP

1. INTRODUCTION

Sandwich structures constructed from stiff, strong and thin facesheets joined to a relatively light and thick core are used in many engineering applications. Sandwich materials are often used in structural engineering applications when weight needs to be minimised without significantly decreasing the in-plane and out-of-plane mechanical properties, particularly the flexural properties [1]. The first significant research into structural sandwich structures began around World War II [2, 3], and involved balsa wood as a lightweight core material [1]. Balsa has remained a popular core material, and is available commerically under different tradenames such as Balsalite, Baltek, ContourKore, ProBalsa, bCores and Banova [4].

Balsa (*Ochroma pyramidale*) is a tropical wood native to South America that is now grown in many countries, and is the lightest commercially available wood used in sandwich structures. Its density is low (typically between ~50 kg/m^3 and ~350 kg/m^3), which is determined by the age, condition and habitat of the source tree [5]. The density of balsa does not solely depend on the continent it is grown, but rather the local climate, and therefore density variations do not occur between regions. The low density of balsa, combined with its relatively high mechanical properties in certain directions, make it suitable as a lightweight core material. Despite the availability of a large number of competing sandwich core materials (e.g. polymer foams, metal foams, honeycombs, lattices), balsa wood is likely to remain an important material for sandwich structure construction. To this end, a significant amount of research is still being performed on sandwich structures with balsa wood cores despite these materials having been used for more than 70 years. Applications for balsa wood are expected to grow as natural and biodegradable materials are of increasing importance to environmental sustainability in engineering materials design. The reduced emphasis on synthetic organic-based core materials made using petroleum-based products (e.g. polymer foams, Nomex) and metal cores made using non-renewable resources requiring energy intensive processing (e.g. metal foams and honeycombs) has made natural, sustainable materials such as balsa more attractive to use in sandwich structures.

This review aims to summarise the existing body of knowledge on balsa core sandwich composites structures and identify potential new areas of research to further their adoption in novel, environmentally sustainable, engineering applications. Other recent reviews have detailed research progress on sandwich structures with foam or prismatic cores [6, 7], but not balsa. The focus of this review is on sandwich structures consisting of facesheets and balsa core, which is a layered hybrid material. The properties of sandwich structural materials are comprehensively reviewed in this paper, however the mechanics and modelling of sandwich structures is beyond scope due to many books, articles and other information already available. The current uses of balsa core sandwich structures in a wide range of applications as well as potential future applications is based on a comprehensive research assessment of their properties. The design and fabrication of balsa sandwich structures as well as their mechanical properties, impact resistance and damage tolerance, environmental durability, thermal and fire performance, and other properties have been studied in detail, with the findings reported in the scientific and technical literature. This paper presents a comprehensive review of published research into balsa core sandwich materials, including a critical appraisal of what is and is not understood about these materials when used in load-bearing structures. The research reviewed in this paper provides the essential information needed to understand the design, manufacture and performance properties of balsa sandwich structures for various applications. Using published research, the paper also presents an appraisal of the performance of balsa core sandwich materials against other types of sandwich structures to identify their relative benefits and limitations. The paper also identifies gaps and deficiencies in our understanding of these materials which need to be resolved by future research.

In this paper, the applications of balsa core sandwich structures are firstly reviewed (**Section 2**). The origin and processing of raw balsa wood into end-grain sandwich structure cores is then described, followed by a review of the manufacturing techniques used to fabricate balsa sandwich structures (**Section 3**). The microstructure (**Section 4**) and mechanical properties (**Section 5**) of end-grain balsa wood are described as these influence the engineered properties of sandwich structures. The engineering properties and performance of balsa wood sandwich structures is then discussed (**Section 6**), including mechanical properties, facesheet adhesion, joining and fracture, thermal and fire performance, water durability, indentation, impact and blast response, and other properties.

Due to their prevalence in civil and marine structures, most published works investigate sandwich structures with an end-grain balsa core and continuous glass fibre reinforced polymer (GFRP) facesheets as shown for example in **Figure 1**. Hence, a significant amount of this review is dedicated to these materials, although other facesheet materials are also considered based on published information and data. To conclude the review, an assessment of the benefits and limitations of balsa wood in sandwich construction are presented, with potential areas for future research also discussed (**Section 7**). These topics are relevant to maintain the commercial competitiveness of end-grain balsa wood against the growing number of other sandwich core materials.

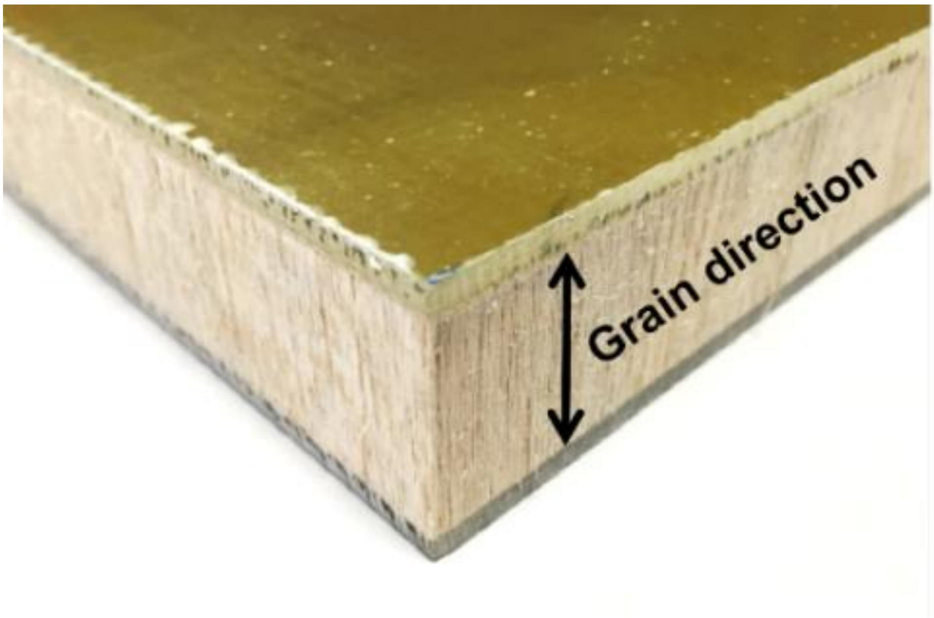


Figure 1. Sandwich structure with a 25 mm thick end-grain balsa core and GFRP laminate facesheets.

2. APPLICATIONS

Balsa wood has been used for structural applications for centuries; Peruvians used it as early as ~500 AD to construct boats [5]. Indeed, the English word "balsa" originates from the Spanish word for "raft". Balsa was first used in aircraft in the 1920s, although its first widespread use as a core material in a load-bearing sandwich structure was in the form of laminated ply wood on the Mosquito aircraft produced in England during World War II [1, 8]. Since then, end-grain balsa wood has been used as a sandwich core material for many applications as summarised in **Table 1**. Applications include wind turbine blades (**Figure 2**), bridge deck sections, building panels, cars, trucks, caravans, trains, aircraft, boats (**Figure 3**), packing, storage, sports equipment and musical instruments. Its performance benefits for use as a sandwich core material in these applications are explored in more detail in the subsequent sections (**Sections 4, 5 and 6**).

Table 1. Typical applications of sandwich structures with balsa cores.

Industry domain	Application	Component(s) with balsa core sandwich structures	Example references
Civil infrastructure	Windmills	Turbine blades (**Figure 2**), spinners, nacelle covers and generator housings	[9-23]
	Bridges	Decking	[9, 24-30]
	Buildings	Insulation, flooring, shop displays	[31-33]
Transportation	Cars	Body panels, interiors and side skirts	[12, 34]
	Trucks	Body panels, trailer decking, trailer insulation	[9, 18, 35-41]
	Caravans	Body panels, interiors and side skirts	[4, 9]
	Trains	Train floors, walls, roof panels	[9, 12, 42]
	Aircraft	Floor panels, galley carts and interior partitions	[8, 9, 43-47]
	Boats	Hulls (**Figure 3**), decks, bulkheads, superstructures and interiors	[48]
Industrial	Packaging	Cargo pallets	[1, 9]
	Storage	Storage tanks	[49]
Leisure	Sports equipment	Skis and snowboards	[50]
	Musical instruments	Indian percussion instruments	[51]

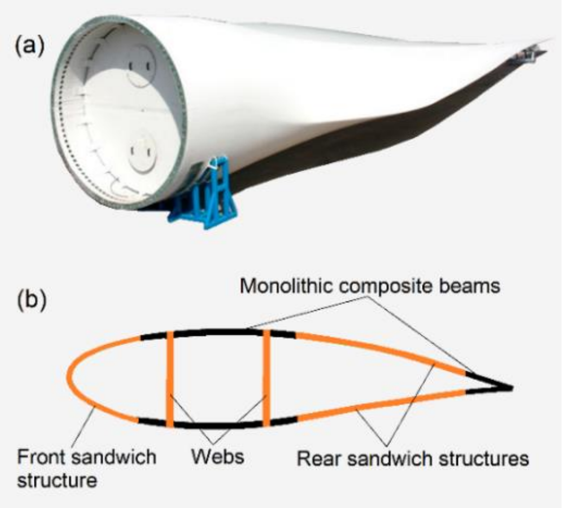


Figure 2. (a) Wind turbine blade and (b) schematic of blade cross-section with opportunities for sandwich structures highlighted in orange. Adapted from [23].

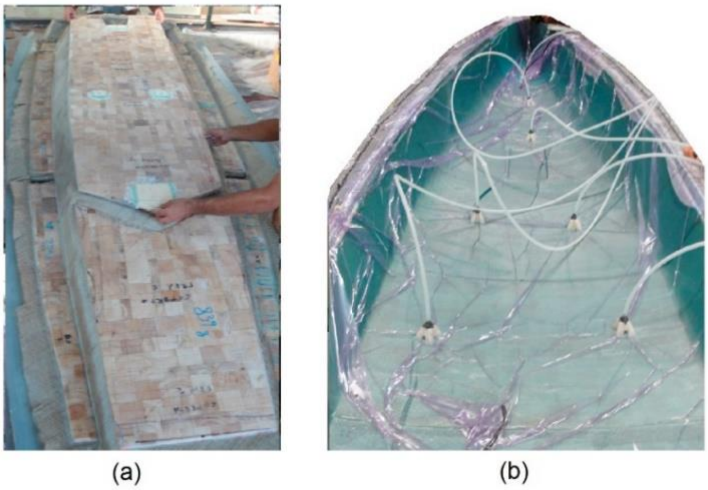


Figure 3. (a) Laying of balsa core in boat hull prior to resin infusion. (b) Vacuum assisted resin infusion process of boat hull. Reproduced with permission from [52].

Most engineering applications of sandwich structures with a balsa core use thin-section fibre-reinforced polymer composite facesheets (such as GFRP) because of processing advantages that can be exploited, including the elimination of the need for adhesives to bond the facesheets and core. Part processing is an important consideration in the successful application of balsa sandwich structures, and this is discussed in detail in **Section 3**. GFRP is the most common facesheet material used due to its moderate cost, particularly in large civil infrastructure applications of sandwich structures that can be readily processed using resin transfer moulding and other manufacturing processes (see **Section 3**). Metallic facesheets (e.g. aluminium alloys and steels) as well as hardwood facesheets are also used in sandwich structures with a balsa core, although are less common than composite laminate facesheets.

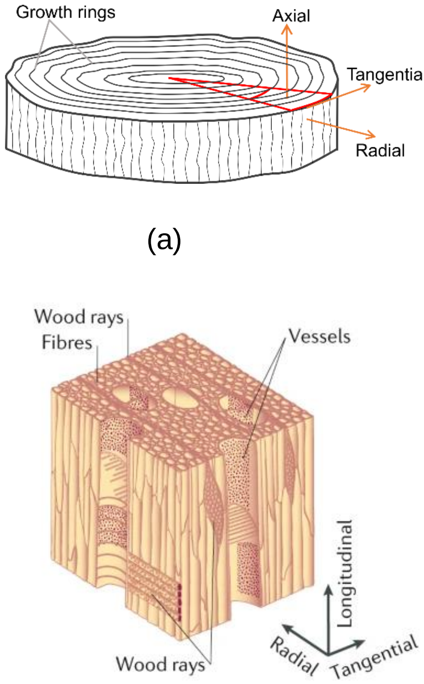
Novel applications of multifunctional energy storage sandwich structures with a balsa core are emerging. For example, Chen et. al. [53] recently reported that balsa coated with carbon nanotubes and ruthenium nanoparticles can be used as highly conductive and flexible cathodes for lithium–oxygen batteries. However, this technology is not commercially available. Innovative applications of balsa wood in novel, sustainable, multifunctional sandwich structures remain largely unexplored in the literature. The microstructure of balsa wood (**discussed in Section 4**) may help unlock further novel applications in other multifunctional sandwich structures.

3. MANUFACTURE

3.1 Balsa production and processing

The global supply of balsa wood has historically been from plantations in Ecuador, although the supply chain has diversified and now there are commercial plantations in other countries including Papua New Guinea (PNG), Indonesia, Sri Lanka, West Africa and the Solomon Islands [13, 54]. In 2008, Ecuador produced ~90% of the world's commercial balsa and PNG produced ~8% [54]. However, following the global financial crisis in 2008, there was a sharp decline in the demand for balsa due in part to uncertainty around the global supply chain. As a result, manufacturers sought to replace balsa sandwich cores increasingly with other common core materials such as polymer foams and honeycombs [55]. This in turn led to increased interest in balsa grown in plantations in PNG, which helped increase and stabilise supply. To this end, the global market share of PNG balsa is expected to grow [13] up to 30% [55]. More recently, the global supply chain of engineered wood products has been significantly adversely affected by the coronavirus pandemic [56]. Supply chain disruption represents a significant barrier to the successful implementation of balsa in a variety of applications, such as civil infrastructure applications (see **Section 2**), where large quantities of balsa are often needed.

