Reconfigurable Cushion Design for E-Commerce Packaging using Kirigami Concept

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ABSTRACT

In packaging, cushion barriers are needed to provide content protection in a disposable form. However, conventional cushioning materials and designs typically require a large volume, which decreases shipping and storage efficiency and increases environmental impact. Especially in e-commerce, where “shipping and handling” occur at an exceedingly rapid pace in large-scale operations, many packages suffer from being over or under packed through the fulfilment process. To solve this issue, this paper presents deployable kirigami-based cushion designs that can be collapsed or deployed depending on the distribution situation. Kirigami is a variation of origami that involves both cutting and folding of paper. The advantage of this design is that the kirigami cushion can be applied on the outside of a shipping container, instead of inside. Therefore, the shipping container itself can be more compact and the cushioning can be accessed and deployed when it is needed. The deployable kirigami cushion design was evaluated using compression and vertical impact tests, and the testing results are presented.

KEY WORDS

kirigami, deployable structure, cushioning, distribution, e-commerce.

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1 INTRODUCTION

In a packaging system, a cushioning structure provides protection, one of the most important packaging functions. Cushioning prevents physical damage of the products during distribution. In general, polymeric foam[1]-[3] and fiber [4],[5] materials have been used widely in package cushioning. Polymeric foam is well developed to optimize the cushioning function.[6] However, it has a negative environmental impact because of recycling issues.[7] On the other hand, fiber materials are used as alternative solutions to polymeric foam but the corrugated cushioning design cannot provide good cushioning function, especially for repeated shocks.

Cushioning is becoming more important to the e-commerce industry. In 2014, the value of U.S. retail e-commerce sales, including digital services, was $298.26 billion (U.S.), and by 2023 is expected to grow to $969.7 billion (U.S.).[8] The growth of e-commerce creates more challenges for packaging for many reasons. First, the distribution environment of e-commerce is tougher than for brick and mortar distribution since most products are delivered through single-parcel distribution systems. Second, the handling process for packages associated with the e-commerce environment requires more steps than for the brick and mortar distribution system. According to an Amcor report in 2016,[9] the minimum handling point for e-commerce distribution is at least three times more than for brick and mortar distribution, and could be exposed to more potential hazards during the distribution. Lastly, e-commerce may require different types of packaging systems than regular package systems for the same products. For example, Amazon gives incentives to their vendors if the packaging is certified by Amazon to meet the Frustration-Free Packaging (FFP), Ships in its Own Container (SIOD), and Prep-Free Packaging (PFP) Program guidelines.[10] Because of these reasons, the packages in e-commerce tend to be oversized and over protective, which impacts the shipping efficiency. Therefore, it would be a significant benefit if cushioning can be reconfigurable depending on the need, so the overall volume and the protective performance of the cushion can be adjusted.

Moving toward a cushioning system with volume adaptability, a deployable structure [11] concept can be considered. This concept has been used widely in different applications from the simple folding chair to structures for satellites and space missions.[12]-[14] A deployable structure is a structure that can change its configuration between a compact and an expanded state, for example, as shown in Figure 1. The main advantage of integrating a deployable structure into cushioning designs is its ability to transform itself between different configurations, depending on the performance requirement in a specific packaging distribution situation. The challenge of integrating deployable structures in cushion designs, however, is that typical deployable structures are made with many different rigid parts that require an assembly. For example, the deployable structure [15] in Figure 1 is made with many rods and hinged joint. Because of this complexity, it is challenging to implement such a deployable structure into cushioning for packaging.

To help resolve these packaging issues for e-commerce, a deployable kirigami cushion design is proposed in this paper. Kirigami is a variation of origami that involves cutting and folding of paper into the desired shape, whereas origami only involves folding.[16] Both origami and kirigami are
traditionally artistic concepts but have been gaining attention for industrial applications over the last few decades.\cite{17-19} Deployable origami structures are used in various applications and sizes, ranging from small scale for biomedical functions,\cite{20} to the large scale required for shelter design.\cite{21} The main advantage of the kirigami design is that the deployable structure can be constructed from a simple pattern. By implementing the kirigami structure into a cushion design, the cushion can be reconfigured when more cushioning is needed. As a result, the overall shipping volume can be controlled based on the shipping conditions. The conceptual design of the deployable cushion is shown in Figure 2. For example, when the product ships as a pallet, all cushions can be collapsed to maximize shipping efficiency. However, when each package is distributed as a single parcel, the cushion can be deployed at the distribution centre to maximize the product protection.

Testing was performed on the deployable kirigami cushion structure to verify the cushioning function. First, the compression test was performed to measure the compression strength of the kirigami cushion. Next, the vertical impact test was performed to verify the benefits of the kirigami cushion design. The major aim of this research was to investigate the effectiveness of two shapes of the kirigami cushion design to increase shipping efficiency and content protection through a sustainable solution. The findings of this investigation can be applied broadly to packaging distribution but especially in e-commerce packaging.

