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An analysis of strain localization and formation of face wrinkles in edge-wise loaded corrugated sandwich panels using a continuum damage model

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ABSTRACT

This paper examines the compressive failure mechanism in edge-to-edge loaded corrugated sandwich panels. The formation of face wrinkles is specifically considered. A detailed finite element model of face sheets and web core of a sandwich panel was developed to provide insight on the failure mechanism. A gradient enhanced continuum damage theory was implemented to capture length effects caused by the material microstructure including formation of damage in the face sheets and core. Distributions of strains in the face sheets determined from finite element analysis (FEA) are compared to experimentally measured strains. The predicted location and orientation of the face wrinkle, as indicated by high values of the second principal strain, agrees well with experimental observations.

Load vs. out-of-plane deflection curves obtained from FEA with the gradient enhanced damage material model are compared to those obtained from a linear-elastic material model and experimentally determined curves. The gradient enhanced solution gives qualitatively better agreement with experimental results, although the magnitudes of strains are less than those determined experimentally.

1. Introduction

The collapse mechanism of corrugated board panels loaded in edge-wise compression is examined. Corrugated board is a paper-based packaging material that is primarily used in transport packaging, such as boxes. The most common form of corrugated board consists of a sine wave-shaped core, sandwiched between two flat face sheets as seen in Fig. 1. Some of the benefits of using corrugated board are that it has a high stiffness in relation to its weight and it is fairly cheap to produce. It also has shock absorbing properties, which help reduce product waste during rough transports. Since corrugated board typically is made from recycled wood fibers it is considered environmentally friendly. During transportation and storage, the boxes are usually stacked on top of each other. Obviously, the boxes in the bottom of a stack are subjected to highest compressive loads and are the first to fail. For this reason the top-to-bottom compression strength is one important aspect in design of such boxes.

The aim of sandwich construction is generally to increase the bending stiffness by using face sheets with a high extensional stiffness and a core that is able to keep the faces separated (Vinson and Sierakowski, 2002). The compression strength of corrugated board boxes is traditionally estimated by semi-empirical models such as the McKee formula (McKee et al., 1963). The compressive strength of a box may also be determined experimentally by loading a box in compression, or by testing a corrugated board panel in compression. The panel test shown schematically in Fig. 2 mimics the loading situation of the vertical side panels in an actual box (Nordstrand, 2004). The panels typically buckle before total failure.

Fig. 3 shows a photo of a corrugated board panel tested to failure in edge-wise compression; the behavior of such panels is described in a number of experimental studies (cf. Nordstrand, 2004; Hägglund et al., 2012; Viguié and Dumont, 2013). The overall bulging shape is a clear indication that the panel has buckled, and is referred to as global buckling. The panel in Fig. 3 also displays local bucking of the face sheets in the form of small dimples between the core pipes. Patel et al. (1997) found local buckling of the face sheets occur due to a combination of normal compressive and shear stresses in the unsupported face sheet elements

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between the fluting tips. Face wrinkles form near the corners, at approximately 50° to the principal loading direction (Fig. 3), at the point of ultimate failure. In the wrinkle zone, the face material has failed due to biaxial loading, and the web core has collapsed locally.

The failure of the panel is thus caused by a complicated interplay between the core and face sheets and very little is known of the actual mechanism. It is obvious that the collapse involves several different length-scales and any model able to predict the failure mechanisms must include multi-scale effects.

In a previous study by the authors (Åslund et al., 2014), corrugated board panels were modeled using a linear-elastic material description, including large deformations and rotations. Such modeling provides a good description of the general behavior of test panels but was found to overestimate the ultimate strength and in-plane stiffness of the panel. It was suggested that the discrepancy between analysis and experiment could be due to damage formation in the constituents. Damage theory is often a good choice when describing the constitutive behavior of paper materials strained into the non-linear regime. The damage mechanisms in paper materials subjected to in-plane compression are complex and are often due to delamination in the sheets (Fellers et al., 1980). This delamination causes a reduction of stiffness on the macroscopic scale and this behavior can be captured on the global scale by a damage model but not with a traditional plasticity model. Plasticity theory is better suited for homogenous materials, such as polymers or metals, where the dominating dissipative mechanism is plastic yielding of the material, without any permanent loss of stiffness.