Balsa trees are fast-growing and reach up to ~20 m in height and up to ~0.75 m in diameter in five to eight years. After a balsa tree is cut it is dried in a kiln to remove excess moisture and kill parasitic organisms, thereby helping to ensure dimensional stability and durability when used as a core material. For sandwich core structures, balsa is typically cut into end-grain cubes where the fibre (wood grain) direction is aligned perpendicular to the plane of the block, leaving visible growth rings (**Figure 4** and **Figure 5**). The end-grain cubes offer the most favourable mechanical properties for sandwich construction when aligned in the through-direction. The individual balsa cubes are typically divided into categories according to their density, and this can reduce cost during processing [55]. Densities divisions are low (80 - 120 kg/m^3), moderate (120 - 180 kg/m^3) and high (above 180 kg/m^3) [55]. The individual balsa cubes are bonded together edgewise with an adhesive such as polyvinyl acetate (PVA) to form a rigid end-grain balsa sheet, as shown in **Figure 5**. Flexible balsa panels can be made by joining individual balsa cubes at one end only, enabling the core to be applied in curved sandwich structures. A disadvantage of joining individual cubes into a panel is that the balsa blocks have different densities, and therefore the block with the lowest density often determines the core failure stress since it has the lowest mechanical properties. Histograms of the density of constituent blocks within single sheets of rigid moderate-density and high-density end-grain balsa panels are shown in **Figure 6**. A large variation in density can occur in a single panel. The differing mechanical properties of balsa blocks with different densities will significantly affect the resultant performance of the sandwich structure to which it they are applied. Therefore, careful consideration is needed in selecting an appropriate balsa panel for any given application, and this is discussed in detail in **Section 5**.



(a)

(b)

Figure 4. (a) Cross-section of balsa tree trunk. (The axial direction of the tree is also referred to longitudinal direction). Adapted from [57]. (b) Schematic of balsa microstructure. Reproduced with permission from [58]. Not to scale.

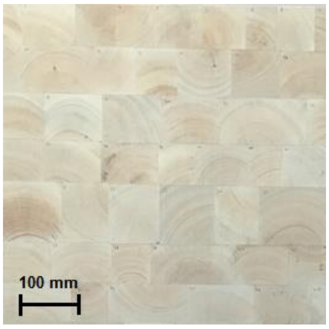


Figure 5. Rigid end-grain balsa core sheet comprised of constituent blocks bonded with PVA adhesive.

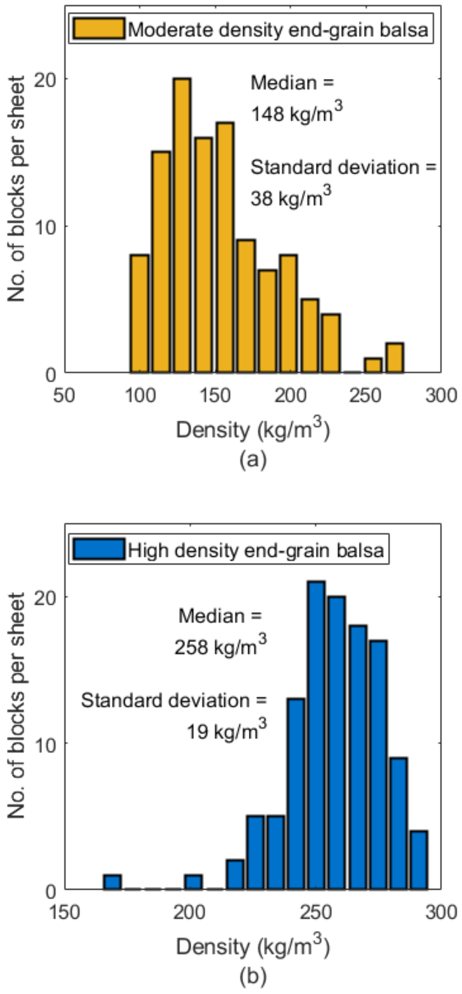


Figure 6. Histograms of density of constituent blocks within single sheet of rigid end-grain balsa: (a) moderate density and (b) high density. Data from [35].

An alternate technique to balsa core production is through balsa veneers, which use balsa chip wood that is laminated together with PVA adhesive to form laminated plywood [9]. Because of the variability in the raw balsa used in veneer production, these plywoods typically have lower mechanical properties compared with high density balsa cores formed by joining individual balsa cubes.

Aside from being a natural, biodegradable material, the production and processing of end-grain balsa is more sustainable than synthetic polymer-based and metal core materials. This is evidenced by **Figure 7**, which shows the primary production energies of common sandwich core materials relative to end-grain balsa. Balsa production requires less energy and therefore has a smaller CO_2 footprint compared with polymer-based foam and honeycomb core materials. While end-grain balsa requires more water in production, this water is sourced naturally from rainfall and because balsa plantations are in locations of high humidity and high annual rainfall, this is unlikely to affect its overall sustainability benefit. Compared with synthetic polymer-based and metal cores, the environmental benefits of balsa wood production is a key advantage likely to be of critical importance to its future applications in sustainable engineering design. This is especially important for the transportation sector, where balsa is already widely used (see **Section 2**), which is striving to significantly reduce greenhouse gas emissions and to use environmentally sustainable materials.

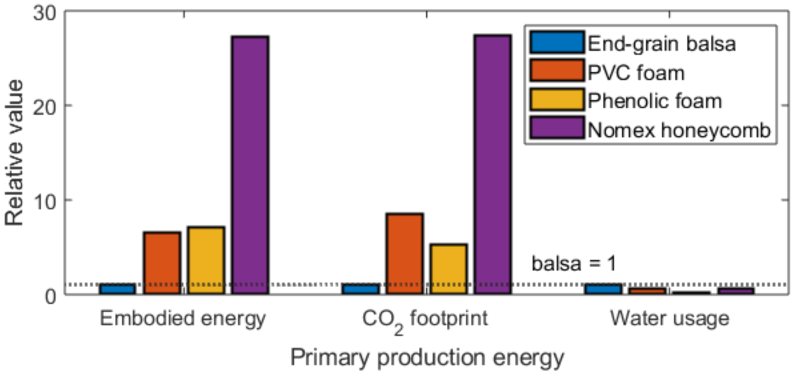


Figure 7. Primary production energy of common sandwich core materials relative to end-grain balsa. Data from [4].

3.2 Sandwich structure fabrication

There are several manufacturing processes used to fabricate sandwich structures with a balsa core. The choice of process largely depends on the facesheet material used, the shape and geometry of the structure and on the performance requirements of the sandwich structure.

Sandwich structures with polymer or fibre-reinforced polymer facesheets, such as GFRP, can be manufactured with a single-shot process, where the facesheets are simultaneously cured and bonded to the balsa core. Examples of single-shot sandwich fabrication processes are vacuum-assisted resin infusion (VARI) [21, 44, 52, 59-67] and wet hand layup [40, 68] for facesheets containing continuous fibres and wet hand layup and spray-up for facesheets containing short or discontinuous fibres. Alternatively, balsa sandwich structures can be manufactured by a multi-stage process whereby the laminate facesheets are cured and then secondary bonded to the balsa core using a structural adhesive such as epoxy, PVA or methacrylate. A combination of single-shot and multi-stage processes (known as co-bonding) can be used, although this is less common. Balsa core sandwich structures with metallic or hardwood facesheets require an adhesive for bonding the facesheets and core. The technical limitations surrounding choice of adhesive should be considered in the initial design of a sandwich structure.

Sandwich structures with continuous fibre composite facesheets were originally fabricated using the wet hand-layup process, but more recently the VARI method (as shown for example in **Figure 3(b)**) is also commonly used due to increased part quality (i.e. higher fibre volume fraction and lower porosity in the facesheet laminates), reduced resin wastage and less volatile emissions during resin gelation and cure. VARI fabrication is now the most common method used for most applications described in **Section 2**. The VARI process involves the use of vacuum pressure to draw liquid resin into a network of dry reinforcement (often fabric mats of glass or carbon fibres) that are stacked into a laminate. The dry fabric is laid onto a mould and a vacuum bag is applied over the reinforcement prior to infusion of liquid resin. After vacuum is achieved, resin is drawn into the structure via plastic tubing like that shown in **Figure 3(b)**. The placement of tubing is critical to achieve complete wetting of the fabrics to the facesheets.

A disadvantage of VARI and wet hand layup processing is the balsa core is susceptible to resin absorption [69, 70], which can increase final component weight. Balsa absorbs more resin than closed-cell polymer foams (**Table 2**), and this has been observed with X-ray computed tomography [70]. The amount of resin absorbed by balsa increases with decreasing density due to the more open wood grain structure. Resin absorption can be reduced by using higher density balsa wood, although this increases the total structural weight.

Table 2. Resin absorption in vacuum assisted resin infusion of 25 mm thick polymer foam cores and balsa wood core [70].

Core material	Resin absorption (kg/m^2)
Closed cell PET foam	1.2
Closed cell PVC foam	1.0
Balsa wood	2.0

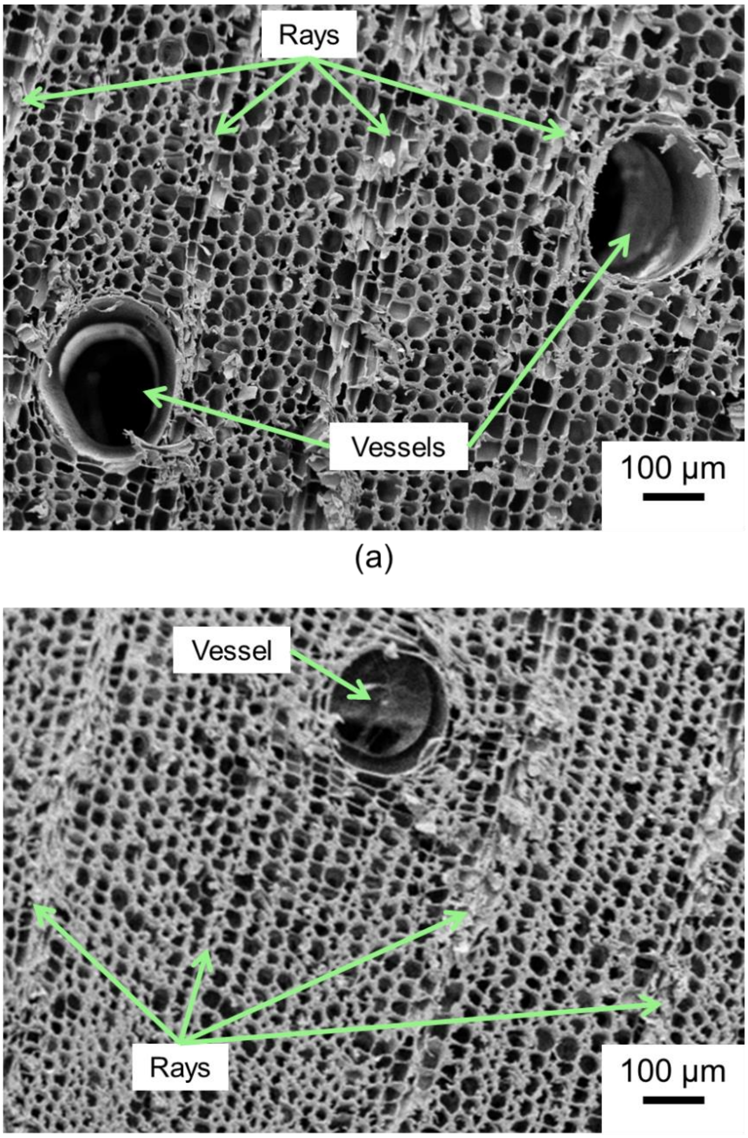
Single-shot manufacturing processes such as VARI are desirable in mass production as they eliminate the need for costly structural adhesives, thereby reducing material costs. The use of single-shot autoclave processing is widespread in high performance polymer composites, although this is rarely used for sandwich structures with balsa core. This is largely due to the high cost of operation and restricted working chamber size of an autoclave and the elevated temperatures needed for curing which can have a detrimental effect on the mechanical properties of balsa and cause swelling (upon heating) and contraction (upon cooling) (see **Section 6.3**).

Notably, there is a lack of literature on the compatibility of a variety of new composite manufacturing techniques. For example, no studies exist exploring the compatibility of balsa cores with emerging additive manufacturing processes, such as fused filament fabrication and fused deposition modelling. Exploration of new part processing techniques may help broaden the engineering applications of balsa beyond their existing applications discussed in **Section 2**.

Several significant design challenges often need to be addressed during the fabrication of sandwich structures with balsa. These include surface coating of exposed balsa edges (that can act as an entry point for water ingress, as discussed in **Section 6.4**), local reinforcement of regions of the sandwich structure used to create joints (**Section 6.2**), and reinforcement of regions of the sandwich structure that may be subjected to localised loads such as impact (**Section 6.5**) or indentation (**Section 6.6**).

4. MICROSTRUCTURE OF BALSA

The microstructure of balsa determines its structural anisotropy and mechanical properties [5, 35, 57, 71-79]. Balsa wood has a high aspect ratio closed-cell microstructure, as shown in **Figure 8**. Hardwoods, including balsa, are comprised of three cell types: fibres/fibrils (66 to 76 vol%), rays (~20 to ~25 vol%) and vessels (~3 to ~9 vol%) [72]. Balsa is sometimes described as a member of the corkwood family, largely because of its low density [5]. The fibres are long prismatic cells with a cross-section that resembles a polygon and are oriented in the direction of growth (i.e. axial/longitudinal direction in **Figure 4**). Fibres in a mature growth tree have a typical length of ~0.5 mm to ~1 mm and diameter of ~0.05 mm [1]. High density balsa (**Figure 8b**) has more cells and fewer vessels per unit area compared to less dense balsa (**Figure 8a**). The cellular structure provides relatively high mechanical properties in the direction of growth, but much lower properties in the other directions (i.e. radial and tangential directions in **Figure 4**). Relatively large diameter tubular vessels occur in the microstructure, which are aligned in the axial direction of the tree trunk and whose primary function is to transport moisture and nutrients. Rays are brick-like structures in the microstructure that store nutrients and sugars, while also contributing to radial strength [80].



