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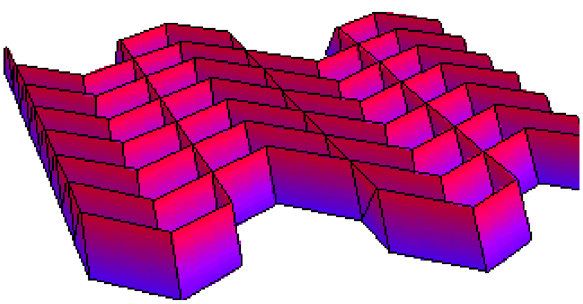
**Packaging Material Innovation: 3-D Folded Structures**

The functions of a package are to: contain, protect and preserve, transport, advertise and sell the product [8]. All of these functions are satisfied by the current industrial standard of the many types of Kraft paper corrugated fiberboard. One way or another, corrugated fiberboard finds its way into everyday packaging; whether the fiberboard is constructed to fulfill a primary, secondary, or a distribution package, or used as pads for cushioning, shock, vibration, and/or impact loads . The primary reason for the popularity of corrugated fiberboard is that it is easily made, biodegradable and economical to produce.

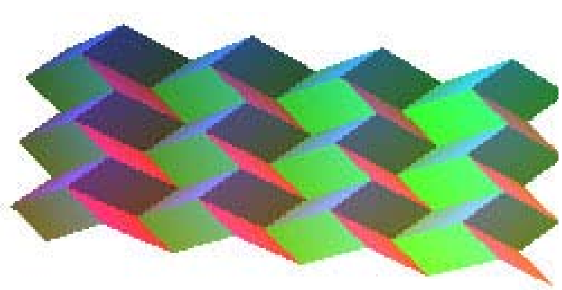
However, the main disadvantage of current Kraft fiberboard materials is that the corrugated core provides a unilateral stiffness, which results in the corrugated fiberboard being able to withstand compressive and bending loads in one direction while <u>it would simply collapse if a load was applied in another direction</u>. Clearly, there is a significant need to be able to produce fiberboard that has equal strength in both perpendicular directions. Such packaging material would enable manufacturers to reduce costs, save space, minimize material usage, lower packaging weight and potentially revolutionize the packaging industry.

A potential solution to the problem with Kraft fiberboard is a novel method of folding sheets of material, including Kraft paper. Any flat sheet of material can be folded into 3-D structures to create a core structure with better mechanical properties. Additionally, since this new technology creates the 3-D structure by folding only, it eliminates material stretching. Hence, this new technology can be applied to almost any sheet material and the application of this technology is not just limited to the packaging industry.

On one hand, this new process may seem to produce 3-D structures similar to that produced by conventional sheet forming techniques such as stretch-drawing, forging, pressing, and stamping [8], but the mechanical properties of the structures produced by one of the traditional processes are significantly different since they stretch or create variations in the thickness of material. The folding of 3-D structures does not produce these undesired qualities: 3-D geometric patterns are created based on a mathematical theory used to design machinery that is used to fold sheet material; however, not all geometric shapes can be folded from these flat sheets. Figure 1 shows two of the different geometric shapes that can be produced by sheet folding. Figure 2 are pictures of different materials that can be folded using the sheet folding theory and machinery.

