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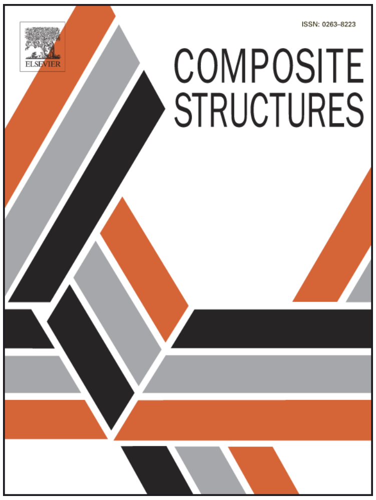

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The Mechanics of Composite Corrugated Structures: A Review with Applications in Morphing Aircraft

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Abstract

Corrugation has long been seen as a simple and effective means of forming lightweight structures with high anisotropic behaviour, stability under buckling load and energy absorption capability. This has been exploited in diverse industrial applications and academic research. In recent years, there have been numerous innovative developments to corrugated structures, involving more elaborate and ingenious corrugation geometries and combination of corrugations with advanced materials. This development has been largely led by the research interest in morphing structures, which seek to exploit the extreme anisotropy of a corrugated panel, using the flexible degrees of freedom to allow a structure's shape to change, whilst bearing load in other degrees of freedom. This paper presents a comprehensive review of the literature on corrugated structures, with applications ranging from traditional engineering structures such as corrugated steel beams through to morphing aircraft wing structures. As such it provides an important reference for researchers to have a broad but succinct perception of the mechanical behaviour of these structures. Such a perception is highly required in the multidisciplinary design of corrugated structures for the application in morphing aircraft.

1- Introduction

1-1 A general description to corrugated structures

The term "corrugated" in general describes a series of parallel ridges and furrows [1]. In mechanical engineering any structure which has a surface with the shape of corrugation either made by folding, moulding, or any other manufacturing methods is called a corrugated structure. Three typical corrugated structures may be classified as: a corrugated pipe, a corrugated sheet and a corrugated panel. The main common feature of all corrugated structures is their exceedingly anisotropic behaviour; high stiffness transverse to the corrugation direction in contrast to the compliance along the corrugation direction [2]. Because of this important feature, these structures have been widely used in industrial applications and academic research.

By adding two face sheets (also known as liners) as upper and lower surfaces to the corrugated sheet (also known as core, medium or fluting) a new geometry would be obtained known, as a corrugated panel [3]. By selecting the appropriate shape, dimensions and materials of the face sheets and corrugated core, a variety of stiffness and strength at low weight of the corrugated panel will be achieved. The structural characteristics of

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this corrugated structure depend mainly on the lightweight corrugated core which separates the face sheets and provides the necessary stiffness for the panel. However by considering different material stiffness for the face sheets and the corrugated core, different mechanical behaviour of the identical geometry would be expected.

If the stiffness of the material of face sheets is higher than or equal to the stiffness of the material of the corrugated core, the structure would be recognized as a corrugated sandwich panel [4]. Such a sandwich panel demonstrates higher shear, bending and tensile stiffness to weight ratio than an equivalent panel made of only the corrugated core material or the face-sheet material [5]. This is because the flexural stiffness of the panel is proportional to the cube of its thickness. Hence the function of a corrugated core in the sandwich panel is to increase the stiffness of the panel by effectively thickening it with a low-density corrugated core material. This results in the increase of the stiffness significantly for very little additional weight of the panel. The behaviour of such a sandwich panel under a bending load is similar to an I-beam where the facings of the sandwich panel act as the I-beam flanges where the upper and lower face sheets are subject to the in-plane compression and tension, and the corrugated core material acts as the beam's shear web where the corrugated core is subject to shear [6]. It can be concluded that one of the most important characteristics of a corrugated core is to keep the face sheets apart and stabilize them by resisting the out of plane deformations which increases the shear strength and stiffness of the panel.

1-2 Applications of corrugated structures

Corrugated structures have wide application in engineering due to their special characteristics such as: anisotropic behaviour, high stiffness to weight ratio and high capacity of energy absorption. The applications of these structures can be classified into the following categories in which more value is given to the special features of these structures.

1-2-1 Packaging industry

Corrugated boards, either made of plastic or cardboard are used extensively to produce rigid shipping containers of almost any shape or size. The packaging containers are exposed to various load conditions such as: static loads due to the compression of packages in a stack during transport and storage and vibration loads during transport. The reason that the corrugated sandwich panels have received huge interest in the packaging industries is because of their stiffness and durability, lightness and cost effectiveness as well as the recyclability and sustainability with the environment [7, 8].

1-2-2 Civil structures

The wide application of corrugated structures in civil engineering may be classified mainly as: beams with corrugated web, corrugated roofs and walls and corrugated pipes.

- Beams with corrugated web

The main benefit of applying corrugated web beams in supporting roofs, floors and columns in steel structural buildings are that the corrugated webs increase the beam’s stability against buckling. Applying these corrugated web beams in the components of the building results in a very economical design by reducing the required web stiffeners and leads to a significant weight reduction in these beams compared with hot-rolled or welded ones [9].

- Corrugated sheets in roof and walls

Corrugated sheets are among the best candidates for application in construction elements, for roofs, claddings and walls, of modern industrial buildings owing to their high strength to weight ratio, much lighter and lower cost than flat isotropic panels of the same strength [10]. Corrugated metal sheets for instance are frequently used as the roof of buildings that have steep slopes to dispose of rainwater quickly.

Their combination of high stiffness and lightweight nature lightens the load on the installation and the underlying building structures.

- Corrugated tunnel and pipe

Large metal corrugated pipes or arches are frequently used in tunnel structures to transport the aggregate and ore across various points on their properties. The need to maximize the surface area on such sites necessitates the use of tunnels for transporting bulk materials under roadways and processing these materials. The application of corrugated pipes and arcs in these tunnels offers advantages in the design, installation and operation of these projects such as: reducing the design time and related costs; simplicity of construction which leads in to the reduction of installation and maintenance costs [11].

Corrugated pipes are often used in sewerage and drainage applications because of their light weight, high strength and compliance which lead into long life performance. The strength of the pipes arises from the corrugated design of the outer wall rather than the wall thickness, in contrast to the normal solid wall pipes. The advantages of the corrugated pipes in general can be classified as their lightness and flexibility. The lightness of these structures reduces the manpower needed for installation and the costs of transportation whereas the flexibility reduces the damages during storage and handling and ease the natural settlements to be tolerated without suffering cracks or leakages [12].

1-2-3 Marine structures

The corrugated sandwich panel has offered a wide range of attractive design solutions to operational shipboard problems in which structural performance and weight are important design issues. The applications of these structures include decks, bulkheads, helidecks and accommodation modules [13]. Another application of the corrugated sandwich panels is in the combatant deckhouse structure of a naval ship since these structures show a good resistance to the possible blast loads [14].

1-2-4 Mechanical engineering structures

- Corrugated hoses:

Corrugated hoses are another case of important engineering structures which are exploiting corrugation characteristics. Because of the special properties of the corrugation structure, these hoses can withstand very high pressure and provide maximum leak tightness. Corrugated hoses also exhibit corrosion resistance and pressure tightness under the most extreme conditions, such as aggressive seawater, extreme temperatures found in space and conveying very hot or cold substances. The other advantage of corrugated hoses is their flexibility which makes them a good candidate to connect elements where they are subjected to movement, thermal expansion and vibrations [15]. Due to these characteristics they are frequently used in hydraulic circuits, protection for electrical cables and light conductors or exhaust gas installations.

- Corrugated gasket

Surface configuration of the corrugated gaskets enables them to adapt to rough or irregular flange surfaces without requiring excessive compressive load. This provides an efficient seal under varying conditions of temperature and pressure. The substrate corrugation geometry promotes the recovery and resilience through thermal cycles and extended service life. Hence they are excellent products for both standard flange and heat exchanger gaskets where low bolt load are present or where high gasket stresses are available [16].

1-2-5 Aerospace and aeronautics application concepts

Corrugated sandwich panels are used in aerospace engineering because of their multifunctional characteristics. These structures offer insulation as well as load-bearing capabilities in addition to their lightness. These multifunctional integral thermal protection structures protect the spacecraft from extreme reentry temperatures, and possess load-carrying capabilities [17, 18]. Moreover, because of their exceedingly anisotropic behaviour of these structures they have been proposed as a flexible skin for the wings of morphing aircraft. This is due to the fact that wing structures must be stiff so as to withstand bending due to aerodynamic forces, and flexible so they can deform efficiently in flight due to morphing actuation [19]. This application is explained exhaustively in section 3.

1-3 Corrugated Structures, Innovation and Developments

As discussed so far, corrugated structures have noticeable impacts on the engineering applications due to their superior structural characteristics which mainly arise from their geometric properties. However the structural performance of these structures is being developed further in the literature by introducing more geometric parameters or using different material properties. Some of the concepts regarding the development of these structures are reviewed in this section.

1-3-1 Innovation based on different material properties

- **Elastomeric face sheets**

There are some specific applications of corrugated panels such as morphing skins in which a change in material properties of the corrugated sandwich panel is considered. The corrugated core is coated with elastomeric face sheets. Although the geometry of this corrugated panel is similar to the corrugated sandwich panel the function is much different. This is because the stiffness of the elastomeric coatings are significantly smaller than the stiffness of the material of the corrugated core. The purpose of the elastomeric face sheets in this structure is not to increase the stiffness of the panel but to provide a continuous external surface to maintain the efficient aerodynamic performance during the flight [2]. More details of the mechanical behaviour of the corrugated core with elastomeric coating are presented later in this article. Figure 1(a) shows a corrugated core with elastomeric coating.

- **Corrugated core materials**

Another way to increase the design space of the corrugated panel is by using composite materials in the corrugated core and consequently providing further improvement opportunities through optimizing parameters such as: fibre orientations in each layup, curvilinear fibres and textile architecture of the plain woven cloth of the fibres. The works of Kazemahvazi et al. [20, 21] in which they introduced a novel composite corrugation concept to prevent the core members from buckling, is highlighted. Another example in this perspective is the interesting idea of combining multi-stable characteristics with corrugated structural performance [22] in which the multi-stability comes from the interaction between internal prestressed laminates and non-linear geometrical changes during deformation. The multi stable characteristics enable the structure to undergo large configuration changes which can be sustained into the new position with no use of any locking mechanism while the corrugation geometry provides the high strength to weight ratio. The wide range of parameters in such a structure enables designers to tailor the stiffness properties to the required application such as morphing wings. Figure 1(b) illustrates the twisted bi-stable corrugated core.

1-3-2 Innovation based on geometric parameters

- Curved corrugated shell

The concept of curved corrugated sheets was proposed by Norman et al. [23]. These structures which are initially manufactured with a curvature along the corrugation profile are capable of significant elastic shape changes, including large changes in overall Gaussian curvature without local stretching of the surface. The detailed kinematics of the curved corrugated shells was studied in this paper and it was demonstrated how the geometrical relationship between the local and global corrugations specify the coupling between stretching of the plate across the corrugations and the global curvature along the curved shell. These structures may be useful to be applied in morphing structures to offer structural integrity and large shape-change capabilities. Figure 1(c) illustrates the curved corrugated sheet and some of its global deformations.

- Bi-directional corrugated-strip-core sandwich panel

A new concept in steel bi-directional corrugated-core sandwich structures was proposed by [24] to improve the stiffness in the more flexible direction of the panel and to modify the transverse shear stiffness of the panel. The geometry of the typical core can be obtained by propagating the corrugated strips in both longitudinal and transverse directions. Depending on the pattern of propagation a variety of different densities and stiffnesses may be obtained. Leekitwattana et al. [25] proposed a derivation for the transverse shear stiffness of a steel bi-directional corrugated sandwich panel using analytical methods. Dayyani et al. [26] simulated the mechanical behaviour of the bi-directional corrugated core with and without elastomeric coatings in tensile and five point bending tests. Figure 1(d) show a schematic of a bi directional corrugated core.

Furthermore, Seong et al. [27] proposed another type of bi-directional corrugated core to reduce the anisotropic characteristics of the corrugated sandwich plates which could restrict the range of the applications of these structures. The design space in this bi-directional corrugate core was extended by introducing two additional geometric parameters, pass angle and corrugation length, in order to minimize the beam buckling of the face sheets with respect to core orientations. In this concept the continuous corrugated channels were first fabricated by using a sectional forming process and then the core was attached to face sheets by means of adhesive bonding. Figure 1(e) shows a schematic of this concept.

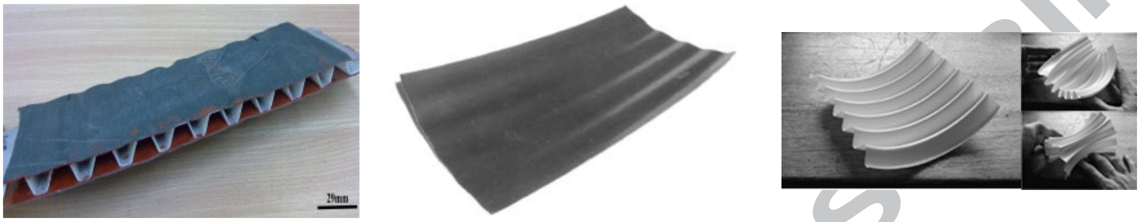
- Hierarchical corrugated core sandwich panel concepts

Improving the transverse compression and shear collapse mechanisms of the corrugated panel, a novel concept based on the second order hierarchical corrugation was offered by Kooistra et al. [28] as shown in Fig. 1(f). The idea was born from the fact that materials with structural hierarchy can have higher stiffness to weight ratio than their single-length scale of microstructure counterparts. Hence the local corrugated elements were introduced to postpone the elastic buckling of the webs of the main corrugated core. However, the manufacturing constraints and the relative high costs of production have limited the application of hierarchical corrugated cores to large sandwich structures. Kooistra et al. derived the analytical expressions for the compressive and shear collapse strengths of the hierarchical corrugated cores and validated their model predictions by comparing to the experimental data. They reported that the strength of a second order hierarchical corrugated sandwich panel is almost ten times greater than the first order corrugated structure of the same relative density.