(a)

(b)

Figure 8. Microstructure of (a) low density (110 kg/m^3) and (b) high density (225 kg/m^3) end-grain balsa. Images in the tangential-radial plane.

The cell walls of balsa, like all woods, are comprised of lamellae which have a composite-like structure consisting of cellulose microfibrils embedded in a matrix of hemicelluloses and lignins [58]. The cellulose microfibrils contain both crystalline and amorphous regions. The crystalline regions dominate the axial mechanical properties of woods, while the hemicelluloses and lignin matrix have a stronger influence on the transverse properties [81]. In balsa wood, the thickness of the cell wall layers varies between the vessels (~4 µm), the rays (~0.9 μm) and the fibres (~0.8 μm to ~3 μm), which increase with the bulk density [5, 57, 72], as seen in **Figure 8**.

The cell walls of balsa wood are comprised of a primary layer and three secondary layers known as S1, S2 and S3. The S2 secondary layer is the thickest and occupies ~85% of the total cell wall thickness. The cellulose microfibrils in S2 have a mean microfibril angle of ~1.4°, meaning that they are highly aligned with the longitudinal fibre axis [72]. The cellulose microfibrils of the S1 and S3 layers of the cell wall are orientated at ~90° from the longitudinal fibre axis. The high specific mechanical properties of balsa wood is due mostly to the alignment of the S2 secondary cell wall layer with the longitudinal fibre axis, as well as the high cellulose crystallinity.

5. MECHANICAL PROPERTIES OF BALSA IN CORE MATERIAL SELECTION AND SANDWICH STRUCTURE DESIGN

The mechanical properties of core materials have a strong influence on many of the load-bearing properties of sandwich structures. The stiffness and strength properties of balsa (of different densities) have been extensively investigated for various load conditions, including shear [35, 40, 73, 76, 82-89], compression [5, 35, 54, 55, 57, 73, 76, 78, 83, 87, 89-92], bending [55, 73, 89, 90, 93, 94], tension [83, 87, 89] and indentation loads [55, 73]. Further information on the mechanical properties of balsa sandwich composites for different load conditions is reviewed in **Section 6**.

Significant variations in the mechanical properties of balsa wood have been reported [8, 73, 88, 95], with the properties increasing with density. As examples, **Figure 9** shows variations in the compression and shear properties with the density of end-grain balsa measured in the axial direction. These properties are typically highest in the axial-tangential plane of **Figure 4**, and therefore it is the most common orientation for balsa when used in sandwich structure applications (as shown in **Figure 1**). A significant amount of scatter occurs in the measured properties of balsa woods with nominally the same density [8, 73, 88, 95], particularly at higher densities. Such variability is a distinct disadvantage when compared to synthetic core materials such as foams and lattices made of polymers or metals which have consistent mechanical properties.

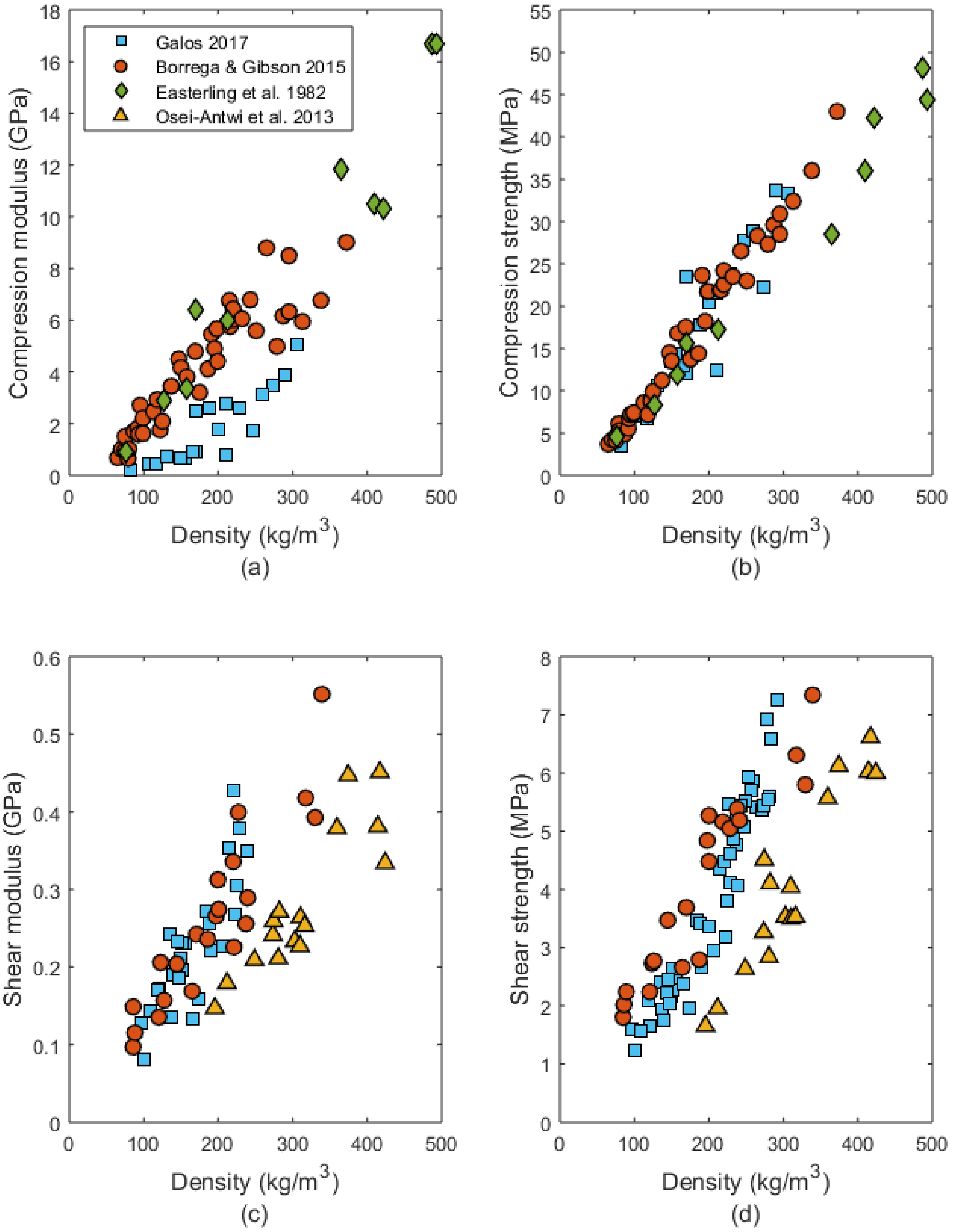
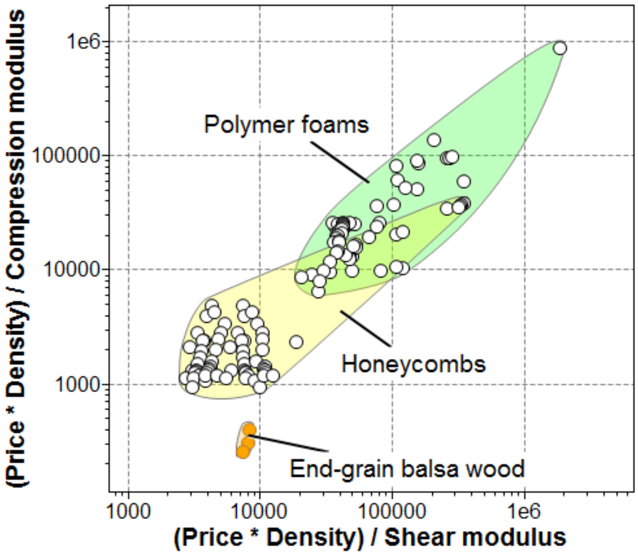


Figure 9. Effect of density on the mechanical properties of end-grain balsa woods. (a) Compression modulus, (b) compression strength, (c) shear modulus and (d) shear strength. Properties measured in axial-tangential plane. Data from [5, 35, 73, 88].

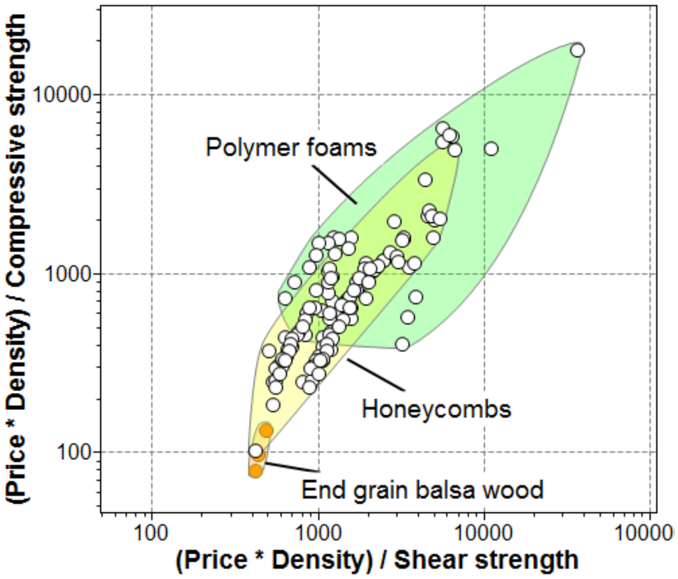
The mechanical properties of balsa have been successfully estimated through the application of analytical models of cellular materials [5, 57, 73, 75]. The natural heterogeneity of balsa wood make it more difficult to accurately predict its properties in comparison with isotropic core materials such as polymer and metal foams. Multi-scale finite element (FE) modelling has been used to accurately predict the elastic constants of balsa [76]. The FE model considered the main features of the balsa microstructure (e.g. cellulose microfibrils, cell wall thickness, rays, fibres, vessels) at multiple length scales spanning the micro- to macro-scales. The model has been validated for numerical accuracy against experimental elastic property data for a wide range of balsa densities [76]. Despite these models, the accurate prediction of damage, ultimate strength and toughness of balsa wood remains considerably more challenging than foams and honeycomb sandwich core materials. Fatigue loadings of balsa core materials also remain largely unexplored.

The shear and compression properties (modulus and strength) are particularly important in sandwich design because they govern the stiffness and strength of a sandwich structure when subjected to flexural and compression loads, which are frequently the critical load cases. For example, core shear failure and/or core indentation failure occurs when the shear and compression strengths of the balsa are not sufficiently high. The relatively high specific shear and specific compression properties of end-grain balsa (for its raw material price) make it an attractive choice of core material for many engineering applications (see **Section 2)**. This is shown in **Figure 10**, which presents material selection charts for common sandwich core materials. The cost-weight specific compression properties are plotted against cost-weight specific shear properties, with modulus properties in **Figure 10(a)** and strength properties in **Figure 10(b)**. The optimal material choice lies closest to the origin of the plots in **Figure 10**, identifying end-grain balsa as the most advantageous choice of core material. However, other design constraints such as thermal conductivity, electrical conductivity, environmental durability, joining and processing compatibility might limit the application of end-grain balsa cores in many engineering applications. Aside from shear and compression properties, the fracture toughness of balsa wood is another important mechanical property that is critical to sandwich structure performance. This will be discussed further in **Section 6.2.2**.

Sandwich structure design optimisation via analytical and finite element modelling is an important area of research [1, 96-99], but is beyond the scope of this review. Nevertheless, the cost-weight specific mechanical properties (**Figure 10**) combined with the sustainability benefits (**Figure 7**) of end-grain balsa make it an attractive choice of core material for many applications, especially those in which extremely lightweight high-performance core materials are not required.



(a)



(b)

Figure 10. Material selection charts for cost-weight specific compression and shear properties ((a) modulus and (b) strength) used in sandwich core material selection. End-grain balsa cores shown with orange markers. Plots created with tools in [4].

6. PERFORMANCE OF SANDWICH STRUCTURES WITH BALSA CORES

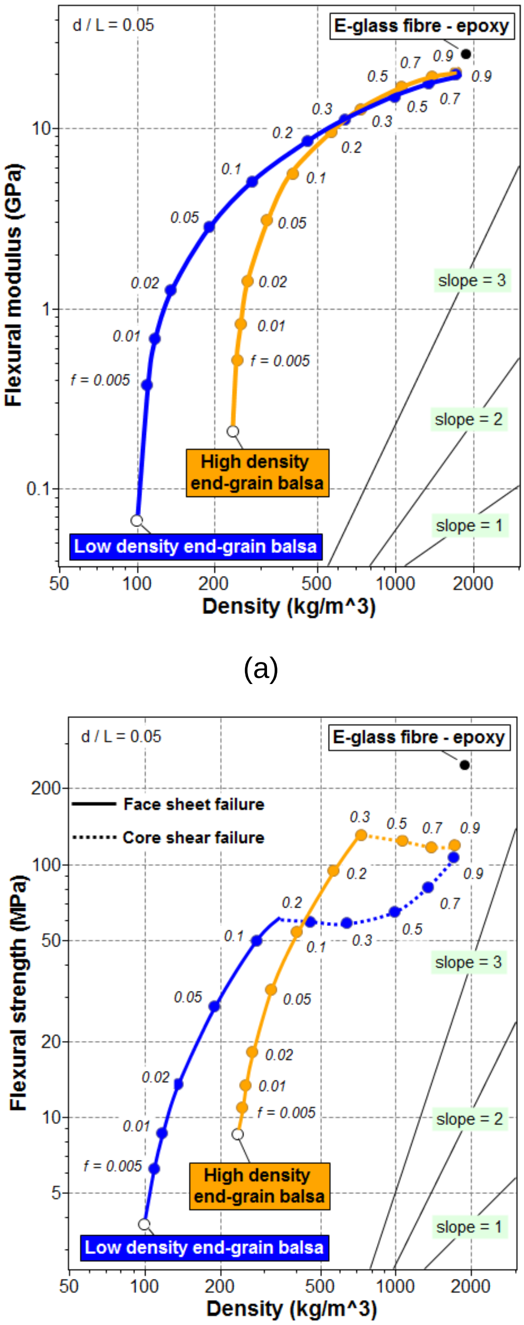
This section gives a critical overview of published research into the performance of sandwich structures with a balsa core. Performance is categorised in seven major topics: mechanical properties (**Section 6.1**), facesheet adhesion, fracture and joining (**Section 6.2**), thermal properties and fire performance (**Section 6.3**), water absorption (**Section 6.4**), impact and blast response (**Section 6.5**), indentation response (**Section 6.6**), and other properties (**Section 6.7**). The advantages and limitations of the performance of balsa compared with other common sandwich core materials (such as polymer foams) are assessed throughout. Moreover, the performance of sandwich structures with a balsa core is related to their part processing (**Section 3**), the microstructure (**Section 4**) and mechanical properties of balsa, and this is discussed throughout this section of the review.