2 MATERIALS AND METHOD

The challenge is that the kirigami cushion design should be simple enough to manufacture and reconfigure but should have good cushioning functions. To accomplish both objectives, the kirigami cushion design is inspired by honeycomb corrugated board. In this section, two different shapes of the honeycomb-inspired reconfigurable cushion designs are presented. Moreover, the testing methods are described to verify the design as a cushioning materials.

2.1 Kirigami Cushion Design: Cylinder Shape

The proposed cylindrical reconfigurable kirigami cushion design is shown in Figure 3, with photos of the collapsed and deployed cushion. The cushion shapes like a cylinder when it is deployed. This kirigami cushion can be attached, in the collapsed form, to the current packaging system and then be deployed when needed. This kirigami design can be made with paper using a simple pattern that creates a honeycomb structure when it is
deployed. The honeycomb structure provides the cushioning function, and that function can be controlled by the number of honeycomb cells in the kirigami design. When the kirigami design has more honeycomb cells in a given cushioning space, it will be stiffer. The number of honeycomb cells is determined by the gluing pattern for the flat sheets.

In this study, two different types of kirigami cushion samples of the same size were prepared with a 4- or 6-partition design. These different kirigami cushions were used to demonstrate how the number of partitions affects the material properties using same size of the cushion. This kirigami cushion is composed of 30 individual 100 × 100 mm with 150 gsm paper sheets that are folded in half and glued in specific configurations. For this study, each 100 × 100 mm sheet was folded in half to convert to 100 × 50 mm, and after folding all sheets the glue lines were applied to the inside and outside; the four-partition design has 3 glue lines and the 6-partition design has 5 glue lines. Glue was applied along the glue lines on alternate sides of the sheets, as shown in Figure 4. The red line represents the fold line and green lines indicate the glue application lines. Each folded sheet was attached to another sheet until all 30 folded sheets were glued. For this study, 10 specimens of each partition design were prepared as described.

2.2 Reconfigurable Cushion Design: Accordion Shape

Another proposed reconfigurable kirigami cushion design has an accordion shape. The Figure 5 shows when accordion shape of kirigami cushion is deployed at the edge of the shipping box. Like the cylinder shape design, the accordion shape kirigami cushion can be attached in the collapsed form. However, the accordion shape design allows more flexibility for the stretch and it cover well the edge of the shipping box as shown in Figure 5 left. Moreover, the stress level on the glue line will be less since the deploy angle of the kirigami structure is only 90 degree when the cylinder shape is 270 degree.

For this design, the paper is cut (instead of folded) into 100 × 50 mm sheets and glue is applied. This kirigami cushion is composed of 60 individual sheets and the kirigami can be deployed like accordion, which allows for more flexibility of the cushioning area. A 90-degree angle deployable origami design is attached to both ends of the kirigami cushion, and this section is used to attach the cushion on the shipping box. The fold lines, glue lines and shape of a 4-partition design are shown in Figure 6.
2.3 Compression Testing

The compression test is to measure the strength of the static load and it represents when the product is sitting on top of the cushion or stacking strength. To measure the compression strength of the proposed deployable kirigami cushions, compression tests were performed using an Instron 5605 Universal Testing Machine. Five specimens were tested for each design and. Each specimen was placed on top of the compression fixture in a 180-degree deployed shape. as shown in Figure 7. The compression rate was set at 12.7 mm per minute, and compressive extension and compressive load were measured during the test. The compression motion was ended after 20 mm of compressive extension, or when the sensitivity of rate of load is 40 percent. All samples are pre-conditioned with 50% relative humidity and 23°C temperature.

2.4 Vertical Impact Testing

To measure how well the kirigami cushion can absorb the impact energy, the vertical impact test is performed using the Lansmont Vertical Impact Tester. Like the compression test, the five specimens of each design were tested and test setup is shown in Figure 8. Based on the ASTM 1596, a 300 mm drop height was used for the entire test and the drop weight was 5.81 kg. Each kirigami cushion was placed on the impact surface in a 180-degree deployed shape. Each specimen was tested with 5 drops, and the transmitted shock (G’s) was measured for every drop to evaluate the cushioning function of the kirigami cushion design. Like compression samples, all samples are pre-conditioned with 50% relative humidity and 23°C temperature before the testing.

3 RESULTS

The compression test is to measure the strength of the static load and it represents when the product is sitting on top of the cushion, or stacking strength. At the same time, the vertical impact test is performed.
to measure how well the kirigami cushion can absorb the impact energy. In the following sections, each testing method and results are described for the cylinder shape cushion design.

3.1 Deployable Kirigami Cushion: Cylinder Shape

The relationship between compressive extension and load for the 4-partition cushion is shown in Figure 9. When the compressive extension is less than 5 mm, the major compression happened in the arc space area between the bottom fixture and the deployed kirigami cushion. Once the cushion started to support the compressive load, then the curve shows a steeper slope between compressive extension and load. The maximum compressive loads are marked with a rectangle on each curve, and the average maximum load was 74.6 ± 5.0 kg (standard deviation [SD]). Because this 4-partition kirigami cushion has a multiple honeycomb structure, the cushion maintains a certain percentage of maximum compressive strength even when the compressive extension passed the maximum compression load.