Kazemahvazi et al. [20,21] and Previtali et al. [29,30] also proposed two works in this regard, although with different purposes. In the first work, the local corrugated elements were replaced by PMI foam and a local sandwich panel were applied to the inclined members of the global corrugated sheet. Figure 1(g) shows a schematic of this concept. The idea was to improve the out of plane compressive properties and in-plane shear stiffness. However in the second work, the local foam was removed and a double wall corrugated sheet was obtained. Figure 1(h) shows a schematic of this concept. In this concept, the deformations of local double walled elements due to the combination of shear and bending loading provided further axial in-plane compliance for the application in morphing skin. This technique almost eliminated the rotation of the upper and lower surfaces of the corrugation when the corrugation was strained.

- Pyramidal lattice truss sandwich structure

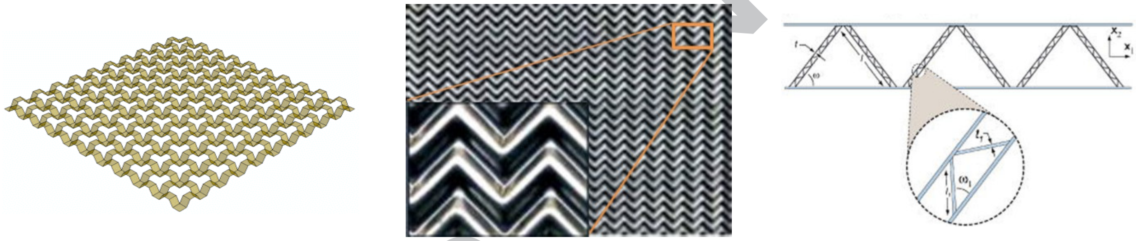
The concept of lattice truss structures was proposed as an alternative to cellular core structures in the literature to further increase the ratio of strength to weight of sandwich panels [31]. The out-of-plane and in-plane mechanical properties of these lattice truss structures are dependant to the topology of the lattice, relative density and the stiffness properties of the core material. Queheillalt et al. [32] proposed a new approach for manufacturing the uniform pyramidal lattice truss sandwich structure. In this method, first the solid corrugated sandwich panel was fabricated by extruding the aluminium slabs through the moulds and then the corrugated core was imposed by electro discharge machining (EDM) by use of alternating pattern of triangular-shaped EDM electrodes normal to the extrusion direction. The result of the process was a lattice truss sandwich panel in which the interface between the core and face sheet possessed the identical metallurgical and mechanical properties. Figure 1(i) shows the schematic of the extruded pyramidal lattice truss sandwich structure.



(a) Corrugated core with elastomeric coating [33]

(b) Twisted bi-stable corrugated core [22]

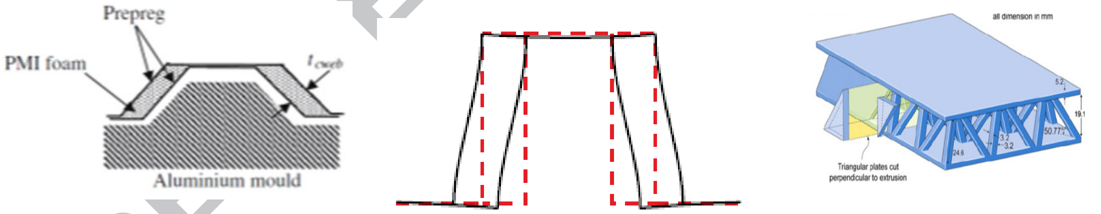
(c) Curved corrugated sheet and some of its global deformations [23]



(d) Schematic of bi-directional corrugated core [26]

(e) Schematic of corrugated bi directional core, [27]

(f) Schematics of Hierarchical corrugated core sandwich panel [28]



(g) PMI foam filled hierarchical corrugated sheet Kazemahvazi et al. [21]

(h) Double wall corrugated concept Previtali et al. [30]

(i) Schematics of extruded pyramidal lattice truss sandwich structure, [32]

Figure 1: Corrugated structures developments and concepts

2- Corrugated panel from different perspectives

The design of corrugated structures for morphing technology is inherently multidisciplinary; a successful design must meet both structural and actuation requirements. In aerospace this must be achieved at minimum weight, and in general many other requirements will be of importance, including but not limited to such factors as vibration characteristics, fatigue life, and damage tolerance. However, multidisciplinary design depends on a strong understanding of each discipline concerned, so this work now proceeds to categorise literature on corrugated panels by individual perspectives.

2-1 General mechanical properties of corrugated panels

A comprehensive set of analyses about the flexural, tensile, shear and out of plane compressive strength of corrugated panels is developed in the literature by means of experimental and finite element analysis. These analyses have considered mainly the nonlinear effect of material properties and geometric parameters as well as analysis of various boundary conditions and loading configurations [3]. When possible in the literature, analytical solutions are introduced in support of these investigations [34].

2-1-1 Bending

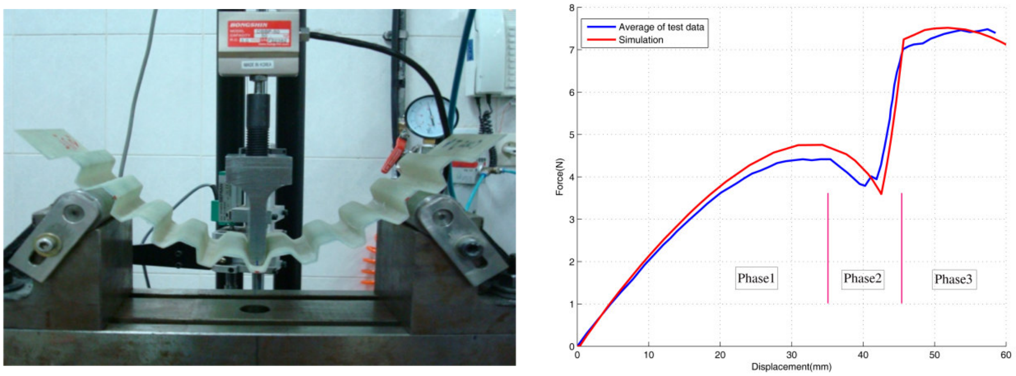
Numerous studies have been conducted on the bending stiffness of corrugated board. These investigations have incorporated analytical solutions, finite element simulations or experiments to find the flexural rigidities of the board. Khalid et al. [35] investigated the mechanical behaviour of structural beams with corrugated webs in three-point bending. They determined the effects of the corrugation curvature, web thickness, material properties of the corrugated web, and the corrugation direction on the beam's load-carrying capability. The experimental tests were used to validate the results obtained by nonlinear finite element analysis. The 30% difference in the flexural stiffness which was observed in the results highlighted the bending anisotropic characteristics of the composite beam with the corrugated web. It was reported also that increasing the radius of corrugation curvature led to higher bending stiffness and could reduce the beam's weight by about 14%.

Chang et al. [36] presented a closed-form solution based on the Mindlin–Reissner plate theory to describe the linear flexural behaviour of the corrugated core sandwich plate with various boundary conditions. They reduced the three-dimensional sandwich panel to an equivalent two-dimensional structurally orthotropic thick plate continuum. They compared the numerical results of the proposed model by the experimental data available in the literature [37] and observed a good agreement. They investigated the effects of several geometric parameters of a corrugated core sandwich panel on its rigidity and state of stress and came up with some recommendations for the selection of the geometric parameters of corrugated- core sandwich plates. These recommendations were mainly about minimizing the ratio of geometric parameters such: the ratio of the height to the thickness of the corrugated core, thickness of the corrugated core to thickness of the face sheet and the length of the corrugated unit cell to the height of corrugation. However such ratios resulted in an increase of weight of the structure and performing a multi objective optimization which considers both structural rigidities and mass of the structure is important.

Yokozeki et al. [2] proposed a simple analytical model for the initial bending stiffness of corrugated composites in both longitudinal and transverse directions and compared the predictions with the experimental results. For the flexural modulus in the more complaint direction, they measured the deflection of one end of the corrugated core due to its own weight, while the other end of the corrugated sheet was clamped. Moreover, four-point bending load was applied to the specimens in the longitudinal direction where both ends of the corrugated core were fixed. Although the applied bending displacement was small, two modes of out of plane flexural deformation and in-plane tensile stretching were coupled. They highlighted the extremely anisotropic behaviour of the corrugated core through comparing the flexural stiffness of the corrugated sheet.

Seong et al., [27] performed three-point bending tests on the bi-directional corrugated sandwich panels for various core orientations and demonstrated that this sandwich corrugated panel has a quasi-isotopic bending behaviour. They explained the effect of geometric parameters of the bi-directional corrugated core on the buckling strength of the face sheets during large bending deformations.

Dayyani et al. [38] studied the flexural characteristics of a composite corrugated sheet using numerical and analytical methods and validated the results by comparing them to the experimental data. A good degree of correlation was observed in their work which evidenced the suitability of the analytical method and finite element model to predict the mechanical behaviour of the corrugated sheet in the linear and nonlinear phases of deformation. The finite element simulation exploited the node to surface and frictionless contact technique, to model the interaction between the corrugated sheet and the supports. The force-displacement curves showed three distinct phases of deformation in the three-point bending test. Three phases of the deformations were distinguished as: deformation due to pure bending of corrugated sheet, deformation due to combined bending and axial forces causing a step increase in the force-displacement curve and again deformation due to pure bending of the corrugated core. They reported that the second phase in which the step was observed arose because of simultaneous contact of the two adjacent corners of the corrugated unit cell with the support. Figure 2 illustrates the corrugated sheet in a three-point bending test and the corresponding force-displacement curves obtained from the experiment and simulation results.



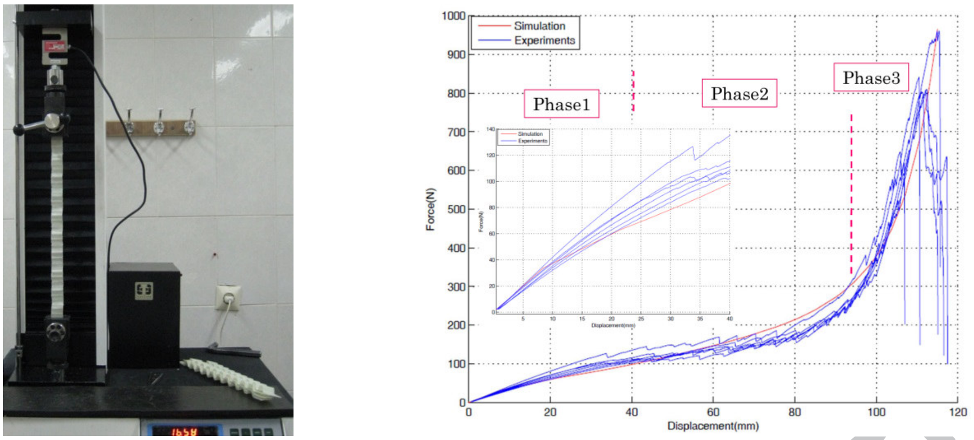
(a) Bending experimental set up (b) Force-displacement curves

Figure 2: Three-point Bending behaviour of a composite corrugated sheet, Dayyani et al. [38]

2-1-2 Tensile

Noting the extreme anisotropic stiffness properties of corrugated sheets [2], Thill et al. [39] investigated the effect of a variety of materials and parameters such as number of plies and corrugation pitch on the overall mechanical properties of the corrugated composite sheet. The output of this study was that the transverse tensile elastic modulus is dependent on the squared laminate thickness and the length of corrugated unit cell length. Three years later, they explained the obtained results via experimental, analytical and numerical analysis methods [40]. They considered trapezoidal corrugated aramid/epoxy laminates subjected to large tensile deformations transverse to the corrugation direction and highlighted the effect of local failure mechanisms of these specimens on the three stages of the tensile force-displacement graphs. They found out that the second stage, which comprised the majority of the displacement, occurred because of aramid fibre compressive properties and delaminations in the corner regions of the corrugated unit cell. This local phenomenon was compared to a pseudo-plastic hinge allowing large deformations over relatively constant stress levels.

As an extension to this work, Dayyani et al. [38] studied the tensile behaviour of corrugated laminates made of plain woven glass/epoxy. Contrary to the literature they observed the occurrence of delamination in all of the members of the corrugated unit cell, not only to the corner regions, and evidence that the three-stage mechanical behavior of composite corrugated core is not confined to aramid laminates and can be observed in other types of laminates. The tensile force-displacement curves in their experiment showed three distinct phases of deformation: 1-small deformations due to tension of both straight and inclined members, 2-rotation of joints at the intersection of straight and inclined members, 3-the tensile behavior of the flattened panel respectively. These three phases are shown in Fig. 3 where the tensile force-displacements are plotted. The plasticity was exploited in finite element simulation as a technique to model the delamination, which dissipated the strain energy of the system during the tensile testing. Assigning the plasticity to all of the regions of the corrugated unit cell resulted in a good agreement between the numerical predictions and the experimental observations. The extreme sensitivity of the composite corrugated sheet to the angle of the corrugated unit cell was also demonstrated in this work which highlighted the importance of the precision of the design and manufacturing process.



(a) Tensile experimental set up (b) Three distinct phases of the tensile force-displacement curves

Figure 3: The mechanical behaviour of the composite corrugated sheet in a tensile test, [38]

2-1-3 Shear and compression

Transverse shear stiffness of the corrugated sandwich panels is one of the important characteristics of these structures which must be accurately characterized in the performance analysis of these structures. Among the early works regarding this issue is the work of Nordstrand et al. [41] who used curved beam theory to study the shear stiffness of a corrugated cardboard. They presented a theoretical study on how the geometry of the corrugation affects the transverse shear moduli. Firstly by assuming rigid face sheets in the corrugated cardboard they derived an upper limit of the transverse shear modulus across the corrugations and then showed how this shear stiffness reduces if deformations of the face sheets are considered in the analysis. Nordstrand and Carlsson [42] experimentally examined the effective transverse shear moduli in the principal material directions of corrugated board using the block shear test and the three-point bend test. They observed that the shear moduli obtained by the three-point bend test were almost half of those determined by the block shear test. This discrepancy was explained by local deformation of the face sheets of the board where they were in contact with the supports in three point bending test.