6.1 Mechanical performance

6.1.1 Flexure

Compared with their monolithic constituent materials, sandwich structures typically have exceptional specific flexural stiffness and strength. For end-grain balsa sandwich structures with GFRP facesheets this is shown in **Figure 11**, which plots the flexural properties (modulus and strength) for different facesheet thickness. Sandwich structures with a balsa core are often used in engineering applications to exploit these high specific flexural properties. Hence, a large body of research on sandwich structures with an end-grain balsa core has focused on understanding and improving flexural performance [16, 29, 35, 40, 60, 62, 69, 82, 83, 86, 89, 93, 100-123].

The different failure modes of sandwich structures with balsa core subjected to flexural loadings are well understood. Flexural loads in sandwich structures generate normal stresses in the facesheets (when thin compared to the overall thickness) and shear stresses in the core (when thick). Hence, different modes (and/or mixed modes) of failure can occur depending on the materials and geometry used in the sandwich structure. One failure mode can trigger and interact with other failure modes [83]. For example, local indentation involving progressive damage of a balsa core can occur underneath the flexural loading roller and this can be followed by catastrophic shear failure of the core [113]. Compared with sandwich structures with a polymer foam core, sandwich structures with balsa core typically show less uniform strain deformations in the elastic region of flexural loading, and this can be attributed to the significant natural variations in the microstructural density [103, 105] (**Figure 6**), as discussed in **Section 4**. These variations can trigger early onset core shear failure or core indentation failure, or a combination of the two. Hence, core shear strength is frequently a critical design requirement for sandwich structures subjected to flexural loads, as discussed in **Section 5**.



(a)

(b)

Figure 11. Variation in (a) equivalent flexural modulus and (b) flexural strength for sandwich structures with GFRP facesheets, low-density (~50 kg/m^3) end-grain balsa cores (blue line) and high density (~250 kg/m^3) end-grain balsa cores (orange line). Note that *f* denotes the volume of the sandwich occupied by the facesheets, *L* denotes the span length and *d* denotes the total panel thickness. Material selection lines plotted in the bottom right quadrant. Plots created with tools in [4].

Core shear failure (**Figure 12(a)**) of balsa core sandwich structures occurs when the shear strength of the core is exceeded. In the failure process, shear cracks typically initiate at the balsa core blocks with the lowest density due to their relatively low fracture toughness. Core shear failure of balsa can be predicted using the Tsai-Wu failure criterion [110]. Balsa cores fracture in the thickness direction parallel to the wood grains and subsequently the facesheets debond from the core [60] or experience wrinkling (**Figure 12(b)**) [83]. Moreover, when the adhesive bonding between blocks of balsa is relatively weak then interfacial failure can occur with cracks propagating along the adhesive layer [110]. Hence, balsa panels formed with many individual end-grain blocks (like that shown in **Figure 5**) require sufficiently high adhesion strength between the blocks to avoid premature failure. The normalised shear stress in the core increases with the span length [60]; hence short beam bending tests are used to induce core shear failure [60, 118, 119, 124] in sandwich structures with a balsa core. The short beam tests show weak strain rate dependency, with a slight decreasing trend in the balsa core shear failure strain for increased strain rate [119].

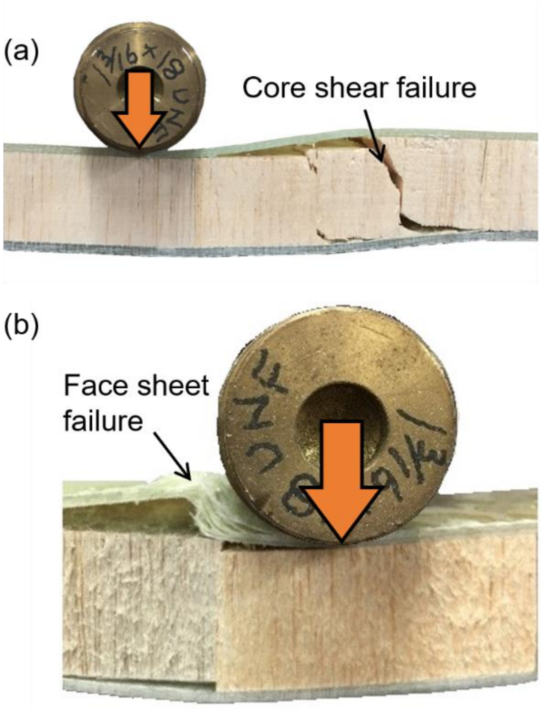


Figure 12. (a) Core shear failure in GFRP-balsa sandwich structure (25 mm thick core). (b) Face sheet yielding, followed by core shear failure observed in GFRP-balsa (SB.150) sandwich structure.

During flexural loading, facesheet failure (**Figure 12(b)**) occurs when the axial stress in the facesheet reaches the yield strength (for elastic-plastic materials) or the microbuckling strength (for brittle polymer matrix composites) of the face material [98]. Ductile indentation during flexure loading occurs when metallic facesheets form plastic hinges at the boundaries of the indentation region [98]. Elastic indentation during flexural loading occurs when fibre-reinforced polymer composite facesheets remain elastic while the core yields plastically [98].

It is worth noting that core shear failure and ductile indentation failure of sandwich structures with a balsa core directly relate to the shear and compression strengths of the core, respectively. For balsa wood, as discussed in **Section 5**, these properties increase with density (**Figure 9**) and so care needs to be taken to achieve minimum mass design. Higher-order sandwich panel theory has been used to accurately predict the axial and shear stresses in sandwich structures with relatively stiff cores and intermediate laminate layers within the core [111].

Research has been performed to improve the flexural performance of sandwich structures with a balsa core [69, 113-115]. For example, cut cores to allow balsa sheets to be contoured for additional resin reinforcement during manufacturing can increase the flexural properties [69]. Combining balsa core with corrugated composite web reinforcement can improve the specific flexural strength and specific flexural stiffness [113, 114] as well as the flexural fatigue life [115]. Stacking of balsa wood plies has been used to improve the shear stiffness of balsa cores, and this can be realised using laminated plywood fabrication technology [86, 125]. However, the properties of plywood made of balsa is beyond the scope of this paper which is focused on monolithic balsa core material.

Because balsa core sandwich structures can be subjected to repeated flexural loadings, such as when used in wind turbine blades or boat hulls, numerous studies have investigated their flexural fatigue performance [60, 82, 101, 115-117, 120-122]. The heterogenous microstructure of balsa can cause large scatter in the fatigue life data of sandwich structures with a balsa core (**Figure 13**), compared to sandwich structures with more homogenous cores such as polymer foams [101]. To overcome the large scatter in fatigue data, probabilistic models have been developed to determine the variability in S-N curves (**Figure 13**) [101]. The analytical model developed by Dimitrov and Berggreen [101] was calibrated to constant-amplitude shear test data using the maximum likelihood method, and can be readily applied for estimating characteristic S–N curves with any required survival probability. As with static flexural tests, sandwich beams with shorter span lengths fail under cyclic bending loads via balsa core shear fracture while long beams via facesheet failure. Both short and long sandwich beams have similar rates of reduction to flexural strength with increasing number of cyclic bending loads [60]. Shear failure in fatigue can also be followed by a secondary delamination failure between the core and facesheets [116]. Fatigue damage in GFRP sandwich structures with a balsa core initially increases slowly before accelerating significantly prior to ultimate failure [116]. Debonding of composite facesheets followed by core shear cracking has been observed in flexural fatigue tests of CFRP-balsa sandwich structures [120].

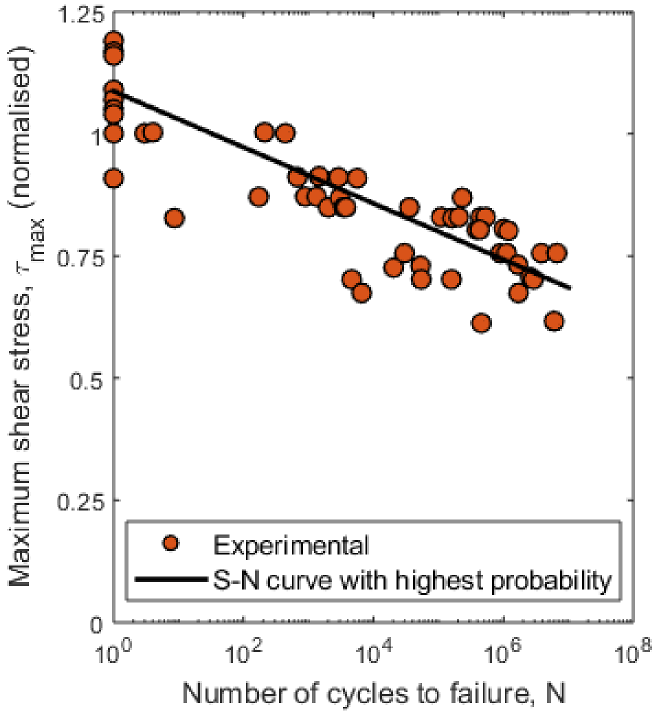


Figure 13. S-N curve measured for GFRP-end grain balsa sandwich structure under cyclic flexural loads in the core shear failure regime. The shear strength of the core is normalised to the ultimate strength (5.7 MPa). Data from [101].

The flexural creep life of sandwich structures with GFRP facesheets and a balsa core has been investigated [107]. The creep behaviour exhibits linear viscoelastic deformation when the load level is less than ~40% of the ultimate load. The influence of other parameters such as temperature and humidity on creep life needs further investigation.

The flexure-after-impact performance of sandwich structures with a balsa core has been studied and compared with sandwich materials with polymer foam cores [100]. Baran and Weijermans [100] found that the damage caused by relatively low energy impact (35 J) changed the failure modes of polymer foam cores, but not panels with a balsa core (which remained as core shear fracture). Compared to sandwich structures with a polymer foam core, the impacted balsa sandwich structures had the smallest reduction in flexural stiffness but the greatest reduction in post-impact flexural strength. Models to predict the flexure-after-impact properties of sandwich structures with a balsa core have not been developed. The impact damage tolerance of sandwich structures with balsa cores is discussed further in **Section 6.5**.

6.1.2 Edgewise compression and buckling

Sandwich structures with balsa cores loaded in edgewise compression [102, 118, 126-132], including buckling collapse from edgewise compression loading [20, 109, 112, 118, 133-135], have been studied extensively. As with flexural failure modes, compression failure modes of sandwich structures with a balsa core can trigger and interact with other failure modes. For example, facesheet debonding can occur in sandwich structures with a balsa core and facesheets made of fibre metal laminate [109] or GFRP laminate [135], which triggers core shear failure. Facesheet debonding is further discussed in **Section 6.2.**

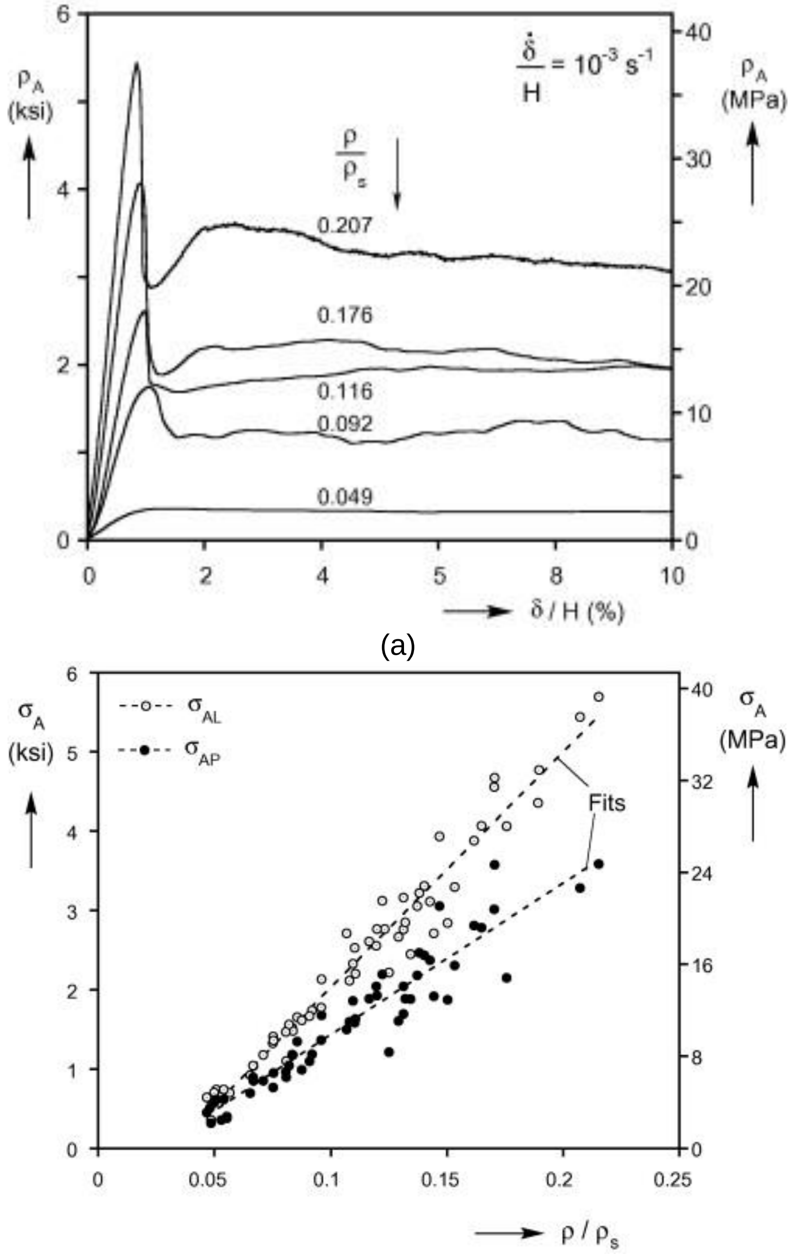
Shivakumar and Chen [118] studied the failure modes of GFRP-end grain balsa sandwich structures loaded in edgewise compression, and found that ultimate failure is governed by the ratio of the unsupported length (L) to the total thickness (d). For L/d ratios < 7, ultimate failure was triggered by facesheet microbuckling. For L/d ratios between 7 and 13, failure involved the combination of facesheet microbuckling, facesheet debonding and global (Euler-type) buckling. For L/d ratios > 13, ultimate failure occurred by buckling, with other modes suppressed. Analytical models have been formulated by Shivakumar and Chen to predict failure of sandwich structures with a balsa core subjected to edgewise compression loads under different L/d ratios [118].