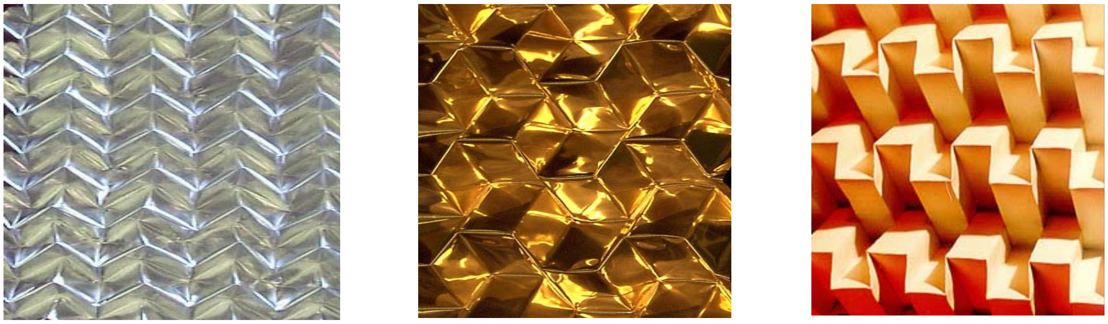


Truss Pattern



Chevron Pattern

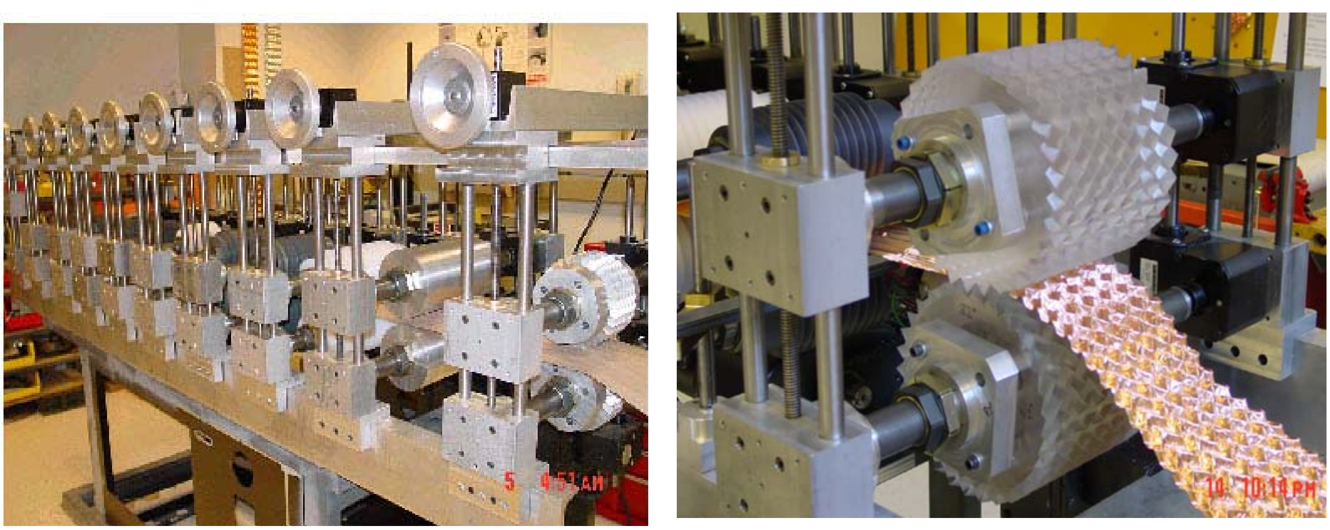
Figure 1



Aluminum Copper Kraft

Figure 2

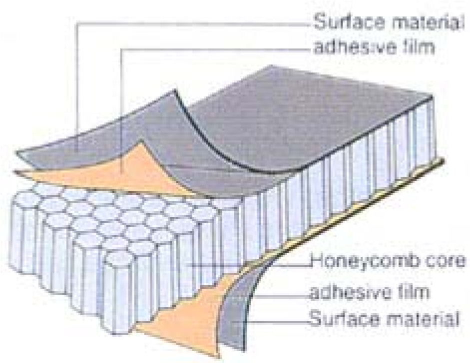
Basily and Elsayed reported on this new and innovative sheet folding technology in [1]. They designed and built a machine, shown in Figure 3, which could produce a continuous sheet folded pattern. The machine was constructed using a new technique in which sheet material is pre-folded through a set of sequential linear folding circumferentially grooved rollers, followed by a final set of cross folding rollers engraved with specific patterns (US Patent applied for) [3]. Figure 2 above are examples of how this machinery can fold patterns of different geometry from different sheet materials.



Continuous sheet folding machine Final sheet folding sequence

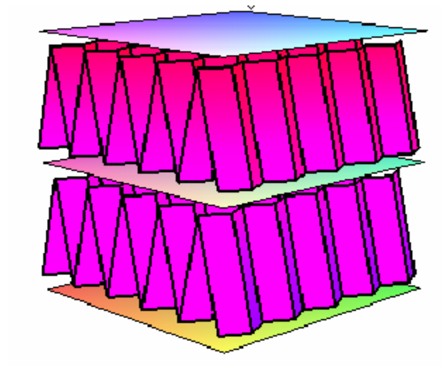
Figure 3

While this innovation in packaging material uses a new packaging machinery technology, the packages can be produced at moderately high rates and "… are also developed at a cost significantly less than other existing manufacturing processes used for production of similar core structures such as the honeycomb" [3]. Figures 4 and 5 show the comparison of honeycomb to a 3-D folded structure.