Isaksson et al. [43] considered a panel of corrugated paper board as a stack of an arbitrary number of thin virtual layers with corresponding effective elastic moduli. The elastic properties of all layers were assembled together to analyze a corrugated board as a continuous homogenous structure. They showed that exploiting the shear correction factors which were derived from the equilibrium stress field can improve the stiffness calculations. Their proposed model was validated by experiments on corrugated board panels with different geometries.

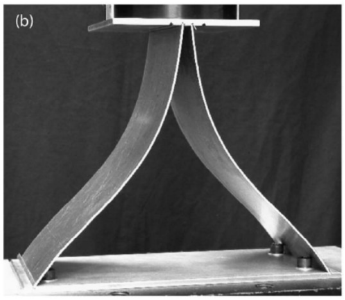
Kampner et al. [44] investigated the possibility of using a corrugated sheet as the facings of sandwich beams to carry shear loads which are traditionally carried by the core. A compliant foam core was used as a ‘‘cushion” between the outer skin and the internal structure in their concept. One of the main reasons for such concept was improving the performance of the panel under shock loads where stiff connections between the facings were prone to localized failure. Finite element simulations, as well as some analytical investigations were used to find out that the introduction of a corrugated face sheet improved the capability of shear carrying and reduced the weight of the panel, predominantly for heavily loaded sandwich beams.

Leekitwattana et al. [25] took into account the concept of a force–distortion relationship to derive a formulation for the transverse shear stiffness of a bidirectional corrugated sandwich panel by use of the modified stiffness matrix method. They showed the consistency of the proposed formulation with a three-dimensional finite element solution. The computation time for the proposed method was claimed to be 40 times lower than the FE method. They assessed the effect of geometrical parameters and compared the performance of a bi-directional corrugated sandwich panel with other one directional corrugated sandwich panels. They realized that for a specific range of parameters the bidirectional corrugated topology shows superior performance in transverse shear stiffness.

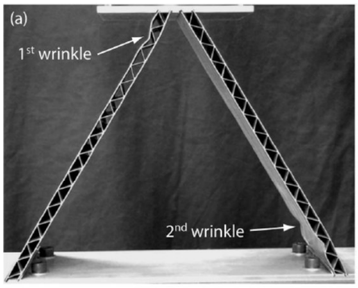
Lu et al. [45] investigated the compressive response and failure mechanisms of a corrugated sandwich panel by use of a combined theoretical and experimental approach. In this work, the corrugated specimens were modelled by use of curved beam elements and surface contact elements. The elastoplastic material was tuned with a bi-linear constitutive model which satisfied the J_2-flow theory and assigned to the finite element model. The effects of boundary conditions, geometrical parameters, and material properties, and geometrical imperfections on the compressive strength of corrugated boards were studied. As a result, they found out that the panel has the highest compression strength when the initially sinusoidal corrugated core deforms into a square wave pattern. Moreover, it was shown that the stress-strain curves of the corrugated panel had an undulating behaviour in compression, which reflects the initiation, spreading and arrest of the localised plastic collapse mechanisms.

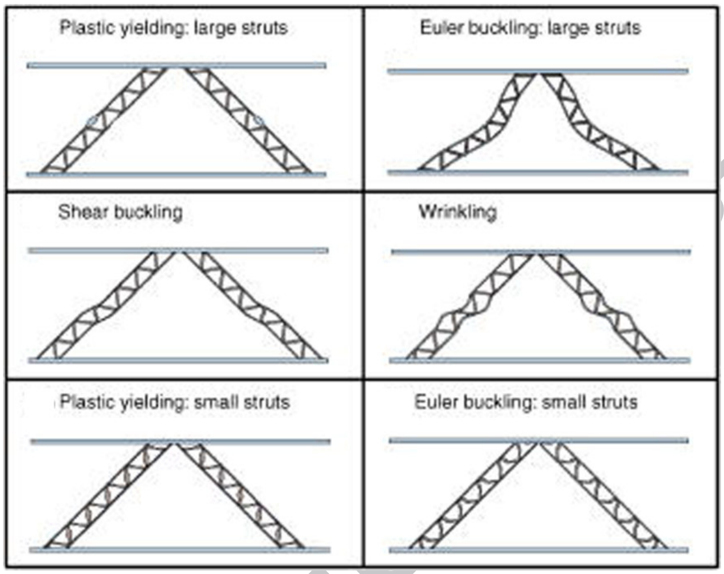
Rejab and Cantwell [46] investigated a series of experimental and numerical analyses on the compression response and subsequent failure modes of the corrugated core sandwich panels which were made of three different materials: aluminium alloy, glass fibre reinforced plastic and carbon fibre reinforced plastic. Particular attention in this work was paid to the effect of the number of unit cells and the thickness of the cell walls in determining the overall deformation and local collapse behaviour of the panel. They realized that the buckling of the cell walls was the first failure mode in these corrugated structures and increasing the compression loading will result in localised delamination as well as debonding between the skins and the core. The experimental results were compared to finite element and analytical solutions. The predictions offered by the numerical models were in good agreement. However the analytical model over-estimated the load-bearing capability of the corrugations due to the fact that the model assumed perfect bonding between the apex of the corrugated core and the skin and neglected the effect of initial imperfections along the cell walls.

As mentioned earlier, Kooistra et al. [28] analysed the transverse compression and collapse mechanisms of a second order hierarchical corrugated sandwich panel. In contrast to a first order corrugated sandwich panel which exhibit two competing collapse modes of elastic buckling and plastic yielding, they showed that the second order corrugated panel has six competing modes of failure: elastic buckling and yielding of the larger and smaller struts, shear buckling of the larger struts, and wrinkling of the face sheets of the larger struts. Figure 4 shows the global and local failure modes of first order and second order corrugated sandwich panels in compression. Analytical expressions for the compressive and shear collapse strengths in each of these modes were derived and used to construct collapse mechanism maps for the second order corrugation models. They used these maps as a base for selecting the geometric parameters of second order corrugated panel to optimize the ratio of collapse strength to mass and validated the proposed model experimentally. They discovered that increasing the level of structural hierarchy does not lead to further enhancements in the stiffness of the corrugated core. In other words, for a given mass the first order corrugation exhibited slightly more stiffness than its second order counterpart suggesting that the hierarchical corrugated construction has applications in strength limited applications.



(a) First order corrugation unit cell, global elastic buckling mode





(b) Second order corrugation unit cell, local failure modes

(c) Schematics of the failure modes in the second order corrugated unit cell

Figure 4: Global and local failure modes of first order and second order corrugated sandwich panels in compression, Kooistra et al. [28]

Likewise, the effect of hierarchy on the stiffness of corrugated structures in compression has been followed by other researchers such as Kazemahvazi et al. [20, 21]. They applied sandwich panel with PMI foam to the local inclined members of the global corrugated core and experimentally studied a range of different failure modes of these structures depending on their geometrical and the material properties. In this regard, first the collapse mechanism maps of different corrugation configurations were analytically obtained. The stiffness model exploited the contribution in stiffness from the bending and the shear deformations of the local core members in addition to the stretching deformation. They claimed that the proposed hierarchical corrugated core can have more than 7 times higher weight specific strength compared to its monolithic counterpart, if designed correctly. The difference in strength arose mainly due to the increase in buckling resistance of the sandwich core members compared to the monolithic corrugated core. It was observed that when the density of the core increases, the monolithic core members get thicker and more resistant to buckling and thus the benefits of the hierarchical structure reduces.

2-2 Buckling

Buckling occurs when a structure makes a rapid change of configuration due to applied load - this applied load may be compression, shear or multi-axial. A structure is often said to have failed when buckling occurs (for example when a column collapses under axial compression), and in these cases all that must be understood is when the onset of buckling will occur, which is usually a linear problem that can generally be achieved through classical analytical methods or using finite element analysis. However, in certain cases (such as in-plane shear buckling of a panel) some load resistance remains after buckling, and this so called post-buckle strength may be exploited. The study of post-buckling is often more complex than that of buckling, and the complex deformations formed during buckling often require the use of nonlinear analysis.

One of the most common methods to analyse buckling of corrugated plate or shell structures is to use a model to homogenize the corrugation as an orthotropic panel, and then to find global buckling modes using analysis similar to conventional panels. Many examples of this approach are presented subsequently. Although a variety of homogenization methods exist (see section 2-6), an FEA unit cell may be used to derive the equivalent properties if an analytical process is not available.

Moreover it is usually possible to make further checks on corrugated structures especially for the configurations which have flat sections, such as trapezoidal corrugations, to ensure that local buckling modes do not occur. However, this approach cannot be applied in a straightforward manner to continuous profiles e.g. sinusoidal corrugations. If it is not feasible to simply check local and global modes separately, or greater accuracy is required, higher fidelity analyses must be used. Clearly, Finite Element methods have a broad role to play, however other higher fidelity methods exist. Liew et al. [47] used the mesh free Galerkin method to analyse the buckling modes of a plate. This method was an alternative to FEA analysis, with the advantage that it could avoid certain problems with element distortion. Pignataro et al. [48] used a finite strip method, with nonlinear kinematics, to study in detail the situations where the global mode interacts with local modes to create a localised region of buckling in the post buckled shape, and reduce the critical load. The work also considered how these interactions led to sensitivity to initial imperfections. Few authors use fully analytical methods to consider both global and local features of a corrugated structure simultaneously; although some examples of this approach are given in Section 2.2.2.

The literature on buckling of corrugations may be separated into the following applications: webs of beam sections, shell structures, naval structures, and the packaging industry. These applications are considered in detail in the following subsections.

2.2.1 Buckling of corrugated webs for beam sections

Corrugations have been widely used in I-beams. The purpose of the web in an I-beam serves to resist shear force, so shear is the primary cause of buckling in these cases. It seems that much of the current literature on shear buckling of corrugations has been driven by this application. An early work in this field is given by Libove [49], where it is briefly demonstrated that shear effects may be important in the analysis, and that therefore homogenized equivalent orthotropic approaches may have poor accuracy. The work then goes on to develop a shell model approach, giving expressions for the total potential energy that can therefore be used in variational analysis to find the buckling modes. The model uses nonlinear Von-Karman strains in the local material, with shear effectively accounted for in the global deformation.

However, assumedly due to the complexity of the model given, later works have adopted an approach using the equivalent orthotropic properties. Elgaaly et al. [50] discussed the global shear buckling of corrugated panels in terms of equivalent homogeneous properties. Their formula for the global buckling mode’s critical shear stress has been cited by many authors since:

$$\tau_c = 36\beta \frac{D_y^{1/4} D_x^{3/4}}{th^2} \tag{1}$$

where D_x and D_y were the equivalent orthotropic flexural rigidities in the x and y directions respectively, t was the thickness and h was the length of the panel along the corrugation channels. β was a constant, between 0 and 1.9 depending on boundary conditions.

At a similar time, Luo and Edlund [51] presented numerical analysis of both buckling and post buckling under shear force applied to a beam with a trapezoidally corrugated web. It was noted that three types of buckling may occur; local buckling (of a single flat section within the corrugation), global buckling (where the entire panel fails) and ‘zonal’ buckling, which was similar to a local mode but could extend over more than one panel. The nonlinear results were compared to some earlier analytical models for shear buckling, which were shown to have only approximate accuracy.

Yi et al. [52] presented a work that focussed on the ‘zonal’ mode, although they referred to it as the ‘interactive’ mode. They compared it to a range of previous analytical formulas in previous literature, which were all of a form similar to

$$\frac{1}{(\tau_I)^n} = \frac{1}{(\tau_L)^n} + \frac{1}{(\tau_G)^n} + \frac{1}{(\tau_Y)^n} \tag{2}$$

Where τ_I is the interactive buckling mode, τ_L is the local buckling failure stress, τ_G is the global failure stress and τ_Y is the yield stress of the material and n is an integer between 1 and 4 depending on the model used. Inspecting the form of this equation shows that if the critical mode of failure (as appearing in the terms on the right) is much lower than the others, it will dominate the overall interactive mode; however if the individual modes have similar critical loads, the resulting interactive failure will be lower than all of them. It is shown by comparison to numerical and previously published experimental data that these methods are approximately accurate, but require empirical corrections when operating near the yield limit of the material. Sause and Braxtan [53] extended the work of Yi et al. [52] with further comparisons to experiment, and further suggested corrections to allow for empirically found areas where the derived models were non-conservative.

2.2.2 Buckling of corrugated shells

Corrugations have been considered as a way of improving the stability of shells. Semenyuk and Neskhodovskaya [54, 55] provide a comprehensive analysis of these problems using deep shell theory. It is shown that under certain conditions, the use of corrugation on a cylindrical shell can substantially raise the critical buckling load. These papers present some every intriguing possibilities for refined analytical approaches to corrugations, because they do not depend on homogenised approaches, so that local buckling modes are calculated simultaneously with global effects. Furthermore, the shell approach used suggests that an adaptation to the curved surfaces of a true wing may be feasible, and maybe a further extension to include the effects of surface pressure along the lines of Semenyuk et al. [56]. The constraints of this approach are a restriction to single layer geometries with smooth corrugation profiles.

2.2.3 Buckling of corrugated structures in naval applications

The American Bureau of Shipping regulations ABS [57] include guidelines for the use of metal corrugated panels, and these are summarised and explained by Sun and Spencer [58]. The overall approach is to separately consider buckling cases of in plane shear (as discussed in the above section) and compressive loading in both directions and also lateral pressure, and combine them so that a safe design is defined by

$$\left(\frac{\sigma_x}{\eta\sigma_{xc}}\right)^2 + \left(\frac{\sigma_y}{\eta\sigma_{yc}}\right)^2 + \left(\frac{\tau}{\eta\tau_c}\right)^2 < 1 \tag{3}$$

where η is a strength knock down factor. These results are shown to be reasonably conservative in comparison to FEA. This work also includes a formula to consider buckling in the corrugation caused by lateral pressure; at present it has not been possible to view the original source of how this was derived, but the final form appears to be that of a local buckling mode. However, accuracy is again reliant on empirical factors so this may not be directly applicable to morphing applications.

2.2.4 Buckling of corrugated panels in packaging application

Many treatments of corrugation come from the packaging industry due to the widespread use of corrugated cardboard, and this provides some valuable data. Indeed, one of few publications to discuss buckling of corrugations where the material is not isotropic is given by Biancolini and Brutti [59], in a study of the ability to stack boxes on one another. This work extends equivalent stiffness formulae for sinusoidal corrugations found by Briassoulis [60] to allow an orthotropic source material, and uses these to calculate the global buckling load. However, further buckling modes are neglected.

