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Review

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.

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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 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 recognised 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