To demonstrate the different compression strength of the kirigami cushion with 6 partitions, specimens were tested at the same conditions and the results are shown in Figure 10. The relationship between compressive extension and load was similar for the 6-partition and 4-partition cushions. However, the average maximum compressive load for the 6-partition samples was 110.2 kg, which is about 35 kg more than for the 4-partition samples.
This result shows that the compression strength can be controlled easily by changing the number of partitions with the same volume and materials for the kirigami cushions.

The vertical impact test results for the 4-partition cushion are shown in Figure 11. The x axis represents the drop number, from 1 to 5, and the y axis shows the impact acceleration (G’s). The average impact acceleration of the first drop was 19.9 G ± 5.9 G’s (SD). At drop number 2, specimens 2, 3, and 5 showed less impact acceleration than at the first drop because the integrity of the kirigami cushion structure was largely maintained at the first drop. The acceleration increased dramatically when the integrity of the structure was lost. From the results, the acceleration started to increase at drop number 2 for specimens 1 and 4, at drop number 3 for specimens 2 and 5, and at drop number 4 for specimen 3. The changes in the kirigami cushion structure through the five drops are shown in Figure 12.

To demonstrate the different cushioning function of the kirigami cushion made with the same materials but with 6 partitions, specimens were tested and the vertical impact test results are shown in Figure 13. The 6-partition and 4-partition cushion vertical impact test results were similar; however, because of more glue lines, the structural integrity of the 6-partition kirigami cushion was maintained better than that of the 4-partition kirigami cushion. As a result, all five specimens had less acceleration at drop 2 and started to increase at drop 3. The average impact acceleration of the first drop was 35.3 ± 2.3 G’s, and the average of the second drop was 19.7 ± 5.4 G’s. The 6-partition cushion results show more clearly that the impact acceleration of the second drop was less than for the first drop. As explained previously, the first drop crushes some of the honeycomb structure and the structure provides more cushioning function.

![Figure 11: Impact acceleration (G’s) for 4-partition cushion (cylinder shape)](image)

![Figure 12: Changes to kirigami cushion structure (cylinder shape) through drops 1 to 5)](image)
In the case of specimen 1, the impact acceleration was maintained well below the first impact acceleration. This result indicates that as long as the kirigami cushion maintains structural integrity, it maintains the cushioning function. This function could be beneficial for distribution environments with repeated impacts.

3.2 Testing Results of the Deployable Kirigami Cushion: Accordion Shape

The relationship between compressive extension and load for the 4-partition accordion-shape cushion is plotted in Figure 14. The average maximum compression load was 103.3 ± 6.2 kg, which is about 30 kg higher than for the 4-partition cylinder-shape cushion and can be explained by the greater contact area. Unlike the cylindrical kirigami cushion, the accordion shape of the kirigami cushion has its full contact surface to the compression load. The entire kirigami cushion structure can fully engage with the compression load, which leads to the higher compression load results. Moreover, the plots show multiple peaks when the compression extension is increasing, indicating that each honeycomb structure from the kirigami design supports the compression load like...
Figure 16: Impact acceleration (G’s) for 4-partition cushion (accordion shape)

Figure 17: Changes in cushion structure (accordion shape) through drops 1 to 5: specimen 1 (top) and specimen 2 (bottom)

4 CONCLUSIONS

In this paper, the deployable kirigami cushion designs are presented with prototype designs. The main advantage of the kirigami cushion is the deployable function, which can enhance shipping efficiency depending on the distribution situation. Moreover, it is easy to control the cushioning properties of the kirigami cushion, as shown in the comparisons between the 4-partition and 6-partition kirigami (cylinder shape) designs. Therefore, depending on the cushioning needs, the designer can simply modify the partitions to ensure the cushioning properties match the products to protect. Additionally, the kirigami cushion(s) can be attached to a pillar. Therefore, even though some honeycomb pillars are collapsed, other honeycomb pillars take over the compression load and provide further compression strength, as shown in Figure 15. This characteristic will be an advantage with repeated compression load, which is a benefit in the e-commerce distribution channel.

The vertical impact test results for the 4-partition accordion-shape cushion are shown in Figure 16. Compared with the results of 4-partition cylinder-shape cushion, the accordion-shape kirigami design shows more consistent testing results. All five specimens maintained the cushioning function up to the third repeated impact (drop 3), and only one specimen (specimen 1) lost cushioning function at the fourth repeated impact (drop 4). These results are shown clearly in Figure 17, comparing the structure deformation between specimen 1 and 2. In case of the specimen number 1 (top photos), the integrity of the kirigami structure was lost at drop 4 and the impact acceleration was high. On the other hand, the integrity of the kirigami structure of specimen number 2 (bottom photos) was maintained throughout repeated impact. The results indicate that the accordion shape of the kirigami cushion performs the cushioning function well as long as the integrity of the structure is maintained.
the current packaging systems used for brick and mortar vendors, and e-commerce vendors do not have to prepare different packaging systems for the same products. These characteristics of the deployable kirigami cushioning are beneficial to the e-commerce distribution with more handling points and tougher conditions.
REFERENCES