In a study on corrugated board, where the effects of the face sheets are included, Nordstrand [61] looks at global buckling and post buckling in the presence of imperfections. The analysis is very clear, and could easily be adapted for the purpose of morphing application. Johnson and Urbanik [62] provide analysis of a similar structure in, with an approach that can be potentially be adapted to any prismatic structure; however their focus is on local buckling modes with the assumption that these initiate failure.

2-3 Vibration

Vibration is an important consideration throughout engineering; the demand for low weight can often result in structures with low damping present, which can result in destructively high amplitude vibrations if modes are excited at their natural frequencies. In general, structural vibration is also an issue of importance for topics such as noise and passenger comfort in vehicles. It is also an important subset of the wider field aeroelasticity, which may be a particularly crucial problem for morphing aircraft where structures are specifically designed to include compliance for actuation reasons. Relatively little work has been dedicated specifically to the vibration of corrugated panels, although clearly many general methods such as FEA are applicable.

Many studies rely on homogenised models of the corrugation to analyse vibration; these have the advantage of simplicity, but have the disadvantage that they may not account for ‘local’ effects within the structure of the corrugation or behaviour that lies outside the assumptions of the fitted model. However, in many cases these deficiencies may simply be addressed with a further check. Hui and Huan-ran [63] presented a linear analysis of a simply supported sandwich plate with a corrugated core; many of the modelling assumptions were directly applicable to corrugations with covering skins (with the exception being that the skins were not considered to be under tension, as an elastomer would be). The model considered first order shear effects, however shear deformation was assumed to be negligible along the longitudinal direction of the corrugation. This assumption led to an elegant derivation with closed form solutions that may be readily used in optimisation. Liew et al. [64] used a mesh free method to understand the vibration of a stiffened corrugated plate. The approach used a homogenisation technique that accounted for first-order shear effects in the panel; the mesh free method was a numerical method but had some advantages to FEA when applied to optimisation problems, because there was no requirement to regenerate meshes after geometry changes.

Other works consider the effect of corrugation on the vibration of shells. Semenyuk et al. [65] used deep shell theory and the Hamilton principal to provide a comprehensive study of the vibrations of a corrugated cylindrical shell, in manner that captures both local and global effects simultaneously. It was shown that homogenized approaches capture the first vibration mode only over a limited range of the corrugation pitch; if the pitch is too long, local modes will occur as the first mode, and if the pitch is too fine then in-plane (or ‘accordion’ style) vibrations occur. In another analytical survey based on deep shell theory, Gulgazaryan and Gulgazaryan [66] established the geometric conditions that could lead to the presence of Rayleigh waves along the free edge of a corrugated cylindrical shell.

Hu et al. [67] discussed an energy harvester, using a corrugated plate as the vibrating element; where the purpose of the corrugation was to allow deformations that alter the natural frequency to match the most prominent ambient vibration frequency. This study highlighted an important phenomenon that will affect the vibration of corrugated skins; that their natural frequencies will be strongly influenced by their states of deformation. Figure 5 shows an example of this; power density, which is largely determined by the natural frequency, was shown to vary significantly with the span length of the corrugated strip.

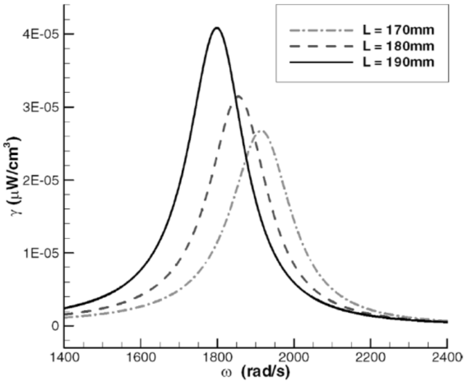


Figure 5: Power density versus driving frequency for a corrugated strip energy harvester, Hu et al. [67]

Experimental studies concerning the vibrations of corrugated plates seem to be somewhat rare; however two such examples are given found in Mandal [68] and Mandal et al. [69] , examining rigid trapezoidal plates. The first work concerns the vibration transmitted through in plane vibration, and finds that the presence or size of corrugations has little conclusive effect. The latter considers the loss factors of different modes of flexural vibration of the plates, and shows that corrugations cause slightly higher loss factors for the first mode, with the effect increasing with increasing corrugation depth. Recently, Yang et. al [70] published a numerical and experimental study of the modal responses of shells made from CFRP corrugated core sandwich. The study considered the influence on modal properties of material thickness, corrugation depth, corrugation angle and also whether corrugations ran around the circumference or along the length of the cylinder. However, there are many different option of corrugation geometry that remain to be considered by these works; indeed neither work can be considered as directly relevant to morphing corrugations because they both consider rigid corrugations only.

Not all work is dedicated to rectangular planforms; in Ren-Huai and Dong [71], the authors consider the flexural stiffness and vibration of circular corrugated plates, with the primary motivation being components of precision machinery. This paper is interesting as it uses an energy based approach to reformulate the response of the corrugations in a radial coordinate system, and also allows for large deflections. However, few practical morphing aircraft components will meet the symmetry requirements of the model developed.

2-4 Impact

There appears to be no literature that is directly concerned with impact loads on corrugated skins within the context of morphing aircraft. However, the low-velocity impact performance of corrugated panels and sandwich cores has been widely studied in other applications. In general, this interest is due to the complex deformations that can occur in a corrugation as it is impacted and potentially crushed; internal buckling, contact friction and plastic deformation can all occur, and these may be seen as energy absorbing processes, that therefore may protect other elements in the structure from damage.

In Toccalino et al. [72], the authors proposed a variety of corrugated forms for use in an impact energy absorber. One of these forms includes an interesting arrangement of two layers of corrugation in close proximity, so that frictional contact between the layers dissipates yet further impact energy. Jiang et al. [73] considered impact on corrugations made from bamboo fibre based composites. This paper finds that the laminate stacking sequence and corrugation direction have a complicated effect on the impact energy absorbed by the impact, with a unidirectional layup with fibres oriented along the corrugation channels being optimal. However, the choice of different layups led to completely different failure modes in response to impact, with the mode varying between tensile fibre failure, delamination or local buckling. A different approach to the impact of corrugations is found in Khabakhpasheva et al. [74], which discusses corrugations impacted by waves of liquid, and the complex dynamics that arise due to trapped gas bubbles that become pressurised as a result of the wave impact.

More literature is dedicated to corrugations when used as cores in sandwich panels, and while a full review of sandwich panels under impact is beyond the scope of this section, a few examples are listed here. Zangani et al. [75] described a sandwich panel with a phenolic foam core, reinforced by an FRP corrugation, with simulations of an impacting ball. Kılıçaslan et al. [76] studied impacts on a multi-layer stack of aluminium honeycomb sandwiches. Russell et al. [77] showed experimental data for impacts of different speeds on an e-glass composite with an integrated corrugated core, both with and without a foam filling to stabilise the corrugation webs, and highlighted the difference between buckling and compressive failure modes. Further examples can be found in the packaging industry, for example Garcia-Romeu-Martinez et al. [78].

However none of these studies address structures that are designed to have the flexibility required for morphing aircraft or adaptive structural elements. In this context the idea of exploiting the complex deformation of corrugations under impact as means of energy absorption is feasible, only if the damage caused by impact is reversible (buckling with no permanent deformation), or limited to an extent that does not impinge on the structural and actuation requirements of the corrugation. However, if these requirements are met, it should be possible to develop corrugated skins with benign characteristics under impact. There remains much scope for new studies that consider the more flexible types of corrugations considered for morphing applications.

2-5 Fatigue

In the context of fatigue of corrugated plates, very little research has been carried out. The few works published in this area focus mainly on the investigation of girders with corrugated steel webs, whose main applications can be found in highway bridges. Here, the use of corrugated plates in girder webs represents an alternative to achieve considerable out-of-plane stiffness and buckling resistance without the need to use stiffeners or thicker web plates. A typical configuration of a corrugated web consists of folds parallel and inclined to the longitudinal direction of the beam, as shown in Fig. 6.

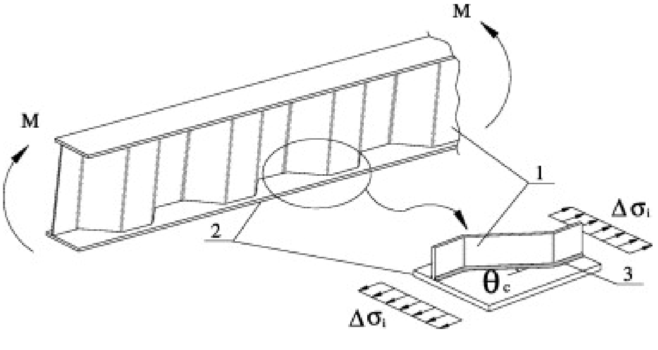


Figure 6: Schematic representation of a welded joint with corrugated plate, Wang and Wang [79].

In this context, Wang and Wang [79] studied experimentally the fatigue assessment of welds joining corrugated steel webs to flange plates. The results of the study revealed that most of the cracks initiated at the weld toe of the external weld line of the transition curvature and propagated through the main plate thickness. The fatigue strength of the test joints was improved with the decrease of the angle θ_c as shown in Fig. 6. Such an improvement was found to be less significant when θ_c increased over 45°. Wang and Wang [80] also investigated analytically and experimentally the carbon fibre-reinforced polymer strengthened welded joints with corrugated plates. The authors showed that the fatigue crack generally occurred in the region of the transition curvature between the longitudinal fold and the inclined fold of the corrugated plate. The authors also reported that the joints with transition curvature region reinforcement and single side reinforcement produce slightly lower rigidity but longer fatigue life in contrast to those with full width reinforcement on the double side of the main plate.

Anami et al. [81] investigated experimentally and analytically fatigue performance of the web-flange weld of steel girders with trapezoidal corrugated webs using large-scale girder specimens. By analysing the fatigue cracks in corrugated web girder specimens, the authors were able to determine the corresponding failure modes.

The fatigue strength of the web-flange weld was also examined by Anami and Sause [82] by means of finite elements and crack propagation analysis. The authors concluded that the fatigue strength is affected negatively by the existence of the longitudinal folds of the corrugated web. They also found that it is necessary to have a large bend radius to eliminate the influence of the longitudinal folds.

Sause et al. [83] studied eight large-scale girders subject to four-point bending fatigue tests. In this study, fatigue cracks initiated in the tension flange at the web-to-flange fillet weld toe along the inclined web folds and adjacent bend regions and propagated in the flange. It was found that steel corrugated web I-girders exhibit a fatigue life longer than that of conventional steel I-girders with transverse stiffeners.

Henderson and Ginger [84] investigated the low-cycle fatigue response of corrugated metal roof cladding to fluctuating wind loads. They demonstrated that the initiation and propagation of cracks, the type of cracks and the number of cycles to failure were similar in several cladding specimens subject to static, cyclic and simulated cyclonic wind loads. The authors also concluded that the peak load during a cycle and its amplitude mainly govern crack initiation and growth, more than the cycling rate and form.

Kövesdi and Dunai [85] studied experimentally the fatigue behaviour of trapezoidally corrugated web girders. Six large-scale test specimens were investigated under static and repeated loading. They determined that the combined loading condition on the corrugated web girders has a significant influence on the fatigue life. Furthermore, the results highlighted the importance of the weld size from the point of view of fatigue design. By using a smaller weld size, the authors concluded that the fatigue life of the girder was longer and therefore, they recommended the usage of the minimal required weld size for design purposes.

Ibrahim et al. [86] showed that the fatigue life of plate girders with corrugated webs is 49%–78% higher than the conventionally stiffened plate girders with full-depth stiffener when subjected to the same stress range. They also concluded that the fatigue life can be improved with the trapezoidal waveband without a significant decrease in the static capacity.

Takeshita et al. [87] investigated the dynamic behavior of new types of shear connectors between a corrugated web and a concrete flange in a composite girder. The shear connectors consisted of studs welded to the top flange; holes with penetrating reinforcement placed on the top of the corrugated web; and holes with penetrating reinforcement and wire net. Two-point fatigue tests were conducted using the above three types of shear connectors. Experimental results revealed that, holes with penetrating reinforcement were more effective than studs in the case of composite girders with corrugated web.

2-6 Homogenization and equivalent modelling

Over the last two decades, homogenisation-based modelling techniques have attracted considerable attention within the computational mechanics community [88-92]. The importance and increasing interest in this area stems mainly from the ability of these techniques to capture the effective response of complex microstructures under a wide range of conditions. In such cases, the structural response has to be approximated to avoid the computational modelling of the corrugations and thus, circumvent the major drawback of excessive computing times. Often the loads are well distributed and only the overall deflections are required. If the dimensions of the whole corrugated panel are much larger than the period of the corrugations, then a suitable approach is the use of homogenisation techniques, in which the corrugated panel is replaced by an orthotropic plate with equivalent stiffness properties [2, 40, 93, 94]. Figure 7 illustrates further details on this concept.

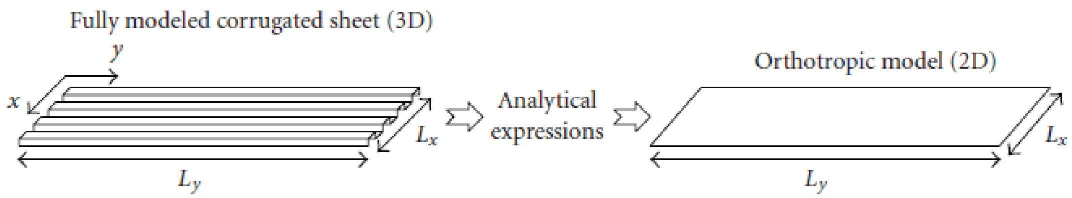


Figure 7: Schematic representation of a fully modelled corrugated sheet and its equivalent orthotropic model, Wennberg et al. [95]

In homogenisation-based equivalent models, the effective response is calculated by means of a representative volume element (RVE) of material or structure. The RVE is such that its domain Ω has a characteristic length much smaller than that of the macroscopic continuum and, at the same time, is sufficiently large to represent the macroscopic mechanical behaviour in an averaged sense. Figure 8 shows the choice of a typical RVE of a corrugated structure.