Sandwich structures with a balsa wood core and GFRP facesheets with wrinkle defects have also been subjected to edgewise compression fatigue loads [130]. The presence of wrinkle defects has been shown to greatly reduce (by ~66%) the fatigue life of these structures when compared to the control material without wrinkles. Therefore, part processing techniques that risk the introduction of wrinkle defects should be avoided or components should be inspected for these defects.

6.1.3 Flatwise Compression

The flatwise compression strength is a measure of the crush resistance of sandwich structures in the through-thickness direction. The flatwise compression properties of a variety of sandwich materials have been determined, including balsa core structures [5, 55, 57, 73, 79, 87]. The flatwise properties of sandwich structures are determined by the core properties due to their lower resistance to through-thickness compression compared to the facesheet materials. The compression properties of balsa have been determined in the axial, tangential and radial directions [5, 55, 57, 73, 79]. For example, Kotlareski et al. [55] measured the average compressive strength for a medium density balsa wood to be about 8 times higher in the axial direction (9.2 MPa) compared to the radial direction (1.1 MPa). Because the wood grains are aligned in the through-direction of sandwich structures, it is the axial compressive properties of balsa which determine the flatwise strength.

The effect of balsa density on the compressive load-displacement response measured in the axial direction is shown in **Figure 14** [57]. Wood deforms elastically with increasing compression strain up to a “yield” stress value, and then the load-capacity often drops sharply before plateauing to a relatively constant strength value over a relatively large strain range. The axial yield stress is determined by the resistance of the balsa wood grains to fail via kinking, and the plateau region is determined by the resistance of the kinked grains to axial crushing [5, 55, 57, 73, 79]. The axial compressive yield stress and plateau stress values of balsa increase linearly with density, as shown in **Figure 14b**. The flatwise compressive strength of balsa also increases with the loading rate [79]. The crushing of the tracheids is dependent on the balsa density. The tracheids undergo concertina-type axial folding with some shear at relatively low density, whereas the failure mode transitions with increasing density towards simultaneous bending and lateral crushing [57]. Therefore, the flatwise compressive strength and through-thickness crush resistance of balsa sandwich structures can be improved using a higher density core, although with the associated weight penalty. Comprehensive studies comparing the edgewise compressive properties of balsa core sandwich structures with sandwich structures using other core types also exist. For example, Da Silva and Kyriakides [57] report that the specific crush energy is comparable to metal honeycombs with the same density.



(a)

(b)

Figure 14. Effect of relative density of balsa (ρ/ρ_s) on the (a) compressive stress (ρ_A)-strain (δ/H) curve and (b) maximum axial yield stress (σ_{AL}) and axial plateau stress (σ_{AP}). δ and H is the instantaneous thickness and original thickness values of the balsa sample, respectively. Reproduced with permission from [57].

6.1.4 Tension

The relatively stiff and strong facesheets used in sandwich structures usually determine the tensile properties, although sandwich materials are rarely used in practice to carry significant tensile loads and therefore is not often the critical load case considered in design. To this end, less research has been reported on the tensile properties of balsa core sandwich structures, although several studies have investigated the effect of fire on the tensile properties of sandwich structures with a end-grain balsa core and GFRP facesheets [126, 136, 137], and this research is discussed further in **Section 6.3** and **Section 6.4**, respectively.

6.2 Facesheet adhesion, fracture and joining

6.2.1 Facesheet adhesion

The adhesion of facesheets to the balsa core is a critical factor in load transfer in sandwich structures and can dictate the resultant mechanical properties. Delamination-like debonding failure between a facesheet (**Figure 15**) and balsa core is governed by the facesheet-core interfacial strength and fracture toughness. Several studies have investigated the effect of adhesion on the properties of balsa core sandwich structures [138-144]. Moreover, the part processing technique and type of resin used in the fabrication of the sandwich structure typically govern the resultant facesheet-core interfacial fracture toughness. Hence, this should be considered in the choice of part processing techniques, as discussed in **Section 3**, and resin-type selection.

The facesheet-core interfacial fracture toughness of sandwich structures with balsa cores and GFRP facesheets is typically lower than those with a polymer foam core and GFRP facesheets [144]. Moreover, sealing or pre-treating (e.g. with resin) the balsa core can reduce further the interfacial fracture toughness as this can prevent the liquid resin in the uncured composite facesheet from seeping into the cells and vessels of the balsa during fabrication which can enable mechanical interlocking that increases the interfacial fracture toughness [144].

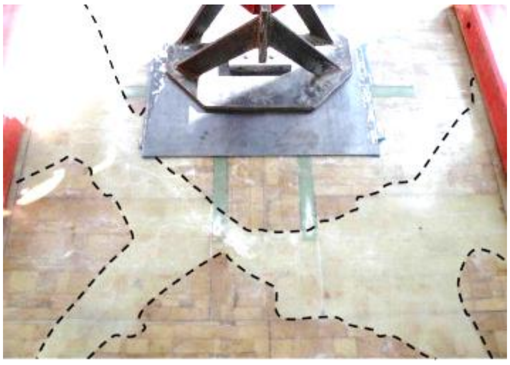


Figure 15. Widespread delamination of a facesheet in a GFRP-end grain balsa sandwich panel subjected to bending. Reproduced with permission from [31].

The mechanical properties of the balsa core and adhesive may degrade due to prolonged environmental effects, as studied by Tarfaoui and El Moumen [141] for E-glass fibre reinforced balsa sandwich used for marine applications. However, prolonged immersion in water does not affect the interfacial fracture toughness of GFRP-balsa sandwich structures. In contrast, prolonged exposure to seawater absorption can enhance significantly the interfacial fracture toughness of sandwich structures with GFRP facesheets and a balsa core [138, 139] due to the increased fibre bridging between the facesheet and core. However, the interfacial fracture toughness of sandwich structures with a balsa core may be reduced at high loading rates, and this is a concern for marine applications involving wave impacts or explosive blast loads [139, 140]. The reduction in interfacial fracture toughness at high loading rates can be attributed to a lack of fibre bridging [139].

While the choice of processing technique used in the fabrication of the sandwich structure is critical to the facesheet-core adhesion, the fabrication process can be modified to improve the interfacial fracture toughness [32, 142]. For example, Truxel et. al. [142] demonstrated that adding a layer of continuous filament fibre mat or machining grooves at the interface can increase the toughness. The continuous fibre mat allowed the resin to flow quickly, thereby evenly wetting the facesheet-core interface leading to improved adhesion. However, the fibre mat added significant thickness and weight penalty to the panel. More conventional resin distribution mediums were also investigated, but found to be less effective in improving adhesion strength compared with continuous fibre mat [142]. Another is example is the use of bonded Z-joints in GFRP-balsa sandwich structures to re-direct failure away from the facesheet-core interface when flexural load is applied [32].

6.2.2 Fracture toughness

The fracture toughness properties of balsa can also play a critical role in the interfacial failure for sandwich structures, as fracture of the core can trigger an interaction with facesheet delamination. As discussed in **Section 4**, balsa and other woods are highly anisotropic due to the heterogenous microstructure; toughness is always higher when crack growth occurs normal to the wood grain direction [95]. Determining the critical strain energy release rate (G_c) accurately is important for quantifying interfacial failure for sandwich structures. Consequently, several methods have been devised to experimentally measure G_c for balsa core sandwich structures with crack growth normal to the grain direction, and these are described by Ma et al. [145]. The toughness of balsa is higher than many other commercially available polymer foam core materials (**Figure 16**), and a detailed study of mode I (opening mode), mode II (sliding mode) and mixed-mode fracture toughness properties by Mohammadi and Nairn [146] has shown that the mode I toughness increases with crack length due to fibre bridging. However, the mode II toughness of balsa does not increase with crack length due to the absence of fibre bridging, although the mode II toughness was higher than the mode I value.

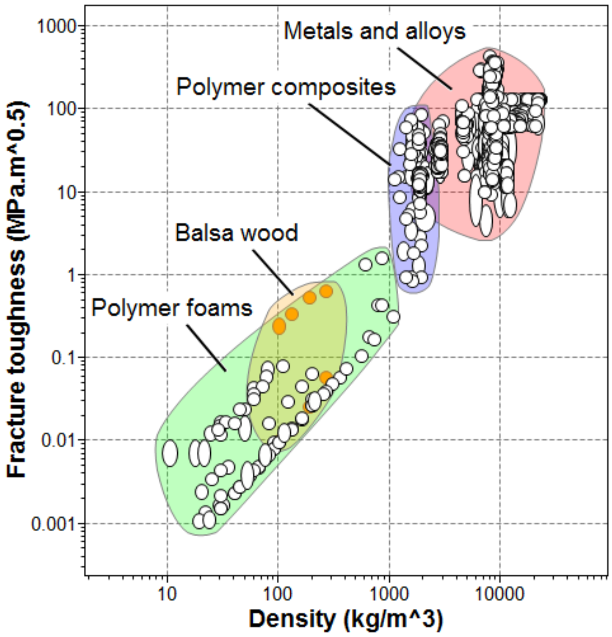


Figure 16. Fracture toughness of balsa wood (orange markers) compared with polymer foams and other engineering materials. Plot created with tools in [4].

The fracture toughness of balsa, like other mechanical properties, shows significant variability and is affected by different conditions (e.g. temperature, moisture content, density). For example, the fracture toughness of balsa wood increases with density when the crack growth direction is normal to the grain orientation [95]. It has been shown that for an adhesively bonded balsa core made of both high and low density layers, a crack initiates in the low density layer due to its lower toughness and propagates preferentially in the radial-longitudinal (RL) plane (see **Figure 4**) causing mixed-mode failure [110]. Laminated veneer lumber (LVL) made from balsa as the core material in sandwich structures can possess a higher fracture toughness compared to solid balsa material, and also fibre bridging effects contribute to further enhanced toughness when the core is used with GFRP facesheets [147]. While not extensively studied, the fracture toughness of balsa can be strongly influenced by the adhesive used to bond the blocks, with the joining interface usually of lower toughness and therefore provides a pathway for crack growth through the core.

6.2.3 Joining

Joining of sandwich sections into structural components is a crucial design consideration for structural assembly. The use of mechanical fasteners, such as bolts, rivets and self-tapping screws [148], can reduce the mechanical and fatigue properties. For self-tapping screws connected to GFRP facesheets and balsa core, the sandwich structure can experience a progressive loss of stiffness during cyclic loading, and structures with a load exceeding the uniaxial tension screw pull-out load are more susceptible to failure [148].

Different types of structural joints are used in sandwich structures, with each type requiring a customised design based on the load condition and failure mode. For example, a T-joint between adjacent compartments in a ship structure made of a sandwich structure (GFRP facesheets and balsa core) is predominantly under tension when subjected to dynamic loads (blast/explosion) [149]. So, the joining is usually formed by filler creating a gradual transition from the base panel to the T-panel, which is then over-laminated with laminates [150]. Another novel example of joining in balsa-GFRP sandwich structures is the development of an adhesively bonded Z-joint to connect adjacent sandwich structures for use in building floor rehabilitation [32, 33]. Provided the adhesive joint is well bonded, the joints can arrest crack growth within a balsa core of a load-bearing sandwich structure [32, 33, 110].

Another key factor in joint design for balsa sandwich structures is understanding the potential pre-damage introduced when performing joining related operations. For example, drilling a hole for bolted joints [151] has an optimum cutting speed and tool diameter, beyond which it may cause delamination in the facesheet and/or damage in the core.

6.3 Thermal properties and fire performance

Balsa core sandwich structures are most often used in ambient temperature conditions (between about -20^{o}C to +50^{o}C), where the variations in temperature are not extreme. The properties of balsa, like other woods, are affected by high and low temperatures, and therefore when used as the core material to sandwich structures they have an effective operational temperature range. Since balsa core sandwich structures are used in applications where fire is an ever-present hazard, an understanding of their response in high temperature environments is important. Sandwich structures can also be used in cold, Arctic-like conditions such as construction materials for buildings and marine craft. This section summarises published research into the thermal, low temperature and high temperature properties of balsa core in sandwich structures. The section also reviews research into the fire properties of these materials.

