An Experimental Study on the Edgewise Compressive Failure of Paper Honeycomb Sandwich Panels with Respect to Various Aspect Ratios

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Abstract. The present work investigates the edgewise compression failure for honeycomb paperboards. Various panels are tested under a fixed loading rate with varying aspect ratios. The influence of the varying properties aspect ratio on yield strength is recorded. The experimental results indicate that the honeycomb paperboards are subject a decrease in yield strength with an increase in aspect ratio towards more slender bodies. Buckling was not observed in any of the tested specimens. All experiments are conducted under the general framework of ASTM C364/C364M-16 with a few noted changes.

1. Introduction

Paper honeycomb panels also known as honeycomb paperboards consists of paper-honeycomb cores between two facing sheets (typically paper or wood) which results in sandwich panels that are utilized in the packaging industry due to their desirable properties including strength, weight, stiffness, cost and recyclability. The increased usage has led to significant research interests.

Due to the significant use of paper honeycomb panels in the packaging and transportation industry, the materials used are typically exposed to a repetition of low, medium and high impacts along vibration. These impacts vary in frequency and affect the structural properties of the material over time. Wang et al. [1] investigate the effect of repeated low-intensity impacts on the cushioning performance of honeycomb paperboard. This is conducted via a repetition of drops from two varying heights to replicate low and medium intensity impacts along with a vibration test. Based on the findings authors conclude that the paper honeycomb can absorb the repeated low intensity impacts through the folding that occurs in the honeycomb resulting in a decrease of the material’s load carrying capacity of honeycomb paperboard after low-intensity repeated impacts declines significantly.

Energy absorption diagrams can provide further insights on the cushioning properties of paper honeycomb panels. Tink et al. [2] investigate energy absorption characteristics of paper honeycomb by conducting compression tests. The authors note that resultant stress–strain curve can be classified into three progressive stages, starting with linear elasticity followed by the plateau and lastly a densification stage. The derived energy absorption model is associated with the thickness-to-length ratio of the cell wall. The paper validates the theoretical model for energy absorption with experimentation to which the authors cite an agreement between the results. Both the works of Wang et al. and Tink et al. have significant and current utility in the packaging and transportation industries.
The versatility of paper honeycomb panels allows for applications in standard furniture. For such applications, creep analysis is likely to be more beneficial when compared to impact or energy absorption properties. Dapeng and Shin [3] attempt to model paper honeycomb as a linear material with viscoelastic property on the basis of experimental results focused on creep analysis. While Chen et al. [4] conduct a multitude of creep tests in order to characterize the creep response of the paper honeycomb panels under three point bending. The authors conducted the experiment for various core and face materials and geometries. The experimental results cited demonstrate a relationship between flexural creep and various material and geometric parameters including shape and thickness of the core and skin materials.

Buckling behavior for honeycomb composites have been examined by Lin et al. [5] and Kaman et al. [6]. The former develops models that represent the critical load in paper honeycombs which are in turn validated to empirical analysis and experimentation. The latter examines the buckling loads for various honeycomb composites including polyester impregnated paper when compared to an ANSYS fine element analysis model. Interestingly, the authors note that regional failures are noted in both the aluminum and paper honeycombs past a certain load value. Both studies cite a strong agreement between the theoretical/numerical analysis and the corresponding experimental results.

Yet despite the growing literature, certain studies such as Hua et al. [7] indicate that investigations into edgewise compressive strength have not been conclusive. Through empirical and numerical analysis, the authors examine the influence of the edge effect on edgewise compressive strength of sandwich paperboards. The paper concludes that the edge could be a significant determinant in edgewise compression strength of fiber and paperboards. However, given the difficulty with experimental repeatability when dealing with paperboards, a larger testing sample set would have been preferable.

The present work attempts at investigating edgewise compressive failure of honeycomb paperboards. The study focuses on the influence of testing specimen’s aspect ratio on the mechanical properties of the board, particularly the yield strength. All experiments are conducted under the general framework of ASTM C364/C364M -16 with a few exceptions that have been noted in the paper.