Periodic boundary conditions are often adopted to model corrugated sheets. Periodic boundary conditions are typically associated with the modelling of periodic media. In this particular case, the RVE is a so-called unit cell whose periodic repetition generates the entire heterogeneous macrostructure [92]. Here, the fundamental assumption consists of prescribing identical displacement vectors u for each pair of opposite points, y_+ and y_-, of the RVE boundary domain $\partial\Omega$, such that, $\mathrm{u}(\mathrm{y}_+) = \mathrm{u}(\mathrm{y}_-)$.

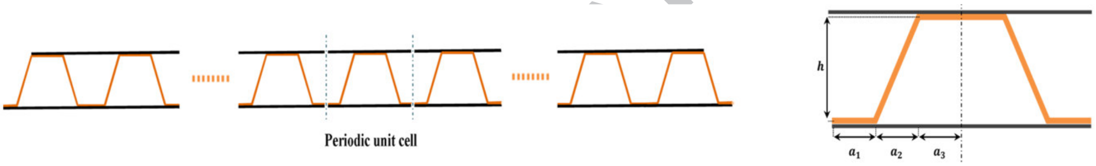


Figure 8: Typical RVE chosen for the modelling of a corrugated structure, Dayyani et al. [121]

In the context of modelling of corrugated panels, Briassoulis [60] and McFarland [96] investigated the equivalent flexural stiffness of sinusoidal and rectangular corrugations. Briassoulis [60] studied corrugated shells on the assumption of thin and uniform thickness, and proposed new expressions for their equivalent orthotropic properties. McFarland [96] investigated the static stability of corrugated rectangular plates loaded in pure shear. Dayyani et al. [38] proposed numerical and analytical solutions for the modelling of composite corrugated cores under tensile and three-point bending tests. Their results revealed that the mechanical behaviour of the core in tension is sensitive to the variation of core height.

Kress and Winkler [97] and Winkler and Kress [98] derived analytical expressions for an equivalent orthotropic plate with circular corrugations. Later, Kress and Winkler [99] studied corrugated laminates by solving a set of six load cases under the assumption of generalised plane-strain. The first three cases correspond to in-plane loading states which are associated with extension along the x-direction ($\bar{\mathrm{N}}_\mathrm{x}$) and y-direction ($\bar{\mathrm{N}}_\mathrm{y}$), and shear in the xy-plane ($\bar{\mathrm{N}}_\mathrm{xy}$). Here, the x and y-axes are assumed to define the plane of the corrugated sheet. The other three cases correspond to out-of-plane loading states represented by bending along the x-direction ($\bar{\mathrm{M}}_\mathrm{x}$) and y-direction ($\bar{\mathrm{M}}_\mathrm{y}$), and twist out of the xy-plane ($\bar{\mathrm{M}}_\mathrm{xy}$). These six cases are independent and can be combined linearly to form any generic loading state as long as the superposition principle holds. This is generally true for linear analyses. Figure 9 shows the schematic representation of these six basic cases.

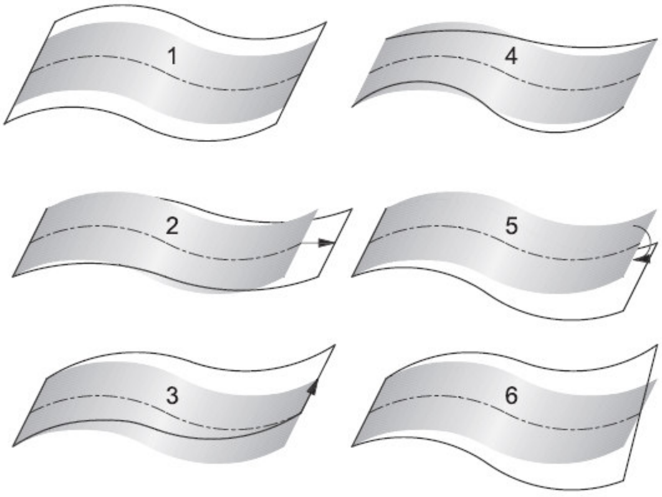


Figure 9: Six basic deformation mechanisms, Kress and Winkler [99]

By assuming that the mechanical response of the corrugated sheet can be established in terms of these six independent cases, the constitutive equation of the equivalent orthotropic plate is determined as (Xia et al. [93])

$$\begin{Bmatrix} \bar{N}_x \\ \bar{N}_y \\ \bar{N}_{xy} \\ \bar{M}_x \\ \bar{M}_y \\ \bar{M}_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{A}_{11} & \bar{A}_{12} & 0 & 0 & 0 & 0 \\ \bar{A}_{12} & \bar{A}_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & \bar{A}_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{D}_{11} & \bar{D}_{12} & 0 \\ 0 & 0 & 0 & \bar{D}_{12} & \bar{D}_{22} & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{D}_{66} \end{bmatrix} \begin{Bmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \\ \bar{k}_x \\ \bar{k}_y \\ \bar{k}_{xy} \end{Bmatrix} \tag{4}$$

where $\bar{\varepsilon}_x$, $\bar{\varepsilon}_y$, $\bar{\gamma}_{xy}$, $\bar{k}_x$, $\bar{k}_y$ and $\bar{k}_{xy}$ are the strain components in the global coordinate system of the corrugated sheet associated with their corresponding force and moment components $\bar{N}_x$, $\bar{N}_y$, $\bar{N}_{xy}$, $\bar{M}_x$, $\bar{M}_y$ and $\bar{M}_{xy}$, respectively. In the above equation, the coupling terms between in-plane strains and out-of-plane loads have been ignored.

For the definition of each of the components $\bar{A}_{ij}$ and $\bar{D}_{ij}$ (with $i, j = 1,2,6$) in Eq. (4), several authors have proposed analytical expressions for different geometries of corrugation. Refer, for instance, to those expressions proposed by [2, 60, 93, 100-103], among many others.

One approach to implement the above constitutive laws Eq. (4), within a standard commercial finite element software is to uncouple the in-plane and out-of-plane mechanical responses. That is, for in-plane loading conditions we have the following constitutive equation

$$\begin{Bmatrix} \bar{N}_x \\ \bar{N}_y \\ \bar{N}_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{A}_{11} & \bar{A}_{12} & 0 \\ \bar{A}_{12} & \bar{A}_{22} & 0 \\ 0 & 0 & \bar{A}_{66} \end{bmatrix} \begin{Bmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \end{Bmatrix} \tag{5}$$

and for out-of-plane conditions we have

$$\begin{Bmatrix} \bar{M}_x \\ \bar{M}_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} \bar{D}_{11} & \bar{D}_{12} & 0 \\ \bar{D}_{12} & \bar{D}_{22} & 0 \\ 0 & 0 & \bar{D}_{66} \end{bmatrix} \begin{Bmatrix} \bar{k}_x \\ \bar{k}_y \\ \bar{k}_{xy} \end{Bmatrix} \tag{6}$$

For an orthotropic sheet subject to in-plane loads, the following constitutive equation applies:

$$\begin{Bmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & 0 \\ 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{Bmatrix} \bar{\sigma}_x \\ \bar{\sigma}_y \\ \bar{\tau}_{xy} \end{Bmatrix} \tag{7}$$

By comparing Eq. (5) with the inverse relation of Eq. (7), it is straightforward to obtain the following expressions for the in-plane equivalent mechanical properties. The Young's modulus along the x-direction (according to Fig. 7), that is, along the corrugation direction, is given by

$$E_x = \frac{\bar{A}_{11}\bar{A}_{22} - \bar{A}_{12}{}^2}{t\bar{A}_{22}} \tag{8}$$

and the Young's modulus along the y-direction is

$$E_y = \frac{\bar{A}_{11}\bar{A}_{22} - \bar{A}_{12}{}^2}{t\bar{A}_{11}} \tag{9}$$

where the parameter t is the thickness of the equivalent plate. Furthermore, the in-plane Poisson's coefficient is

$$\upsilon_{xy} = \frac{\bar{A}_{12}}{\bar{A}_{22}} \tag{10}$$

and the corresponding in-plane shear modulus is

$$G_{xy} = \frac{\bar{A}_{66}}{t} \tag{11}$$

On the other hand, for an orthotropic sheet subject to out-of-plane loading conditions, the following stress-strain expression applies:

$$\begin{Bmatrix} \bar{\sigma}_x \\ \bar{\sigma}_y \\ \bar{\tau}_{xy} \end{Bmatrix} = \frac{12}{t^3} \begin{bmatrix} \bar{D}_{11} & \bar{D}_{12} & 0 \\ \bar{D}_{12} & \bar{D}_{22} & 0 \\ 0 & 0 & \bar{D}_{66} \end{bmatrix} \begin{Bmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \end{Bmatrix} \tag{12}$$

By comparing Equation (7) with the inverse relation of Equation (12) we obtain the following equivalent mechanical properties. The Young's modulus along the x-direction is

$$E_x = \frac{12\left(\bar{D}_{11}\bar{D}_{22} - \bar{D}_{12}{}^2\right)}{t^3\bar{D}_{22}} \tag{13}$$

and the Young's modulus along the y-direction is

$$E_y = \frac{12\left(\bar{D}_{11}\bar{D}_{22} - \bar{D}_{12}{}^2\right)}{t^3\bar{D}_{11}} \tag{14}$$

In addition, the in-plane Poisson's coefficient is

$$\nu_{xy} = \frac{\overline{D}_{12}}{\overline{D}_{22}} \tag{15}$$

and the corresponding in-plane shear modulus is

$$G_{xy} = \frac{12\overline{D}_{66}}{t^3} \tag{16}$$

With the above equivalent mechanical properties at hand, it is straightforward to introduce them in a commercial finite element program and model the corrugated geometry via a standard shell-type finite element without resorting to more computationally expensive modelling techniques.

As commented earlier, the previous modelling strategy relies on the linear combination of six independent cases, which is generally valid for linear problems. However, non-linear effects have also been investigated. Samanta and Mukhopadhyay [100] performed non-linear geometric analyses on trapezoidal corrugated panels. They proposed an equivalent orthotropic model by taking into account both extensional and bending rigidities. Peng et al. [104] investigated the equivalent elastic properties of sinusoidal and trapezoidal corrugated plates by means of a mesh-free Galerkin method. Liew et al. [105] used this method for the geometrically nonlinear analysis of stiffened and unstiffened corrugated plates. Large deflection von Karman theory was adopted in the nonlinear analysis of the orthotropic plate. Both the equivalent flexural and extensional properties were employed in the analyses.

In the particular context of morphing wings, corrugated laminates represent an ideal solution for the design of morphing skins in adaptive aircraft structures. Yokozeki et al. [2] developed a simple model for the in-plane stiffness of corrugated composites. They manufactured carbon fiber plain woven fabrics as candidates for flexible structural components. They tested them under tensile and bending loads in both in-plane longitudinal and transverse directions and their results were compared with the analytical predictions. Thill et al. [40, 106] compared the homogenised plate properties for candidate morphing aircraft skins to experimental results by adopting the same procedure proposed by Samanta and Mukhopadhyay [100].

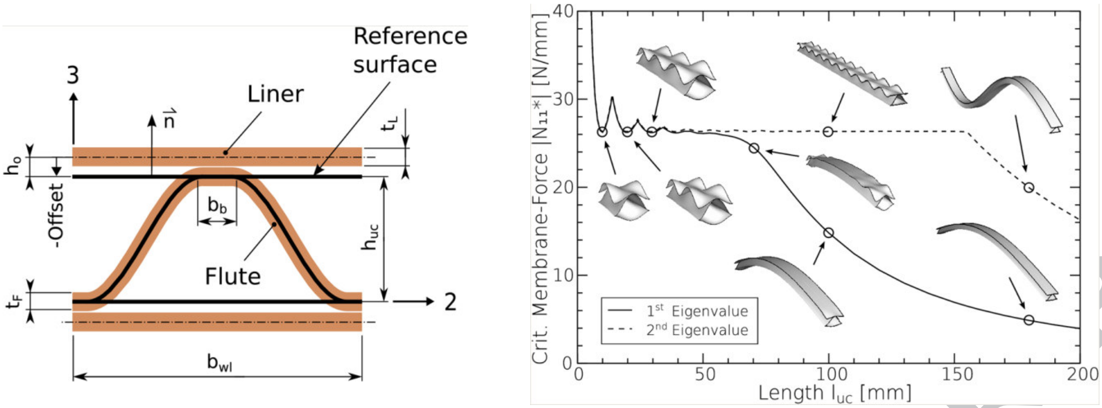
2-7 Optimization

The design of corrugated structures can be improved significantly by implementing the optimization techniques in which the geometrical parameters and material properties of the structure play a dominant role. Some of the goals for the optimization may be represented as: minimizing the weight of the structure, maximizing the structural stiffness of the structure, postponing the buckling load of the structure as much as possible, and maximizing the distance between the natural frequencies of the structure and the excitation frequencies and maximizing the impact energy absorption. However the key question in the optimal design of these structures is the measure of what is desirable about a design. In practical applications, the design process is often measured with respect to multiple objectives which are often conflicting. In other words achieving the optimal value for one objective requires compromise on other objectives. In this case the goal may be to find a representative set of Pareto optimal solutions, and/or quantify the trade-offs in satisfying the different objectives, and/or finding a single solution that satisfies the subjective preferences of a human decision maker. In this section a review of the literature for the optimization of the mechanical behaviour of the corrugated structures is presented.

Liang et al. [14] investigated the optimum design of metallic trapezoidal corrugated core sandwich panels subjected to blast loads by using a combined algorithm in which the Feasible Direction Method [107] was coupled with the Backtrack Program technique [108]. A simple-beam theory and small-deflection plate theory were adopted to model the behaviour of the corrugated core sandwich panels. They considered a simply supported boundary condition for the panel and estimated the blast load by an equivalent static pressure. Geometric parameters such as: the corrugation leg, corrugation angle, face sheet thickness, core thickness and corrugation pitch were selected as design variables. The optimization problem was performed with the objective of minimizing the weight of the corrugated sandwich panel with regards to explicit constraints arising from structure buckling and failure behaviour. Manufacturing limitations on the sizes or shape of corrugations were considered as implicit constraints. They realized that the corrugation leg, corrugation angle, core thickness and corrugation pitch were important design parameters for the core component with respect to buckling strength. For the face sheet with respect to axial stress, the corrugation leg and face sheet thickness were key design parameters.