6.3.1 Thermal properties

The thermal properties of balsa, including thermal conductivity, specific heat capacity and thermal expansion coefficient, are similar in values to other woods with the same density [152]. The thermal properties of woods (including balsa) are not constant values because they are influenced by several factors, most notably the grain density and moisture content. The thermal properties are also direction-dependent, and are different in the longitudinal, tangential and radial directions to the wood grain orientation. The coefficient of thermal expansion of balsa (and other woods) increases linearly with temperature (over the temperature range of approximately -50^{o}C to +50^{o}C) but is non-linear at higher temperatures due to moisture loss and decomposition. The thermal conductivity and specific heat capacity vary over a range of values depending on the density, moisture content, grain direction and temperature [153-155]. For example, Kotlarewski et al. [153] measured thermal conductivity values for balsa used in sandwich structures in the range of 0.038 - 0.067 W/mK, with the value increasing with the wood grain density and higher in the longitudinal compared to the tangential and radial grain directions. The thermal conductivity and specific heat capacity of balsa is typically in the range of other core materials with similar density values, such as polymer and syntactic foams.

6.3.2 Low temperature properties

There is little information on the properties of balsa core sandwich structures at low temperature. In general, the mechanical properties of woods increase with decreasing temperature below 0^{o}C [156-161], although the magnitude of the property increase depends on the moisture content, wood grain density, load condition and other factors. Properties such as elastic modulus, compression strength and flexural strength increase with the temperature below freezing, with studies performed at temperatures as low as -196^{o}C. The mechanical properties increase due to freezing of water in the wood, with the strength of ice increasing with decreasing temperature [156, 157, 159-161]. The properties also decrease due to hardening of the wood cell walls and stabilisation of the crystalline structure [156, 157, 159-161]. Based on these studies on wood, it is expected that the mechanical properties of balsa will increase with decreasing temperature, thereby improving the properties of sandwich structures. However, the mechanical properties of the laminate facesheets may be improved, reduced or remain unchanged at low temperature [162, 163]. Therefore, it is difficult to predict changes to the properties of balsa core sandwich structures at low temperature without performing the test measurements, of which there is little available data. Moreover, the low temperature performance of balsa core sandwich structures is closely related to the facesheet and adhesive materials.

6.3.3 Thermal stability and decomposition

Balsa core sandwich structures soften and decompose at high temperature, and therefore have an effective maximum temperature operating limit (which is typically ~60-80°C). Many studies have been performed on the thermal softening of the laminate facesheets to sandwich structures, which is determined by the glass transition temperature (T_g) of the polymer matrix. The T_g values for the thermoset and thermoplastic matrix laminates used as facesheets are typically in the range of 60-150°C. The polymer matrix begins to thermally decompose above ~250-300°C (depending on the resin type) [164]. The effect of high temperature on the properties and weakening of balsa and other woods has also been determined [74, 154, 165-171]. An example of mechanical property reductions of balsa is shown in **Figure 17**, which plots the effect of temperature on the shear and compression properties of end-grain balsa in the axial direction. Water evaporates from balsa above ~100°C provided there is a pathway to exit the sandwich structure, otherwise the facesheets trap the moisture as superheated steam within the core which generates internal strain. Viscous softening of balsa occurs at ~120-150°C, and provided it is not heated above this temperature then the mechanical properties fully recover when cooled to room temperature [165]. Balsa thermally decomposes over the temperature range of ~250°C to 500°C resulting in a large, irreversible loss in the mechanical properties [74, 154, 165-171], which is a similar decomposition range to many types of laminate facesheet materials and other types of core materials (e.g. foams, Nomex) used in sandwich structures. **Figure 18** shows the typically temperature ranges over which the main constituents of balsa decompose, with the decomposition process beginning with the break-down of lignin and cellulose at ~250°C and hemicellulose at ~300°C. Balsa is fully decomposed into carbonaceous char and volatiles by ~500°C.

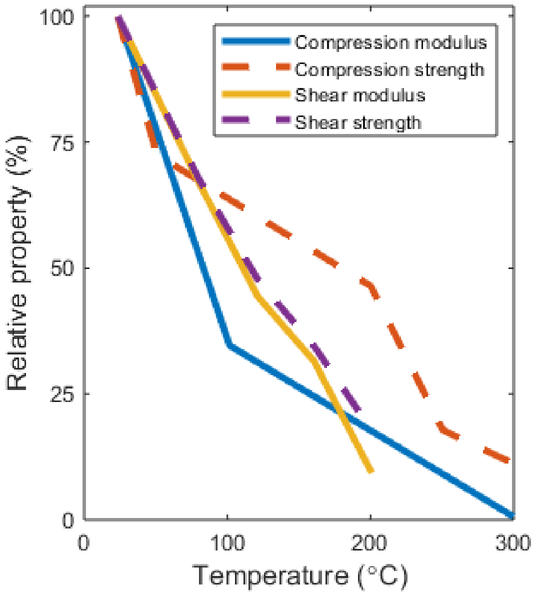


Figure 17. Effect of temperature on shear and compression properties of end-grain balsa in the axial direction normalized to room temperature. Data from [84, 171].

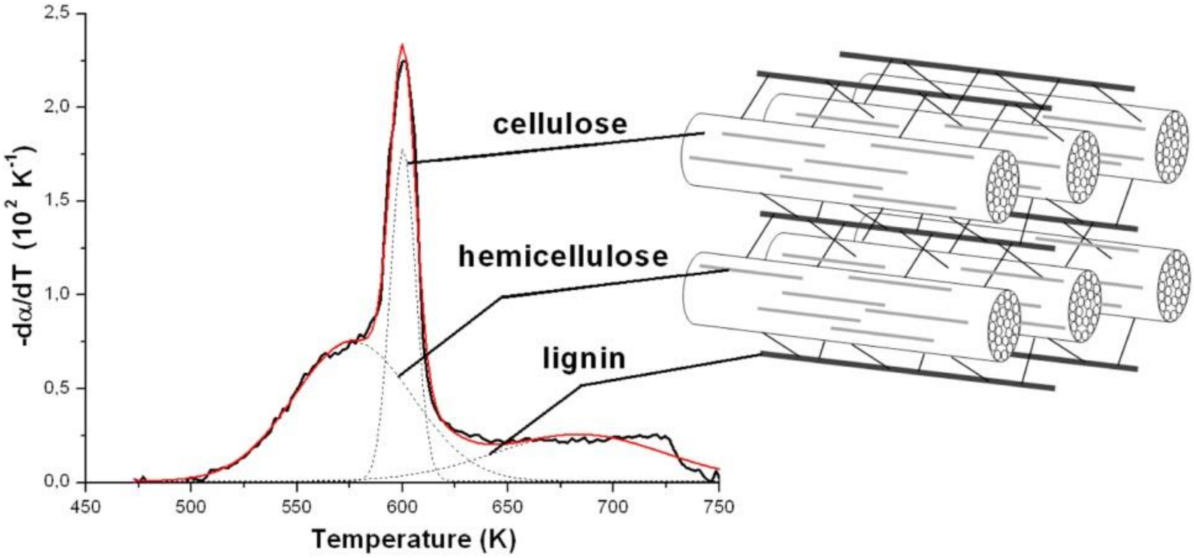


Figure 18. First temperature derivative of the mass fraction as a function of temperature for balsa wood. The −dα/dT curve is deconvoluted into each of its three principal components. Reproduced with permission from [167].

6.3.4 Fire reaction properties

The fire reaction properties of sandwich structures have been extensively studied, including time-to-ignition, heat release rate, mass loss rate and smoke density [164]. This includes the determination of the fire properties of balsa core sandwich structures [172, 173]. However, few studies have compared the fire properties of sandwich structures with a balsa core and other types of core materials, such as polymer foams [172]. For this reason, the relative fire performance of balsa core sandwich structures compared with other types of sandwich materials has not been thoroughly assessed, and therefore not well understood.

The balsa core to sandwich structures provides a heat insulating effect due to its relatively low thermal conductivity. During one-side heating by fire, the rate of heat conduction through the front facesheet slows considerably in the balsa core thereby generating a thermal gradient in the through-thickness direction of the sandwich structure. For example, **Figure 19** shows the temperature-time history for a balsa core sandwich material measured at the front surface of the laminate facesheet exposed directly to the fire, the middle of the core, and at the back surface opposing the fire [126]. For this example, the temperature difference between the front and back surfaces is up to several hundred degrees, and this is largely due to the low thermal conductivity of the balsa slowing heat conduction through the sandwich structure. Ulven and Vaidya [174] report that the insulating effect of the balsa core in sandwich structures increases with decreasing wood grain density. They found that a lower density (150 kg/m^3) balsa core insulated the back surface more effectively than a higher density core (180 kg/m^3) when the sandwich structures were exposed to fire. These results demonstrate the heat insulation effect of thick-section balsa core sandwich materials.

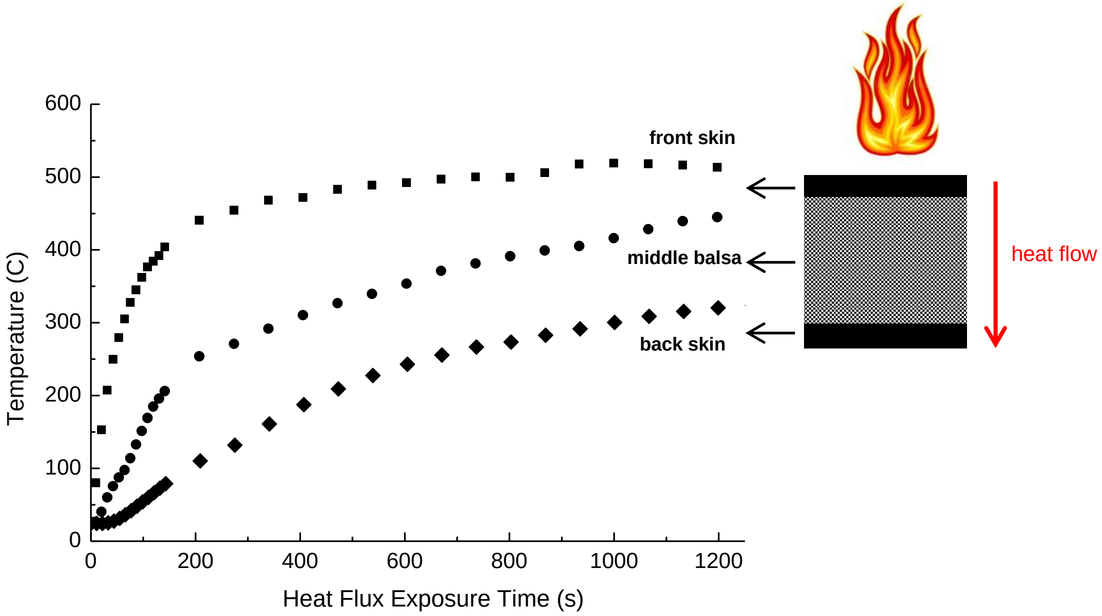
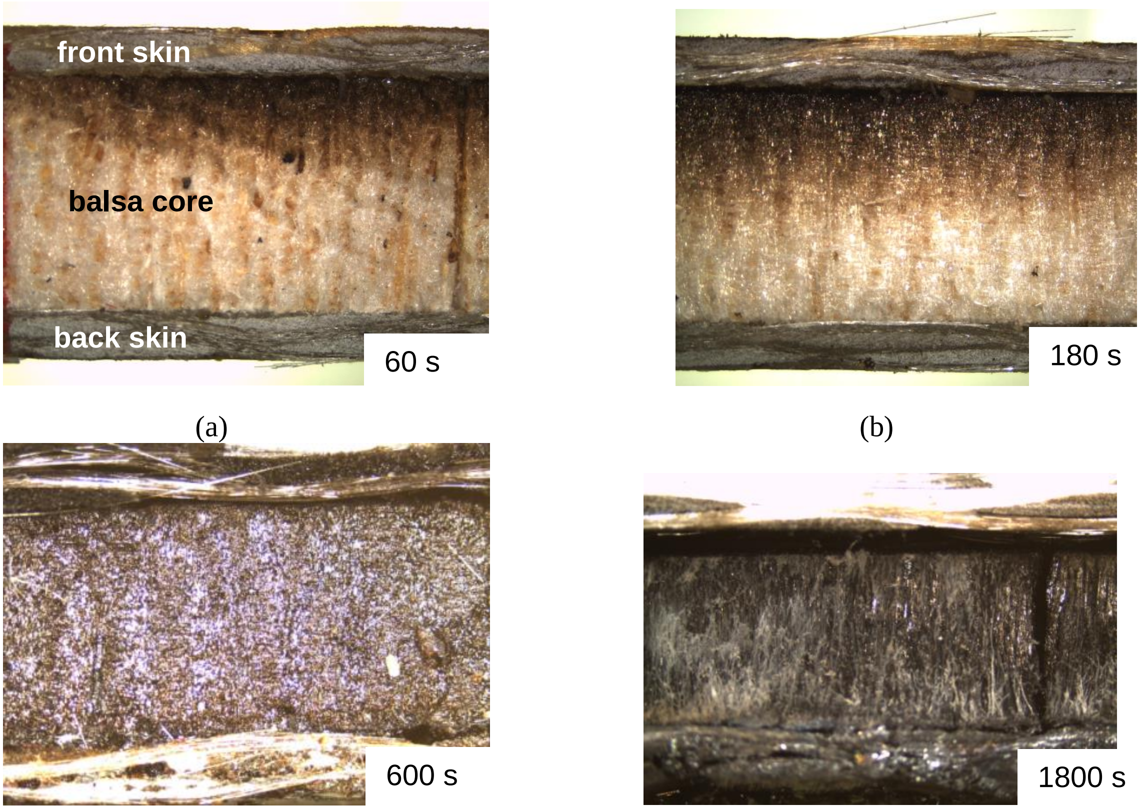


Figure 19. Temperature–time profiles at the front (heated) laminate facesheet, middle of the balsa core, and back facesheet of the sandwich structure exposed to thermal flux representative of fire. Adapted from [126].