The aim of this work is to study the mechanisms of wrinkle formation and to answer some of the fundamental questions related to failure of corrugated board panels loaded in compression. The dimpling and wrinkling of corrugated board panels creates regions of large strain magnitudes. In these regions a damage model is needed to accurately describe the evolution and distribution of strains. A damage material model is implemented in the numerical analysis, to explore the extent to which the wrinkles are caused by weakening of the constituents (i.e. material damage).

For a classical local action approach, i.e. assuming that the mechanical state in one particular point in the material is independent of the mechanical state in neighboring points, the introduction of a damage variable in the constitutive equations tends to concentrate degradation of material properties to small, isolated areas (Needleman, 1988; Pijaudier-Cabot and Bazant, 1987). A remedy for this is to use a nonlocal, or gradient enhanced, form of constitutive equation by introducing an internal length parameter (cf. Peerlings et al., 1996, 2000; Geers et al., 1997; Ganghoffer and DeBorst, 2000; Comi, 2001; Eringen, 2002). This approach provides means for scaling the damage zone upon softening to a certain width and is explored in this study. Thus, in contrast to earlier known studies on the subject (cf. Nordstrand, 2004; Viguié and Dumont, 2013; Åslund et al., 2014; Biancolini and Brutti, 2003) the analysis performed here incorporates damage and length effects.

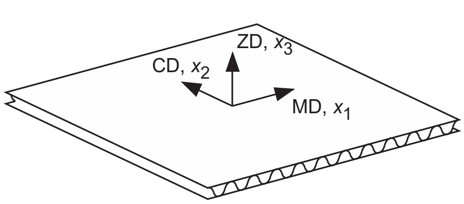

Fig. 1. Single wall corrugated board with the principal material axes, i.e. machine direction (MD), cross direction (CD) and thickness direction (ZD), and $x_1x_2x_3$ coordinate system defined.

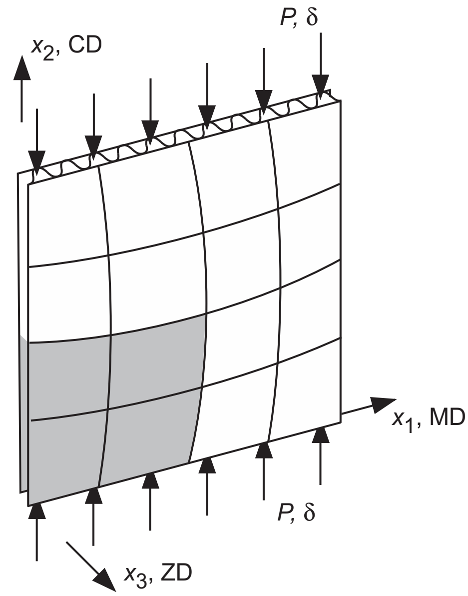

Fig. 2. Fundamental buckling mode of a square corrugated board panel with simply supported edges loaded in in-plane compression. The gray area represents the selected quarter symmetry section.

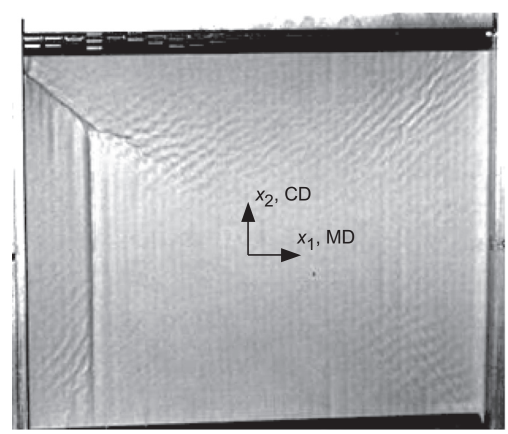

Fig. 3. Failure of corrugated board panel loaded in top-to-bottom compression.

2. Damage modeling

2.1. Non-local damage theory

It is here assumed that the constituent paper layers in the sandwich panel can be described as a homogeneous orthotropic material, following (e.g. Baum, 1986; Xia et al., 2002; Huang and Nygårds, 2010). Because the paper constituents are typically thin, a state of plane stress is assumed for each sheet making up the corrugated board. An orthotropic material description is used for each layer of the sandwich panel. To capture degradation of the material, a continuum damage theory is applied, (cf. Pijaudier-Cabot and Bazant, 1987 or Geers et al., 1997). Although paper is normally characterized as an orthotropic material, an isotropic scalar damage parameter D is introduced characterizing the degradation in a point of the material. Apart from an intention of keeping the number of model parameters low, the assumption of a scalar valued damage variable may be justified by the plane stress conditions assumed here and the loading being predominantly uniaxial.