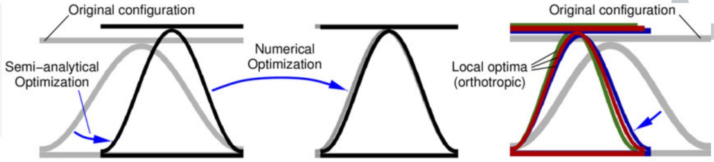
Rathbun et al. [109] implemented a general methodology for the design of the geometry of light weight sandwich panels. They considered several core topologies, such as: square-section truss members in pyramidal and tetrahedral configurations, square honeycombs and triangular corrugated sheets. Closed-form analytical solutions were proposed for the optimal design when the number of design parameters was up to three; however for a further parameter which was needed to fully characterize the corrugation geometry, they used numerical techniques. The geometric parameters they considered were: face sheet thickness, core thickness, height of corrugation and corrugation length. The four possible failure modes of the structure including face yielding, face buckling, core yielding and core buckling were represented as constraints in the optimization problem. Minimizing the weight of the structure for a prescribed load, a numerical procedure described by Wicks and Hutchinson [110] was used. The results revealed that the four parameter optimization was kind of marginal benefit; i.e. leading to a design weight slightly lighter than that of the three parameters optimization. It was shown that the variations in the weights of the optimized panels were quite small in almost all cases, specifically in contrast to the weight of a solid panel. However for the case of a transverse corrugated core panel, the optimized weight was reported almost twice as heavy as the others. They concluded that other objectives or constraints, representing the manufacturing costs and prospect of multifunctionality must be considered in the optimization problem. The structural analysis, however should have been developed further to take to account the coupled effects arising from the anisotropy of the structure; i.e. different characteristics of longitudinal and transverse orientations.

Daxner et al. [111] optimized the corrugated paper board with the purpose of attaining the maximum reduction in the area-specific weight of the structure in the presence of bending stiffness constraints as well as local and global stability constraints. They considered only the geometrical parameters of the sinusoidal corrugated profile in the optimization (as shown in Fig. 10(a)) and studied the effective mechanical behaviour of the structure within the limits of linear shell theory by application of appropriate periodicity boundary conditions. Both isotropic and orthotropic material models were considered in their analysis; the corrugated board with isotropic material was analysed by a semi-analytical approach and for orthotropic material, the optimization algorithm was wrapped around a finite element model. Calculation of the critical loads with respect to local instabilities involved a minimization scheme within the optimization loop in order to find the critical buckling wavelength and the unit cell size was adjusted accordingly (Fig. 10(b)). In their analysis, the function 'NMinimize' in Mathematica was used with different optimziation techniques: Downhill-Simplex method and a genetic algorithm to solve the problem. The optimized results (as shown schematically in Fig. 10(c)) introduced a set of parameters describing a new design of corrugated board with the same buckling strength, but an area-specific weight which was reduced by more than 18% with respect to the original design.



(a) Geometric parameters of optimization

(b) Systematic variation of the unit cell length and its influence on the critical compressive membrane force



(c) The original configuration (grey), the optimized geometry by the semianalytical optimization for isotropic material (black), best three designs for orthotropic material model

Figure 10: Optimum design of corrugated board under buckling constraints, Daxner et al. [111]

Bapanapalli et al. [17] proposed the corrugated sandwich panel as a candidate of the integral thermal protection system of the space vehicle from extreme aerodynamic heating, due to their heat transfer and load bearing capabilities. They developed an optimization problem as a part of the design process with the objective of minimizing the mass per unit area of the trapezoidal corrugated sandwich panel. The constraints were represented in terms of heat transfer and structural mechanics, such as: sustaining the face sheets temperature below certain limit and maintaining the structure far from the global and local buckling due to mechanical and thermal forces. The response surface approximations (Roux et al., [112]) of transient heat transfer and buckling analyses were constructed by use of finite element software, ABAQUS. The FE toolbox was a function called in the optimization process which was performed by use of fmincon command in Matlab. The optimized results showed that the corrugation webs should be as thin as possible in order to reduce the mass of the structure as well as the amount of heat entering the corrugated sandwich panel. In other words, they realized that the material for the corrugation webs should have a very low conductivity and high Young's modulus. They suggested that the conductivity of the webs can be decreased further by removing some material from the corrugation webs which will also reduce the weight of the corrugated sandwich panel. They claimed that the buckling capacity will also improve in this case, contrary to intuition. However, a disadvantage could be the shear stiffness of the sandwich panel which reduces considerably.

Hou et al. [113] investigated the effects of the shape (trapezoidal and triangular configurations) and the corresponding geometrical parameters on the crash behaviour of corrugated sandwich panels. Two different types of impact loading were considered in their analysis: the low-velocity local impact and the global planar impact which were simulated using ANSYS Parametric Design Language (APDL) and LS-DYNA finite element software. The surrogate modelling method (Forrester et al. [114]) was used as an approximate modelling technique to mimic the behaviour of the finite element simulations as closely as possible, while reducing the cost of computations. For the case of low velocity local impact, the corrugated core with both trapezoidal and triangular corrugation profiles was optimized with the purpose of maximizing the energy absorption (internal energy) of the structure. However for the case of global planar impact, a multi-objective particle swarm optimization (Mostaghim et al. [115]) was performed with the objectives of maximising the internal energy and minimizing the peak crushing force. The comparison of two optimal configurations with the identical face sheet thickness and core density showed that the triangular configuration has better crashworthiness performance.

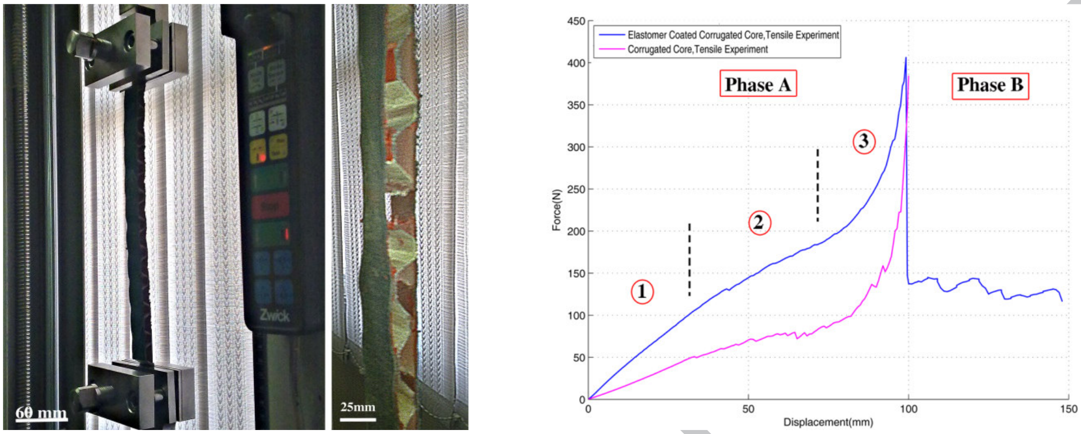
3- Corrugated skin for morphing wing

Improving the performance of an aircraft is significantly important for a variety of reasons such as: reducing the energy consumption, decreasing the toxic emissions and noise pollution or increasing the maneuverability of the aircraft (Argüelles et al., [116]; European Commission, [117]; Barbarino et al. [118]). The problem with the current traditional aircraft is that they cannot be optimized for every single point of the flight envelope [118]. In other words the wings of an aircraft are a compromise that limits the flight to a range of conditions where the performance of the aircraft at each condition is sub-optimal. Hence, a new generation of aircraft, known as morphing aircraft, are needed for further improvement of the aircraft performance without unacceptable penalties in terms of cost, complexity and weight. The morphing aircraft have the ability to adapt their shape in flight so as to always match the optimal configuration. Three major types of the morphing deformations which can be envisaged for an aircraft wing maybe classified as: planform alteration involving span, chord, and sweep changes; out-of plane transformation including twist, dihedral/gull and spanwise bending; as well as airfoil adjustment such as camber and thickness alteration. However, the requirements of morphing aircrafts are conflicting. For instance the design of a proper skin is a huge challenge and a key issue. The skin must be stiff to withstand the aerodynamic loads, but flexible to enable the expected large shape changes. Among all possible structures for morphing skins such as segmented structures, reinforced elastomers or flexible matrix composite tubes embedded in a low modulus membrane, corrugated skins has attracted more attention in the literature. This is because the corrugated skins have exceedingly anisotropic behaviour; they are stiff along the corrugation direction, but flexible in the transverse direction. In addition, corrugated skins have other remarkable characteristics, such as high ratio of strength to density, good energy absorption and easy fabrication.

3-1 Introduction, General Challenges

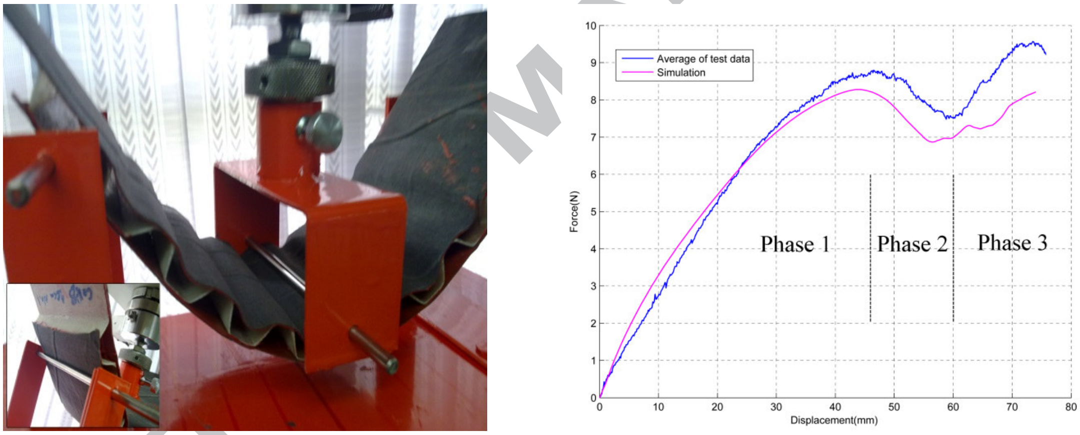
A variety of possible materials and structures such as: elastomer matrix composites and auxetic materials are suggested as morphing skins in the literature (Thill et al., [119]). Among the potential candidates mentioned in the literature, corrugated cores have exceedingly anisotropic behaviour; they are stiff along the corrugation direction, but flexible in the transverse direction. Yokozeki et al. [2] demonstrated the use of corrugated composite sheets as a candidate material for flexible wing skins. As mentioned earlier, the mechanical properties of the corrugated sheets obtained by experiments were presented and followed by a simple analytical model. They proposed the use of stiff rods with corrugated skin in the longitudinal direction to increase further the anisotropy of the skin and suggested the use of elastomeric coating for maintaining the smooth aerodynamic surface of the skin.

However the optimal design of these structures requires high-fidelity models of the coated corrugated skin to be incorporated into multi-disciplinary system models. Hence numerical and experimental investigations were required which maintain the dependence on the nonlinear static and dynamic behaviour of these structures. Dayyani et al. [33] noticed this necessity and studied the nonlinear effects of the elastomeric coating and the mechanism of deformation of the composite corrugated core. They performed a series of experiments such as: static and cyclic tensile tests on the standard samples of composite laminates and elastomeric strips; static and cyclic tensile tests on the composite corrugated skin with and without elastomeric coating and three–point bending test on the coated corrugated skin. The linear stress–strain curves of the glass fibre laminates demonstrated the high stiffness of corrugated core. The large elastic deformation capacity of the elastomers was also demonstrated; the elastomeric specimens stretched 1.5 and 3.3 times over their original length in longitudinal and transverse directions respectively. The experiments and FE simulations of the coated corrugated skin in tensile and bending tests are shown in Fig. 11. The tensile behaviour of the coated corrugated skin, i.e. the three stages of the deformation mechanism with respect to the function of the elastomer coating was discussed before and after the failure of the corrugated core. In terms of the flexural behaviour of the coated corrugated skin, they realized that the elastomer coating functioned as springs that undergo only tension. In other words the elastomer coating resisted the gap opening between two adjacent corners of each unit cell of the corrugated core. Because of the membrane function the elastomer coating showed, the other elastomer coating, which was subjected to the compressive forces, wrinkled and caused non-smooth surface for the skin during bending. This was maybe the main drawback of the corrugated skin for maintaining the aerodynamic performance as high as possible. However they suggested two concepts to deal with this drawback: pre-stretching the elastomer coating and a reentrant corrugated configuration.



(a) Tensile test of the composite corrugated core with elastomeric coatings

(b) Tensile properties of the corrugated core with and without elastomeric coatings



(c) Coated corrugated skin during the three-point bending test

(d) Bending force-displacement behaviour; experiment and simulation

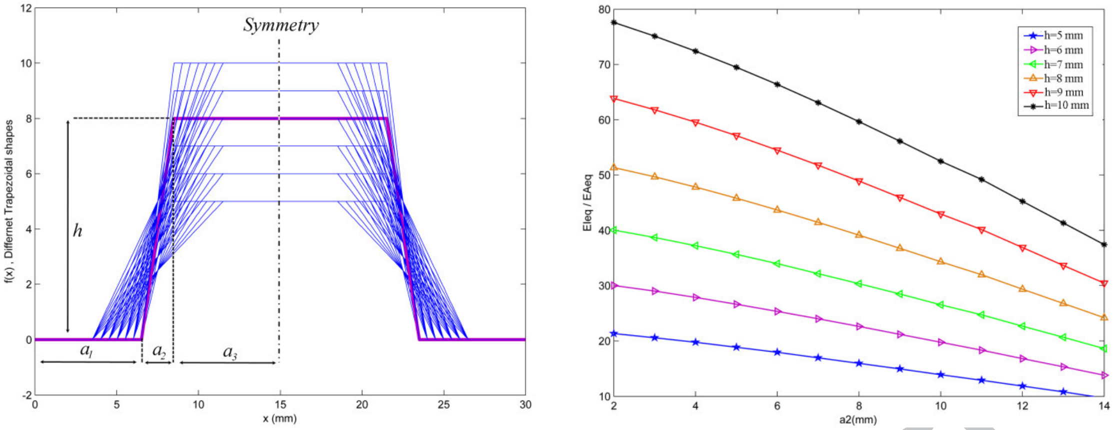
Figure 11: Experiments and FE simulations of the coated corrugated skin in tensile and bending tests, (Dayyani et al. [33])

Structural components which are subjected to cyclic loading may yield due to fatigue, causing them to fail at stress levels lower than static mechanical loading. The cyclic loading behaviour of composite corrugated skin for morphing applications, where the source of cyclic stresses may be the aerodynamic flow over the skin or the actuator, is important. In this regard, Dayyani et al. [33] investigated the cyclic loading behaviour of the corrugated skin with and without elastomeric coating before and after the elastic limit and compared the energy dissipation in each case. It must be mentioned that the authors of this paper interpreted the limit in which the delamination cracks initiated and started dissipating the strain energy of the structure as the elastic limit. They observed the Mullins effect (Diani et al., [120]) in the elastomer coatings even before the elastic limit of the corrugated skin, because of the microscopic damage which resulted in considerable energy dissipation in the elastomeric coatings.