Balsa core sandwich structures soften and then decompose when heated to sufficiently high temperatures by fire. The laminate facesheet exposed directly to fire begins to decompose when heated above ~250-300ºC causing a large loss in stiffness and strength due to matrix degradation, delamination cracking, fibre weakening and, in some cases, cracking along the facesheet-core interface [175]. The polymer matrix facesheet decomposes into a porous char with the release of hydrocarbon gases and other volatiles in the fire, which can add to the fuel load. Heat is conducted from the hot, decomposing front facesheet into the balsa core which decomposes above ~250ºC. **Figure 20** shows an example of the progressive burn-through of a balsa core sandwich structure following one-sided radiant heating representative of fire, with the darker regions being where the material has decomposed to char [126]. Substantial softening and weakening occurs during the softening and decomposition of balsa core sandwich structures in fire [66, 136, 137, 176-181]. Finite element and analytical models have been developed to predict the deterioration to the mechanical properties of balsa core sandwich structures in fire [126, 137, 177-181].

The damage caused by fire can also reduce substantially the residual post-fire mechanical properties of balsa sandwich structures after fire has been extinguished [66, 126, 169, 178, 179]. An example of this is shown in **Figure 21** which plots residual flexural modulus and residual flexural strength of water saturated and dry GFRP–end grain balsa sandwich structures subjected to a 750°C fire. The reduction to the mechanical properties during and following exposure to fire depends on the multitude of parameters, including the type and thickness of the laminate facesheets; the density, moisture content and thickness of the balsa core; and the temperature and flaming conditions of the fire. Systematic assessment of the influence of these parameters on the fire structural performance of balsa core sandwich structures has not been performed. Furthermore, the deterioration to the mechanical properties of balsa core sandwich structures in fire and the residual properties following fire have not been compared to other types of sandwich materials to assess the relative fire structural performance.



(a) (b) (c) (d)

Figure 20. Cross-sectional views of balsa core sandwich structure following exposure to the thermal flux representative of fire for different times: (a) 60, (b) 180, (c) 600 and (d) 900 seconds. The upper surface was directly exposed to the fire.

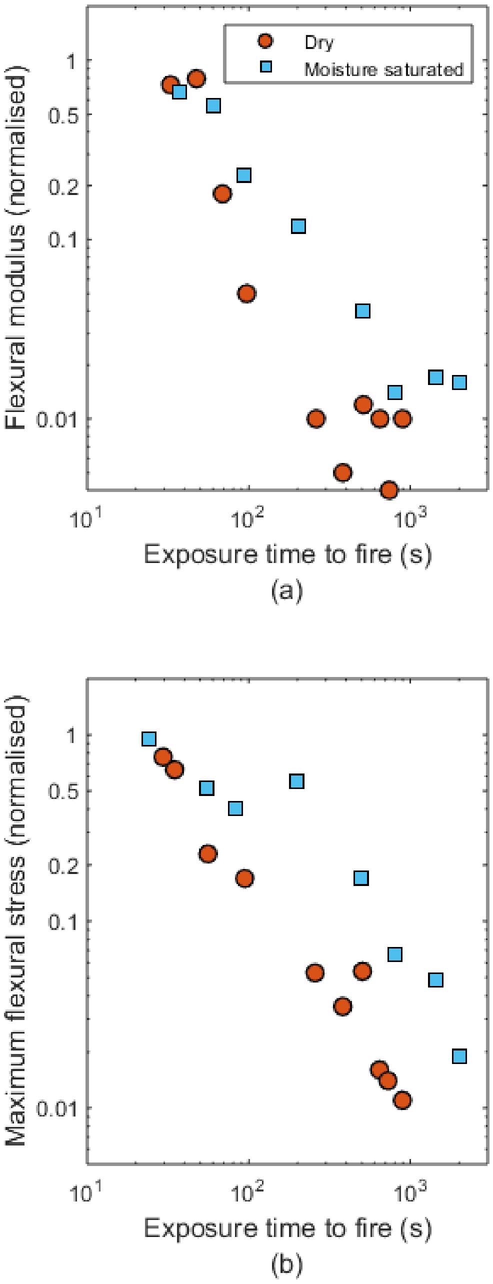


Figure 21. (a) Residual flexural modulus and (b) flexural strength of saturated and dry GFRP – end grain balsa sandwich structure subjected to 750°C fire (at a 26 mm stand-off distance) normalised to room temperature values. Data from [169].

Very few studies have investigated materials or techniques to improve the fire resistance of balsa core sandwich structures with fibre-reinforced polymer facesheets. Giancaspro et al. [182, 183] found that laminate facesheets containing a heat resistant inorganic (geopolymer) matrix improved substantially the fire resistance of balsa sandwich structures. Kandare et al. [184] found that the addition of fire retardant additive (ammonium phosphate) and glass veil to the laminate facesheets created a thermal barrier effect which increased the fire performance of balsa sandwich structures. Many other techniques are available to protect balsa core sandwich materials in fire, including intumescent and passive heat insulation coatings and the incorporation of flame retardant additives to the polymer matrix of the laminate facesheets [164].

6.4 Water absorption

The absorption of water by balsa wood and its adverse effects on mechanical properties have been studied extensively [64, 90, 91, 136, 138, 140, 169, 185-187]. Moisture in balsa (and other hardwoods) is first absorbed at the wood cell walls and then, once saturation is reached, moisture subsequently fills the wood cells [94]. The absorbed water acts to soften the cellulose and lignin within the cell walls, causing reductions to the mechanical properties (stiffness and strength) with increasing moisture content until the saturation point [91]. An example of this is shown in **Figure 22**, which plots the effect of moisture content on the axial compression strength of two end-grain balsa woods with different density values. Beyond fibre saturation (while wood cells are filled with water) the mechanical properties do not generally further reduce [94], while the additional weight acts to increase the mass density and significantly reduce the mass-specific mechanical properties. Reductions to specific mechanical properties are a critical concern for sandwich structures as this can negate the benefits of selecting balsa as the core material. Balsa wood shows very high weight gain compared to closed-cell polymer foam cores, and in addition to weight gain, balsa can experience significant swelling due to water absorption [91]. The moisture absorption of sandwich structures with a balsa core and polymer composite facesheets can be approximated using analytical models based on Fickian diffusion theory [186, 188-190]. The internal stresses induced by moisture absorption in balsa core sandwich structures with GFRP facesheets have also been studied using finite element models [186].

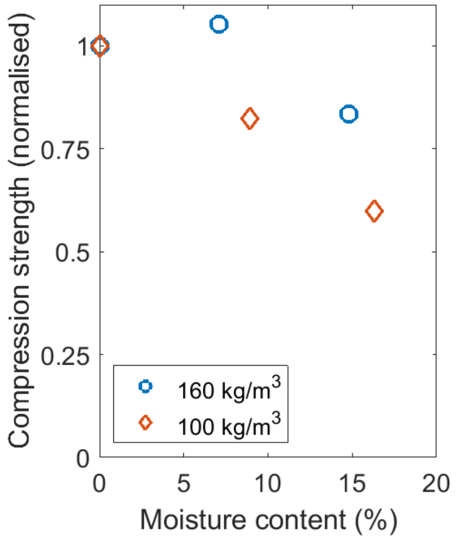


Figure 22. Effect of moisture content on the room temperature compression properties of end-grain balsa in the axial (RL) direction normalised to dry (0% moisture) properties. Values are shown for two density values of balsa. Data from [90].

The negative impact of water absorption on balsa dictate that care needs to be taken to ensure that exposed balsa surfaces in a sandwich structure are sealed against moisture ingress, and this is can be achieved with a polymer coating [138]. The presence of laminate facesheets also significantly reduces the percentage weight gain at saturation after full immersion in water, as shown in **Figure 23**.

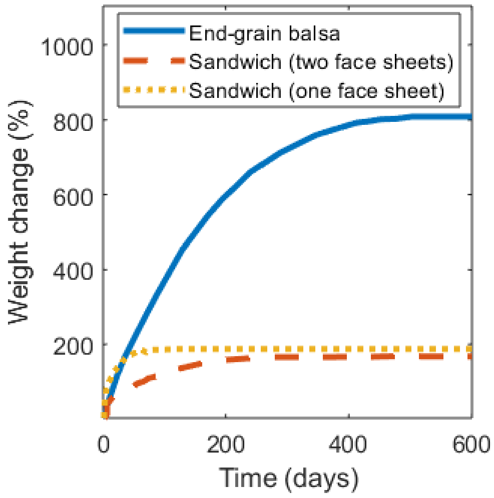


Figure 23. Percentage weight gain after immersion in water. Balsa values from [91]. Sandwich panel values from [169].

6.5 Impact and blast response

The impact response of sandwich structures have been studied extensively for a variety of high strain rate events, including impacts from low energy objects [191] and blast-induced shock waves [192] and, to a lesser extent, ballistic projectiles and hypervelocity particles. The impact properties of a wide variety of sandwich structures composed of different facesheet materials (e.g. fibre-polymer laminate, metal) and core materials (e.g. polymer foam, metal foam, lattice) have been investigated. The impact response and damage to sandwich materials is dependent on a multitude of parameters, including the incident energy and shape of the impacting object, the mechanical properties and thickness of the facesheets, and the properties, density and thickness of the core. The core material can be very important in determining the deformation, energy absorption, damage mechanisms and penetration resistance of sandwich structures. This section reviews published research into the impact response of balsa core sandwich structures under low energy, ballistic and explosive blast conditions.

6.5.1 Low energy impact

The low energy impact response of balsa core sandwich structures have been studied for a wide range of impact conditions [66, 174, 193-205]. In this paper, low energy impact is defined by the impacting object having sufficiently low energy that it cannot completely perforate sandwich structures. The majority of studies have experimentally measured the impact response of balsa core sandwich structures with thin fibre-polymer laminate facesheets, usually containing glass or carbon fibres.

Many studies have compared the low energy impact response of sandwich structures with a balsa core with other types of core material [100, 102, 195, 196, 198, 201-203, 205-209], usually polymer foam such as closed cell PVC. However, it is often difficult to assess the relative impact performance of balsa core materials to other types of sandwich structures because the different core materials usually have different density values. The impact properties of sandwich structures, including the impact force, absorbed energy, damage mechanisms and post-impact mechanical properties, is influenced by the core density [210]. It is therefore difficult to compare the impact response of sandwich structures when the core materials have different density values, which is the case for most studies into balsa core materials. Wang et al. [209] reports that the specific impact energy (i.e. absorbed energy normalised to core density) for balsa wood is similar or slightly superior to other common core materials such as cork and polystryrene foam. Ramakrishnan et al. [201, 206] found that the peak impact force increased whereas the amount of absorbed impact energy decreased with increasing density of the balsa core. Wang et al. [209] found that the amount of deformation to the facesheets caused by low energy impacts was reduced by increasing the core density.

Under low energy impacts the damage sustained by the balsa core usually consists of localised crushing, compaction and cracking immediately below the impact point [193, 195, 198, 203, 211]. Debonding between the facesheet and core is common due to the relatively weak interfacial bond strength for many balsa core sandwich structures. Fatima et al. [212] recently reported that increasing the bond strength using a structural adhesive can increase the impact damage tolerance. Vertical cracks can grow along the rays of the balsa when the grain direction is aligned in the through-thickness direction of the sandwich material, as shown for example in **Figure 24** [198]. This core damage results in a large loss in structural integrity [197, 198, 203]. The deformation and damage to balsa can absorb a substantial amount of the energy imparted to sandwich structures by the impacting object.

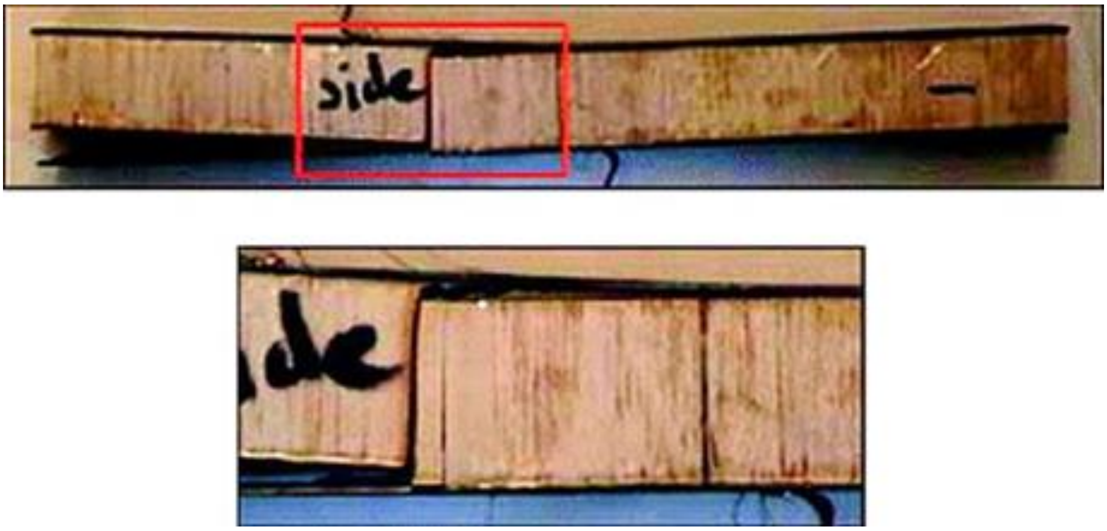


Figure 24. Impact damage to the balsa core of a sandwich structure, including cracking in the wood grain direction. The upper surface was impacted. Reproduced with permission from [198].