2. Experimental Methodology
The primary objective of the experiment is to determine the effect of aspect ratio on the edgewise compressive strength of honeycomb paper panels. A total of 15 specimens were tested, which were cut from a single honeycomb paperboard. The specimens were grouped into sets of three, with the sets varying only in terms of height. The base width has been kept constant along with all other properties related to the paperboard. Figure 1 illustrates variation in height across the test specimens. Further details on the test specimens provided in Table 1.
Table 1. Test specimen details

| Test Specimens | Dimensions    | Thickness | Cell Width | Number of samples |
|----------------|---------------|-----------|------------|-------------------|
| C1 to C3       | 100x100 mm    | 25 mm     | 12 mm      | 3                 |
| C4 to C6       | 100x150 mm    | 25 mm     | 12 mm      | 3                 |
| C7 to C9       | 100x200 mm    | 25 mm     | 12 mm      | 3                 |
| C10 to C12     | 100x250 mm    | 25 mm     | 12 mm      | 3                 |
| C13 to C15     | 100x300 mm    | 25 mm     | 12 mm      | 3                 |

The experiment is conducted using a standard universal testing machine. The test specimen is placed in between two flat plates. The lower plate is placed on a stationary head and is self-aligning to ensure slight deviations from the central axis is self-corrected. The upper plate is connected to a moveable crosshead. Specimen orientation is noted and labelled before initializing the test to provide directional information on local failures. Speed of testing is set to 1 mm/min for all specimens, with the tests concluding once 20% strain has been achieved. Lateral end supports have not been utilized in the experimental setup, which along with the unlevel surfaces of the specimens posed a challenge in aligning the specimen.

![Figure 2. Experimental setup](image)

Specimens were placed centrally on the plates, with a slight preloaded force to ensure level and even contact on the top and bottom surfaces. Testing parameters including load, stress, strain and elongation were recorded for each specimen at a frequency of 10 Hz.

3. Results & discussion
The main parameter considered in this study is the variation of the yield stress with respect to various aspect ratios. The stress strain curves are plotted in Figure 3. The plots are grouped with respect to their aspect ratios to allow for equivalent comparisons.
Figure 3. Stress strain curves for the tested specimens grouped by aspect ratio

In general, there was a low degree of repeatability across samples of similar aspect ratios. This is believed to be the result of two reasons, namely the uneven top and bottom surfaces produced when cutting out the specimen size and intrinsic behavior of paperboards make it difficult to achieve repeatability. Moreover, a few specimens have a visible toeing effect in the results due to the shape irregularities of the testing specimen.

However it can be noted that there are three notable states that the specimen undergoes during the test. The first state is an elastic deformation, which is characterized by the linear or quasi-linear behavior observed. This occurs in low strain region, where the linear slope represents the overall modulus of the specimen. The second state is a failure, which is characterized by a drop in the stress experienced by the specimen. The failure is likely to be local and occurring at nodes or cells. This state is closely followed by a compact state, where the specimen regains strength through the stacking of failed cells on top of each other. The second and third state repeat in an alternating fashion, which is
the cause for the wavy pattern in the stress strain plot in the plastic region. The experimental results are summarized in the table below.

| Group | Yield Stress (MPa) | Standard Deviation | Coefficient of Variation |
|-------|--------------------|--------------------|--------------------------|
| C 1-3 | 0.15               | 0.05               | 36%                      |
| C 4-6 | 0.13               | 0.05               | 35%                      |
| C 7-9 | 0.14               | 0.04               | 32%                      |
| C 10-12 | 0.08             | 0.01               | 16%                      |
| C 12-15 | 0.07              | 0.02               | 35%                      |

The yield stress is generally observed to be reducing with an increase in aspect ratio. However, there is a high degree of uncertainty due to the lack of repeatability and the small sample sizes which resulted in a large coefficient of variation. Moreover, buckling was not visible in any of the specimens conducted. All the failures noted were a combination of crushing at the top/bottom surfaces and internal honeycomb collapse as illustrated in Figure 4.

4. Conclusion and future work
The material exhibits a cyclic pattern of failure followed by compaction and consequently regain of strength. Results suggest that the yield stress increases with an increase in aspect ratio towards slender body honeycomb paperboard specimens. However, a larger sample size is required to obtain a statistically significant result.

In the future, it will be necessary to repeat the experiment with end supports. This will allow for testing using fixed support as opposed to the hinged support.
The fully fixed boundary conditions may mitigate some of the uncertainty and lack of repeatability observed under the latter. Early experimental results show significant improvement and repeatability as can be observed in Figure 5.

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