However the optimal design of these corrugated skins required simple models of the structure to be incorporated into multi-disciplinary morphing system models. Therefore equivalent structural modelling and homogenizations techniques were required to retain the dependence on the geometric parameters and material properties of the coated corrugated skin, while reducing the cost of computations. Dayyani et al. [121] investigated an analytical homogenization model which took into account the function of the elastomer coatings based on Castigliano's second theorem. They proposed two analytical solutions for calculating the equivalent tensile and bending flexural properties of a coated composite corrugated core in the longitudinal and transverse directions of the skin. The effect of combined loading and the number of unit cells on the mechanical behaviour of the coated corrugated skin were investigated in their work and were verified with numerical simulations and experimental analysis in the literature. The comparison demonstrated the suitability of the proposed equivalent model for application in further design investigations.

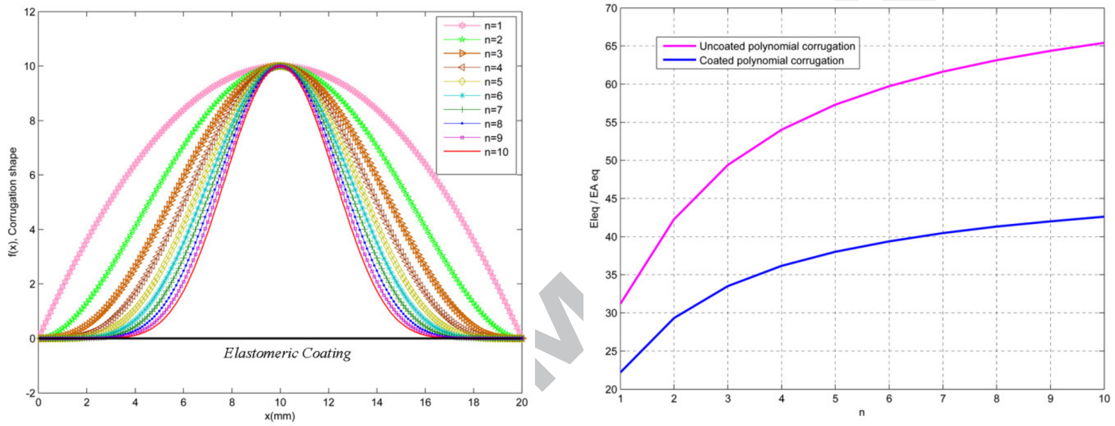
Dayyani et al. [122] investigated the mechanical properties of the morphing corrugated skin with regard to different corrugation shapes. They took into account three typical configurations as re-entrant, rectangular and trapezoidal corrugation and modelled their mechanical behaviour in ABAQUS to realize which configuration leads into higher out-of-plane stiffness, lower in-plane stiffness and mass. The sinusoidal corrugation shape was not included in their analysis, because of the presence of a single line of contact between the elastomer coating and corrugated core, providing insufficient area for bonding as opposed to other counterparts. They found out that although the uncoated reentrant corrugated core had maximum bending stiffness and minimum tensile stiffness, adding the elastomeric coating to the corrugated core resulted in minimum bending and maximum tensile stiffness. This story was reversed for the trapezoidal corrugation shape. Hence they evidenced the suggestion of the coated trapezoidal corrugated core for the application of the morphing skin, which had the highest ratio of the bending stiffness to tensile stiffness. The calculation revealed also that the coated reentrant and coated rectangular corrugated cores were 30% and 11% heavier than the coated trapezoidal corrugated core.

Dayyani et al. [123] proposed a general super element for a corrugated core unit cell with elastomeric coating for the application of morphing skin. The direct stiffness method and Castigliano's second theorem, together with appropriate boundary conditions, were applied to obtain the stiffness matrix of the generic super element which captured the small deformation of 2D thin curved beams with variable curvatures. Numerical and symbolic analytical models were investigated to validate the accuracy and efficiency of the presented super element model. The super element used the geometric and mechanical properties of the panel as variables that could be applied for further topology optimization studies. They used the ratio of the bending stiffness of a panel to the in-plane stiffness as a performance metric of the morphing skin for a variety of corrugation profiles such as: trapezoidal and polynomial curvature corrugation as shown in Fig. 12, where the bending stiffness determined the out-of plane displacement due to aerodynamic loadings, and the in-plane stiffness determines the required actuation forces. They showed that for the trapezoidal corrugation shape, the stiffness ratio increased with the height of the corrugation and the angle of the sloping side panel and for the polynomial corrugation shape, the stiffness ratio increases when the corrugation shape became narrower. Low fidelity system level optimization of morphing aircraft, can be one of the main application of the developed model, where the in-plane and out-of-plane stiffness of a corrugated skin may be estimated accurately and efficiently from its geometry rather than a detailed finite element model.



(a) Different variations of the trapezoidal corrugated unit cell

(b) Distribution of corresponding out of plane to in-plane stiffness for trapezoidal corrugation



(c) Corrugated unit cell with geometry of polynomial functions

(d) Distribution of corresponding out of plane to in-plane stiffness for polynomial functions

Figure 12: A variety of the corrugation geometry of the unit cell obtained by use of super element of a curved beam, (Dayyani et al., [123])

3-2 Corrugated skin, Different Morphing Applications

To the knowledge of the authors the investigations for the application of the corrugated skin is so far limited to the camber morphing, winglet morphing and span wise morphing extension. Although each of these applications have their own specific boundary conditions, structural and aerodynamic loading configuration as well as the geometric and manufacturing constraints; the corrugated skin shows these two main characteristics in common: highly anisotropic behaviour and lightness. In addition the aerodynamic performance in all these applications is highly dependent on the corrugation geometry and Reynolds number. The aerodynamic performance however can be improved further if the corrugated skin is coated by pre stretched elastomeric face sheet, a segmented skin or used with foam slices filling the empty surface between the corrugated unit cells. On the other hand these solutions lead to the further mass of the structure. Hence any concept for modifying the performance of the corrugated skin should pass through the multi-objective optimization and multidisciplinary system level design.

Low fidelity analysis in the first steps are highly necessary for use in these system level analyses and optimizations, since they provide a feasible estimate of each design objective while keeping the computations efficient in terms of time and cost. This section reviews the literature of the corrugated skin with the given focus to camber morphing, winglet morphing and span extension morphing.

3-2-1 Camber Morphing

One of the effective ways to change the aerodynamic forces generated by a wing is through actively varying the airfoil's camber, which allows for control of the aircraft flight path and optimization of the aerodynamic performance over different flight regimes. In addition to the fixed-wing applications, rotary aircraft have also followed the concept of the change in camber to postpone effectively the occurrence of stall and vibration control of the rotary blades. However, the concept of camber variation is not a recent novel achievement and has been traditionally proposed and followed through the use of discrete trailing edge flaps. Nevertheless, a smooth and continuous change in camber is still an interest in the aerospace industries so as to reduce significantly the drag and noise penalty associated with rigid flap deflections. A smooth and continuous change in the camber through a highly anisotropic skin can also lead to a further reduction in the system complexity which decreases the mass of the structure and production and maintenance cost as well. In this section, the applications of the corrugated skin for the camber morphing structures which are proposed in the literature are discussed.

Thill et al. [19] used the composite corrugated sheets for the skin of the trailing edge of a NACA 0024 aerofoil section. Both cord wise extension and camber morphing deformations were considered for the trailing edge section which was about 35% of the 1 meter length cord. They used a simple scissor mechanism to extend the length of the cord and adjusted the manual camber deflections by use of locating pins. The skin was manufactured from attaching and filling foam into two corrugated laminates. Considering the manufacturing limits, the dimension of a corrugated unit cell was between 5-10 mm, which represented about 1% of the chord length for acceptable aerodynamic performance. Low speed wind tunnel testing and open source code XFOIL as well as a two-dimensional computational fluid dynamics (CFD) panel method with viscous effects (Derla, [124]) were carried out to explore the limitations of these concepts. Reynolds number and Mach number which were used in the analysis were about $2*10^6$ and 0.1 respectively, over a range of angles of attack for the NACA 0024 with morphing trailing edge. Figure 13 shows the trailing edge section of the morphing NACA 0024 airfoil with corrugated skin, as it is stretched up to 4% and deflected up to 12◦. The main problem of this concept was the lack of internal structure to support the skin against the aerodynamic and structural loadings. This problem caused the global buckling of the lower skin during the actuation, as it is subjected to compressive strains. The wind tunnel results highlighted a major increase in drag generation, when the morphing arifoil was compared to the conventional NACA 0024. Improving the aerodynamic surface of the skin, they suggested the use of discontinuous segmented composite laminates on top of the corrugated sheets.

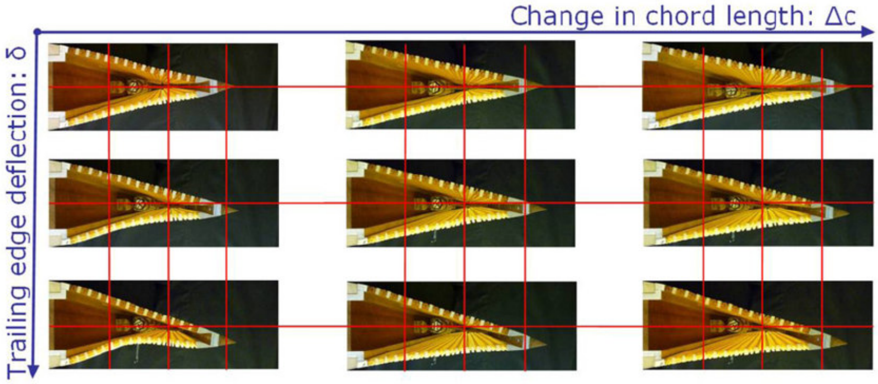
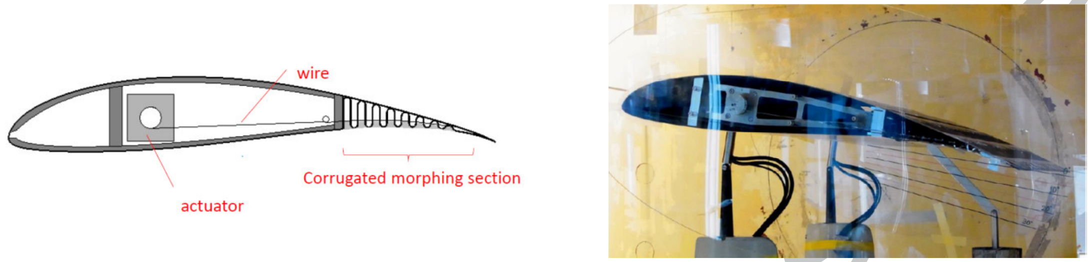


Figure 13: The trailing edge section of the morphing NACA 0024 airfoil with corrugated skin, Thill et al. [19]

Yokozeki et al. [125] proposed a camber morphing airfoil in which the corrugated sheet was used as internal structure in the trailing edge section. The morphing section consisted of a circular corrugated structure and upper thin skin, both of which were made of carbon fibre reinforced plastic. The lower surface of the corrugate region was coated by a thin plastic sheet. The morphing section consisted almost 30% of the chord length, as shown in Fig. 14. Nonlinear finite element analysis was used to confirm the feasibility of the proposed morphing system in terms of actuation force and displacement. They developed a low speed (30 m/s) wind tunnel test for the camber morphing airfoil (Wortmann FX63-137 baseline), inside which two servomotors were used as the actuation system to control the airfoil shape by the chord-wise tension of the connected wires. The aerodynamic performances of the morphing and hinged mechanism wing were compared together and it revealed that the morphing model exhibited superior properties in lift coefficients. However the proposed concept had some restrictions as it limited the morphing deformation to downwards trailing edge displacement. Although this might be useful for “flaps” and low speed maneuvers such as take-off and landing, but is not suitable for higher speed maneuvers. In addition the unsmooth lower surface of the morphing trailing edge has considerable impact on increasing the generated drag.



(a) Schematic representation

(b) Wind tunnel testing

Figure 14: Camber morphing airfoil with corrugated structure in trailing edge, Yokozeki et al. (Images courtesy of Tomohiro Yokozeki.)

As mentioned before the role of internal structure for the support of corrugated skin in the camber morphing deformation is very important. This is because the internal structure supports the skin against the aerodynamic loadings, structural shear and buckling loads and vibration. In addition the internal structure has a main role in enforcing the morphing trailing edge to move on the right path from the start point of the actuation to the desired destination. A further point of discussion of the role of the internal structure is the influence of the structure on the actuation energy required to morph, as the correct design of the internal structure can lead to minimizing the power required for actuation.