Further research is needed into the low energy impact properties of balsa sandwich structures. All impact studies have been performed with the grains aligned in the through-thickness direction of the sandwich material, and the effect of the wood grain orientation on the impact response has not been studied. The mechanical properties and energy absorption of balsa is highly directional, and it is expected that the impact properties will also be affected significantly by the grain orientation. The influence of the moisture content of balsa, which also affects the mechanical properties, on the impact response has also not been studied. Finite element models have been developed to calculate the impact load and displacement of balsa sandwich structures [193, 194, 213], however models have not yet been developed to predict impact-induced core damage.

6.5.2 Ballistic impact

Balsa core sandwich structures are not usually used in applications requiring protection from ballistic projectiles, and consequently only a limited amount of research has been published on their ballistic performance [214-217]. Experimental studies have shown that the balsa core is heavily compacted and cracked ahead of the projectile as it penetrates the sandwich structure. Finite element models have been developed to predict the ballistic performance and damage to balsa core materials [213, 214, 216]. However, much remains unknown about the effect of the balsa properties of the ballistic resistance of sandwich structures, including the effects of density, grain orientation and moisture content.

6.5.3 Explosive blast

Sandwich structures are used in applications where they can be subjected to dynamic loading via the shock wave generated by an explosive blast. This includes the use of sandwich structures with a balsa core in naval ships which may be attacked using airborne or underwater munitions [48]. The effect of blast loading of sandwich structures by shock waves generated by an explosive event have been extensively studied, as recently reviewed [192]. The deformation and damage of sandwich structures with different core materials, including polymer foams, metal foams, Nomex and other light-weight materials, caused by explosive blasts have been investigated experimentally and using finite element analysis. The explosive blast response of balsa core sandwich structures has also been investigated, although not extensively [218-222].

The blast response of sandwich structures is controlled by a multitude of parameters, including that the intensity and duration of the shock wave, the type and thickness of the facesheet material, the properties and thickness of the core, and the skin-core interfacial properties. In general, the core materials to sandwich structures can absorb more of the shock wave energy than the facesheets via irreversible deformation and damage [192].

The response of balsa core sandwich structures to shock waves has been investigated experimentally using several techniques, including small explosive charges [223], shock tubes [220], and high velocity projectiles [218]. The balsa core absorbs a substantial amount of the energy of a shock wave as it propagates through sandwich structures via deformation and crushing of the fibrils and other energy absorbing damage processes. For example, **Figure 25** presents a through-thickness view of a sandwich structure following explosive blast loading which shows crushing and compaction of the balsa core [222], and this is an effective mechanism in absorbing the shock wave energy and suppressing its transmission to the back facesheet. The response of the balsa core to shock wave loading and the resultant damage is expected to be influenced by its density, moisture content and wood grain orientation, although this has not been investigated. Furthermore, there is little information available on the relative performance of balsa compared to other core materials (e.g. polymer foam) in improving the blast performance. While several studies have compared sandwich structures containing balsa to other core materials, the core density values were different making it difficult to compare between materials. Gargano and colleagues [222] found that the out-of-plane deformation and amount of damage to sandwich structures with end-grained balsa and PVC foam cores (with near identical density) were similar, although further research is needed to fully assess the blast resistant properties of balsa core materials compared to other types of sandwich structures.

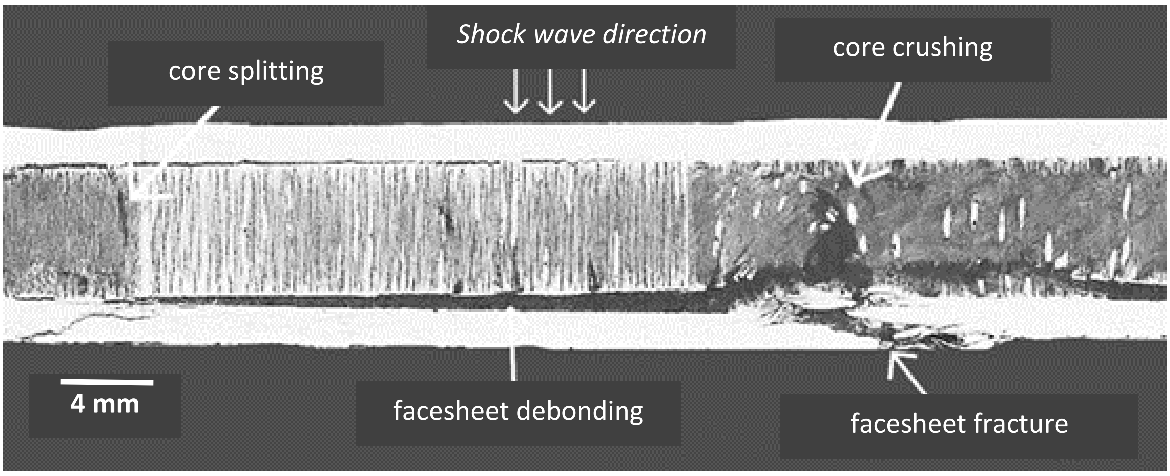


Figure 25. Cross-sectional X-ray computed tomography image showing skin and core damage to a balsa core sandwich material subjected to explosive blast loading. The direction of the shock wave loading is indicated. Reproduced with permission from [223].

Many finite element and analytical models have been developed to compute the explosive blast response of sandwich structures [192]. However, these models have been developed for polymer foam, metal foam, metal lattice and other core types with isotropic material properties. It is challenging to model the blast damage to balsa cores due to their non-uniform microstructure, anisotropic mechanical properties, strain rate sensitivity, and the adhesive used to bond the balsa blocks (which is often the weakest point). Validated models to analyse the deformation and damage to balsa core sandwich structures under explosive blast loads are lacking.

Virtually all studies into the explosive blast response of balsa core (and other types of) sandwich structures consider only the effect of the shock wave on the deformation and damage response. However, munitions usually release energetic fragments (i.e. shrapnel) upon detonation which can also cause damage. Ranwaha et al. [224] performed an experimental study comparing different core materials to stop high velocity metal fragments representative of small pieces of shrapnel. It was found that balsa wood provided some protection, although it was not as effective as some other core materials such as metal and polymer foams (although the density values were different between the study materials). Hence, further studies on the effect of the explosive blast damage, especially shrapnel damage, on the performance of balsa sandwich structures are required.

6.6 Indentation response

Sandwich structures can be used in structural applications where the applied loading is localised rather than distributed, and therefore the indentation resistance is an important engineering property. The indentation properties of sandwich structures under localised static loads have been studied extensively using experimental tests, analytical models and finite element analysis [225-234]. The properties are usually determined by the low-rate indentation of the facesheet using a hemispherical ball, cylindrical rod or flat punch plate, which induce different indentation contact conditions. In addition to the type of indentation, the indentation properties of a sandwich structure depend upon its design and the properties of the facesheets and core.

Most studies of the indentation properties have been performed on sandwich structures with foam cores [225, 226, 230-232], with only a few studies into balsa core materials [31, 43, 207]. Armstrong [43] performed the first published experimental study into the indentation resistance of balsa core sandwich structure. Using a steel ball, it was found that the deformation resistance of the balsa was equivalent or slightly higher than other core materials (such as PVC and Nomex) that were studied. Similarly, Garrido et al. [207] found that the indentation resistance of a sandwich structure with a balsa core was superior to polymer foam of near-equivalent density. Garrido and colleagues reported that the indentation stiffness and loading resistance were higher and the out-of-plane displacement of the facesheet pressing into the core was lower for the balsa core sandwich structure. Tagarielli et al. [235] developed a FE model to predict the indentation resistance of balsa wood (without facesheets) using an elastic-plastic constitutive model for transversely isotropic foam-like materials. They observed experimentally that under increasing indentation force the balsa was compressed by localised deformation and crushing of the wood grains, which were aligned parallel to the indentation direction. Despite these studies, much remains unknown about the indentation resistance of balsa core composites, including indentation fatigue performance, as well as the effects of grain density, grain orientation and moisture content. Hence, further studies could aid adoption and service-life extension of balsa sandwich structures in a variety of engineering applications involving indentation and other localised loads.

6.7 Other properties

6.7.1 Acoustic and vibration properties

Balsa core sandwich structures possess comparable acoustic and vibration properties as some polymer foam core materials, as shown in acoustic, noise or vibration related applications. In musical instruments, for example, the use of sandwich structures with carbon fibre/epoxy facesheets and balsa core for a drum has been demonstrated to produce similar acoustic performance and frequency response to that of a traditional wooden instrument [51]. Balsa core sandwich structures can be optimised to provide acoustic noise shielding in ships and other marine vessels, including the reduction of underwater noise due to vehicle motion [236, 237]. Likewise, balsa core sandwich structures can be used in aircraft floors for effective noise control to minimise noise transmission into the passenger cabins. This has been proven via a series of acoustic tests measuring transmission loss for various sandwich materials over a wide frequency range (315-8000 Hz) and also via calculations using higher-order sandwich panel theory [238]. The acoustic performance of balsa core sandwich structures can be enhanced using natural material-based facesheets [239], which not only improves the coincidence frequency (a measure of acoustic performance) and reduces noise radiation, but also promotes renewability and recyclability of materials. Importantly, a combination of natural fibre reinforced facesheets (e.g. flax fibre reinforced epoxy laminate) with balsa core in sandwich structures is superior to synthetic core materials (e.g. polymer foam cores [208]) in terms of acoustic properties, such as sound absorption and damping.

One of the key mechanisms of effective sound absorption is the multi-scale architecture of the natural fibres constituting the facesheet as well as the microstructure of the balsa core [240], thus resulting in superior acoustic insulation performance compared to sandwich structures based on synthetic facesheets and cores.

Balsa core sandwich structures have good vibration damping properties and can be used for a number of applications in dynamic and vibration analysis. Bio-based sandwich structures have been characterised to evaluate their dynamic properties, including the damping coefficient, dynamic stiffness, and loss factor [239]. For example, the dynamic performance of a sandwich structure made of flax fibre thermoplastic facesheets and balsa core were evaluated experimentally and numerically, including studying separately the distinct effects of the constituent materials as well as the complete sandwich structure [241]. The core thickness and facesheet layup also influence the dynamic response, particularly the damping coefficient and natural frequency [242]. In other ways, the changes in structural dynamics and vibration responses of balsa core sandwich structures is used for structural health monitoring to determine the types, sizes and locations of damage [243, 244].

6.7.2 Electrical properties

Balsa core sandwich structures are used in applications when the electrical properties can be important, such as wind turbine blades that are susceptible to lightning strikes. Balsa, like other woods, is electrically insulating with conductivity values in the range of ~10^{-14} to ~10^{-16} S/m (depending on grain orientation, moisture content, density etc.) [245]. Balsa, like polymer foams, is an effective insulator between the facesheets which resist current flow in the through-thickness direction of a sandwich structure. Due to the high insulation properties, balsa core sandwich structures are subject to damage when struck by lightning and therefore protective measures are needed when used in applications at risk such as turbine blades [23, 246, 247]. Additional studies on preventing damage from lightning strike could assist in prolonging the service life of balsa sandwich structures in many civil infrastructure applications, especially wind turbines. On the other hand, various approaches have been used to increase the electrical conductivity of balsa core sandwich structures, such as conductive surface coatings for planar conductivity [248] and z-pins for through-thickness conductivity [249].

7. CONCLUSIONS AND FUTURE OUTLOOK

This paper has presented a critical overview of published research on sandwich structures with balsa wood core. These materials are used in a variety of engineering structural applications. Efforts towards greater use of environmentally sustainable materials have created opportunities for balsa to replace non-renewable, petroleum-based cores such as polymer foams and energy-intensive production of metal foams in a broad range of sandwich products. For example, sandwich structures that use natural fibres (e.g. jute, flax fibres) in composite facesheets and end-grain balsa cores have been developed to reduce the environmental impact of conventional sandwich structures with polymer facesheets and polymer-based core, which are often difficult and expensive to recycle [106, 123, 250, 251]. However, further improvements in the mechanical performance of bio-composite facesheets are needed to compete with conventional skin materials such as GFRP laminate.

The significant natural variability in the mechanical properties of balsa can limit its use in high performance applications where components frequently need to meet strict performance criteria. Moreover, the fabrication of sandwich structures with a balsa core is inhibited by resin absorption during infusion processes, as well as limitations on processing temperature. The effects of the extent of excess resin absorption on the resultant mechanical performance and damage tolerance of balsa sandwich structures have not yet been systematically studied. Further investigation of novel processing techniques, such as emerging out-of-autoclave composite processes [252-254], could help circumvent manufacturing challenges associated with vacuum-assisted resin infusion processes. Moreover, an investigation of the compatibility of balsa cores with additive manufacturing processes, such as fused filament fabrication and fused deposition modelling, is absent from the literature.

The properties of balsa and sandwich structures with a balsa core can be significantly affected by factors such as high and low temperatures, water absorption, impact, blast and indentation damage. However, it is difficult to predict changes to the properties of balsa core sandwich structures without performing physical testing due to a lack of published data. Hence, the further development of experimentally validated analytical and FE models to predict the properties, damage response and post-damage performance of balsa core sandwich structures would aid future optimised design of many applications. Moreover, the effects of various in-service damage types on the fatigue performance of balsa sandwich structures have not been investigated. For example, a balsa sandwich structure with indentation damage subjected to repeated loading could trigger progressive failure below the design limit load.

The material structure and pronounced anisotropy of balsa imparts high specific mechanical properties compared with many other conventional core materials. The unique microstructure of balsa also creates opportunities for design of future multifunctional energy storage sandwich structures integrating batteries and other energy storage devices [255].

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