Honeycomb Structure

Figure 4



3-D Sandwiched Structure

Figure 5

An important characteristic of this new technique of paper folding is that the folded paper can absorb great amounts of energy in comparison to the current industry standards of impact absorption and damage prevention of the honeycomb structures. Additionally, the folded paper structure outperformed the honeycomb at a greatly reduced production cost.

A demonstration of the of folded structure energy absorbing ability is given in [1], where samples of both the honeycomb and Chevron pattern were made of kraft paper and subjected to impact loading. The samples could be tested under different impact speeds using the Dynatup 950 INSTRON Impact Testing Machine. The Chevron folded structure samples, in the shape of cubic blocks and cylindrical slugs, were tested. The blue arrows in Figure 6, show how the structures were oriented under impact [3].

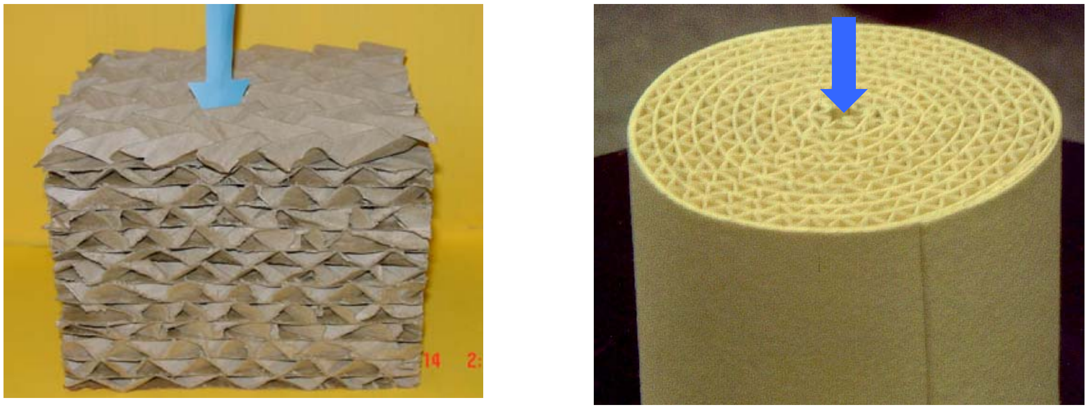
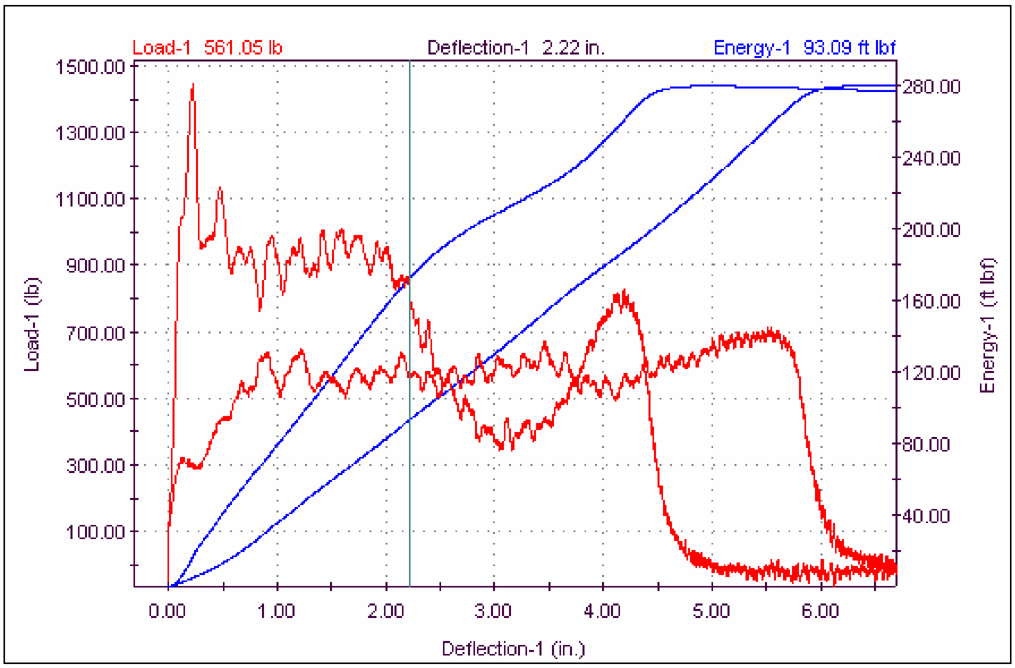