Probably Dayyani et al. [126] were the first authors in the literature who noticed the importance of investigating the mechanical behaviour of the corrugated skin in interaction with the internal structure, mainly in terms of of aero-elastic effects and the boundary conditions arising from the internal wing structure. They proposed the design of an elastomer coated corrugated skin for the camber morphing airfoil which exploited the FishBAC internal structure (Woods and Friswell, [127]), as shown in Fig. 15. Considering the boundary conditions and the number of FishBAC stringers, the geometric parameters of the coated corrugated skin were optimized to minimize the in-plane stiffness and the weight of the skin and to maximize the flexural out-of-plane stiffness of the skin. In this regard a finite element code for thin beam elements was used with the aggregate Newton’s technique for performing the multi-objective optimization. The optimization was repeated for a variety of weight distribution in the aggregate method optimization corresponding to the dominant objective functions and the normalized optimum Pareto surface was attained. Collecting all of the best compromise points corresponding to all of the configurations of FishBAC stringers and corrugation unit cells, the design decision was made by repeating the process of finding the best compromise point among the collection in the normalized space of objective functions. Taking to account the cord length of 305 mm, the height and the length of the corrugation unit cell corresponding to decision point were about 4.6mm and 11 mm. In addition, they discussed in detail the advantages of the corrugated skin over the elastomer skin for the FishBAC morphing airfoil based on finite element comparison studies. Some of the advantage might be classified as: almost 18% decrease in weight of the whole morphing structure, almost five times more flexibility for stretching the skin in the morphing actuation process and about 4.5 times more resistance to out-of plane deformation due to aerodynamic loads and buckling deformations caused by actuation. These benefits were in addition to the structural anisotropy of the corrugated skin, which helps it to withstand more aerodynamic loads in the spanwise direction. Considering the specific characteristics of the corrugated skin and the pressure distribution over the airfoil, they suggested variable distance between FishBAC stringers; more distance between the stringers in regions exposed to lower pressure which resulted in a further reduction of the mass of the structure.

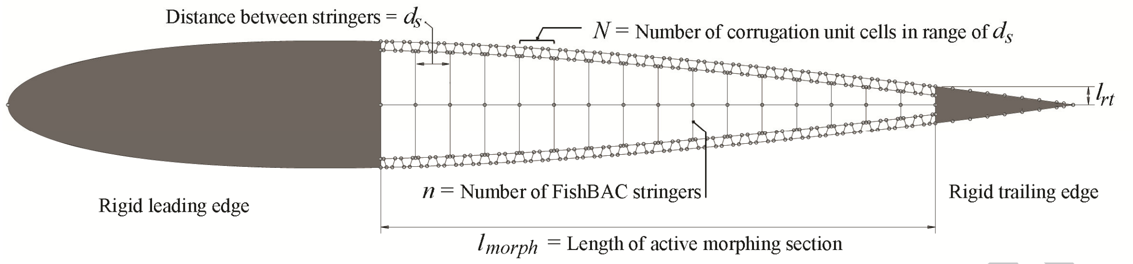
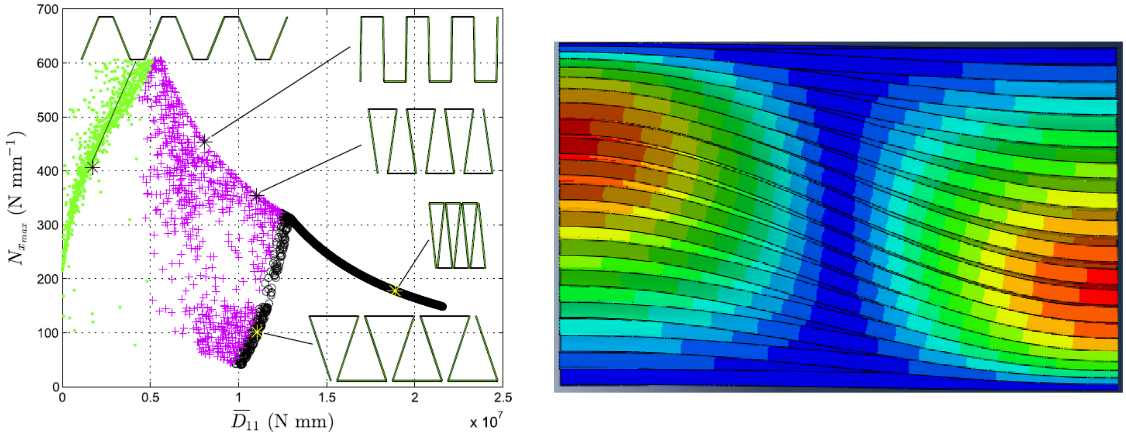


Figure 15: The geometric design parameters of the NACA0012 camber morphing airfoil with FishBAC internal structure and coated corrugated skin, Dayyani et al., [126]

The literature on the buckling of the corrugated skins in morphing applications is fairly light, specifically when the effect of the internal structure should be considered. Many of the key publications on morphing analysis or experimental work have briefly discussed buckling but give little detail on the methods used, for an unusual corrugation incorporating rigid stiffener sections. Shaw et al. [128] continued the proposed design of skin in Fig. 15 and investigated the optimization problem for the buckling loads along the spanwise direction of the wing. Weight, buckling performance, and actuation compliance of the corrugated skin were three objectives they tried to optimize. Classical buckling models with homogenised plate properties were used for deriving the equivalent plate properties of the skin to obtain approximate estimates of the buckling loads. Figure 16(a) shows the trend of max loads with out-of-plane stiffness for optimal solutions of a variety of corrugation geometry. In addition to the global and local out-of-plane buckling modes of the skin, they observed the existence of a further buckling mode which occurs entirely in-plane. This unique in-plane mode was due to extreme anisotropic behaviour of the skin. As shown in Fig. 16(b), this mode affected deep, finely pitched corrugations where the transverse in-plane stiffness became less than the out of plane stiffness. Finite element analysis was used to evaluate the accuracy of the results obtained by the optimization method which exploited the equivalent methods.



(a) Trend of max loads with out-of-plane stiffness for optimal solutions of a corrugation

(b) In plane buckling mode of a corrugated skin subjected to compressive load in the vertical direction

Figure 16: Multi objective optimization of the corrugated skin

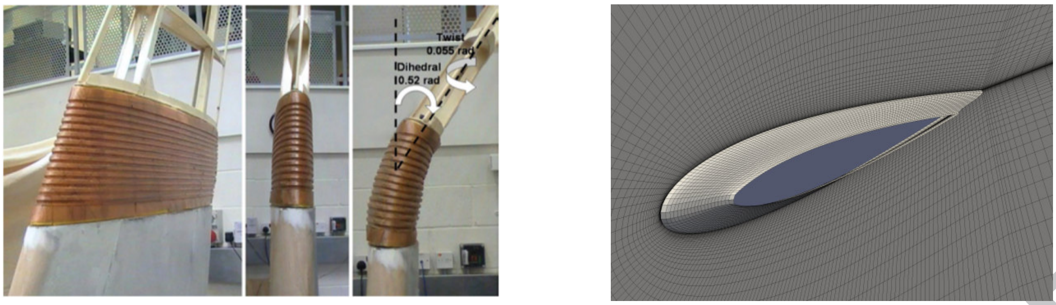
with regards to buckling constraints, Shaw et al., [128]

The aerodynamic performance of the skin is perhaps the main challenge of the morphing wing. In this regard, Xia et al. [129] investigated the 2D aerodynamic performance, particularly lift and drag characteristics of the NACA0012 airfoil with unsmooth rigid corrugated surface. The effects of corrugation size and Reynolds number were analysed and quantified experimentally and numerically in compare to the standard NACA0012 airfoil. They evidenced that the increase in the roughness of the surface i.e. increasing the corrugation size, had negative impact on both lift and drag. In addition, the aerodynamic performance of corrugated airfoils at low angles of attack i.e. the lift-to-drag ratio decreased slightly as the Reynolds number was increased. They showed through CFD simulations how the local flow maintained an attached flow as eddies filled the corrugation troughs and smoothed the shape of the corrugated airfoil, similar to flow around streamlined airfoils. In particular, for a deformable trailing edge, the increased drag from the camber morphing skin is in trade off with the reduced drag obtained from avoiding the sharp changes in camber at the hinge mechanism which lead to flow separation.

3-2-2 Corrugated skin; application in Winglet and Span extension morphing

In addition to camber morphing, there are some other effective ways to change the aerodynamic forces generated by a wing, such as: through actively varying winglet and wing span. Both these methods can control the aircraft performance over different flight regimes and can increase the range and endurance of the aircraft. For example, the increase in the wingspan leads to a higher aspect ratio and wing surface; hence it results in a higher lift and higher lift to drag ratio in some aerodynamic configurations (Beaverstock et al., [130]). As a result, the range or endurance of the aircraft increases although the wing-root bending moment can increase considerably due to the larger span. Therefore both aerodynamic and structural characteristics of the aircraft should be investigated in the design of winglet and span extension morphing wings. Corrugated skin may be a good candidate for the application in both concepts, when the corrugation profile is swept along the airfoil, as shown in Fig. 17. The extreme anisotropic behaviour of the corrugated skin provides sufficient compliance for the actuation and increases the out of plane stiffness of the wing to withstand more aerodynamic and inertial loads. This is because of the combination of the global airfoil curvature along the wing span and the local curvature of the corrugations. Furthermore, since the corrugation lines are along the flow direction the aerodynamic performance is less influenced than the camber morphing application. However from a structural perspective, the combination of the global airfoil curvature along the wing span and the local curvature of the corrugation makes the mechanical behaviour of the structure much more complex in contrast to the camber morphing application. Although the concept of the application of corrugated skin in winglet and span extension morphing is attracting, not too many efforts have been devoted to these concepts in the literature, maybe because of the complexity of the manufacturing method and required 3D structural and aerodynamic analysis.

Ursache et al. [131] presented a preliminary demonstration of morphing wingtip with corrugated skin in span wise direction, as shown in Fig. 17(a). One of the key challenges in the demonstration of the corrugated skin in the span wise direction is the special manufacturing process required to hand lay the composite laminates around the corrugated mould with air foil cross section. They preferred the plain woven Kevlar over other type materials because of its ease of manufacture into corrugations and its especial characteristics such as: lightness, good durability and impact resistance as well as high stiffness and strength. Finite element simulation was performed to assess the mechanical behaviour of the corrugated skin while winglet morphing deformation. The FE results and the trends of the deformation showed some local instabilities of the skin and highlighted the need for updating the model to enhance shape adaptability.



(a) Demonstration of morphing wingtip with corrugated skin in span wise direction, (Ursache et al. [131])

(b) Structural and aerodynamic mesh of a half of a corrugated unit cell in span wise direction, (Image courtesy of James Fincham).

Figure 17: The application of corrugated skin in the span wise direction, winglet and span extension morphing

Xia et al. [129] studied the feasibility of the concept of using corrugated skin for the application in span extension morphing wing. The geometric parameters of the corrugated skin were optimized to minimize the axial stiffness of the skin with respect to out-of-plane deformation constraints. The equivalent structural properties of the skin were calculated by ANSYS APDL finite element simulation based on the global and local geometric parameters. They estimated the aerodynamic performance of the skin by use of low fidelity aerodynamic solvers: Tornado Vortex Lattice Method (Melin, [132]) and XFOIL in which the effect of camber thickness and airflow in corrugated channels were neglected. The results showed that the constraint on maximum out of plane displacement forced the optimizer to choose fewer corrugations in the span direction.

Fincham et al. [133] noted the sharp leading edges generated in the span wise application of the corrugated skin and examined the low pass filtering and arc fitting for rounding of the leading edge to improve the aerodynamic performance. They examined the effect of corrugation wavelength and corrugation depth on the aerodynamic performance, in both 2D and 3D CFD simulations. They realized that that corrugation wavelength has minor effect in the aerodynamic efficiency of the wing in contrast to the corrugation depth which incurred a significant performance penalty. They emphasised that the aerodynamic penalty of corrugated surface would be too large to be practical without some kind of compliant skin covering the corrugated surfaces.

4- Conclusion

Corrugated structures have noticeable impacts on the engineering applications due to their superior structural characteristics such as extreme anisotropic behaviour and high stiffness to weight ratio, mainly arising from their geometric properties. In this paper a detailed review of the literature on corrugated structures was presented through three sections. The first section described different types of corrugated structures, their specific characteristics and their categorized applications. Extending their applications, innovation and developments of these structures were discussed in terms of introducing further geometric parameters and combining different material properties.

In the second section, a comprehensive set of analyses about the mechanics of these structures was presented. The in-plane and out of plane stiffness of the corrugated panels were reviewed in details through experimental, numerical and analytical homogenization analysis. The most common methods to analyse buckling and vibration of corrugated sheets were discussed such as FEM and combination of their homogenized models with the classic shell and plates methods. Although the latter methods had the advantage of simplicity, they could not account for local effects and higher modes, within the structure of the corrugation. The complex deformations occurring in corrugated structures during impact such as: internal buckling, contact friction and plastic deformation were discussed in terms of energy absorbing capability of these structures.The fatigue assessment of the corrugated structural components subjected to cyclic loading was also reviewed. The results revealed that the crack initiations and delamination were two main factors for the fracture of these structures. Finally the optimization problem as an important tool in the design of corrugated structures was discussed. A variety of optimization objectives were represented, where some of them had potential conflicting nature. This highlighted the importance of finding the best compromise situation in the multidisciplinary design problems.

The third section of the paper reviewed the use of corrugated structures in morphing applications. It highlighted the importance of a study which ensures that all likely aspects of the morphing corrugated skin will be considered and integrated into a complete analysis. The applications of corrugated skin in camber morphing, winglet morphing and span wise morphing extension was discussed in detail in terms of specific boundary conditions, structural and aerodynamic loading configuration as well as the geometric and manufacturing constraints that each application poses. The aerodynamic performance in all these applications was reported highly dependent on the corrugation geometry and Reynolds number. This could be improved further if the corrugated skin was coated by a pre stretched elastomeric face sheet, a segmented skin or used with foam slices filling the empty surface between the corrugated unit cells, although these potential solutions could lead to the further mass of the structure. In fact any concept for modifying the performance of the morphing corrugated skin should pass through the multi-objective optimization and multidisciplinary system level design. The low fidelity analysis were found highly necessary for use in these system level analyses and optimizations, as they provided a feasible estimate of each design objective while keeping the computations efficient in terms of time and cost. The high fidelity analysis of the corrugated skins was required in validation of the initial results and modelling complex deformations. This review shows that the level of maturity for morphing corrugated skins is yet low and for most of the concepts analyses such as: vibration and aeroelasticity, buckling, impact, fatigue and fracture and chemical resistance, have not been so far noticed.

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