Figure 6

The results shown in Figure 7 are for samples tested at a predetermined speed of 30 ft/sec using a hammer weighing 21.0 lbs which provided a pre-calculated impact energy of about 285 ft-lb. Similar impact tests were done on a 5.5”x5.5” sample of honeycomb. Also, different heights of honeycomb were used, ranging from 2 to 4 stacks of the 2.9” block height. For 2 stack honeycomb that experienced 30ft/sec impact loading, the maximum impact load is 1444lbs and the maximum deflection is 4.85in. The absorbed impact energy is 279.52 ft-lb.

Testing conducted on the Chevron samples was similar to the testing of the honeycomb structures. These tests showed that the Chevron sample absorbed the same energy as that of the honeycomb; however, what is important is that the Chevron folded sample outperformed the honeycomb in that it absorbed the same amount of energy but showed a loading reaction of nearly half that of the honeycomb. This means that the Chevron folded structure has twice the energy absorbing capacity than that of the honeycomb and half of the volume of Chevron material could be used to absorb same amount of energy as the full volume of honeycomb for the same stress levels. Therefore, there could be a significant reduction of the Chevron material usage that would still give equivalent results of the larger volume honeycomb material pattern.

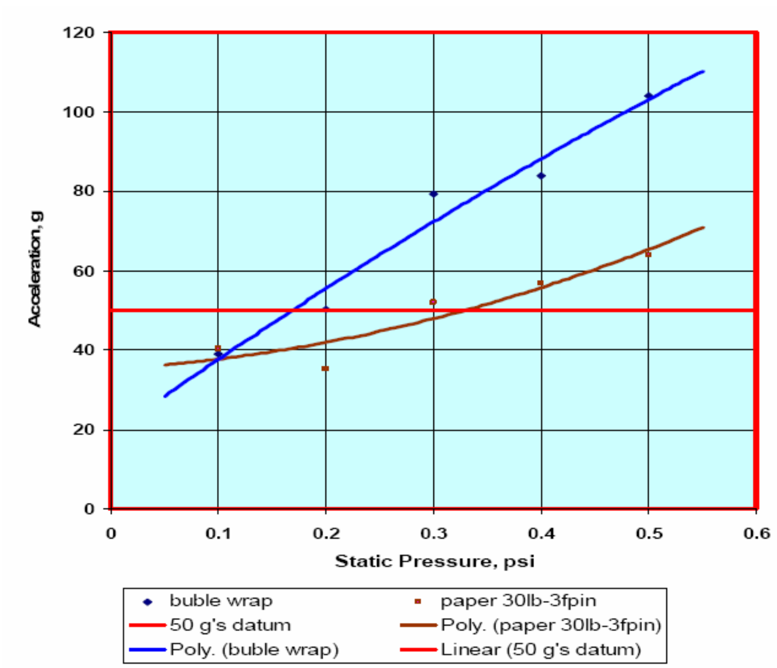
In packaging, this can tremendously reduce the size and weight of a package, saving the manufacturer an enormous amount of resources and capital. Lighter packages are more easily distributed and handled which reduces the probability of impact damage from dropping; as well as, shipment costs can are reduced by lighter packages.




Load-energy-deflection curves for
Honeycomb pattern (two humped curve) and Vertically Oriented Chevron structures
30 ft/sec impact velocity
Figure 7

The test results for the cylindrical sample are similar to that of cubic samples and may be used according to package geometry. The other big advantage of the folded structure is its capability of energy absorption in different directions (side, vertical, and flat orientations), while the honeycomb can only absorbs energy in one direction [3].

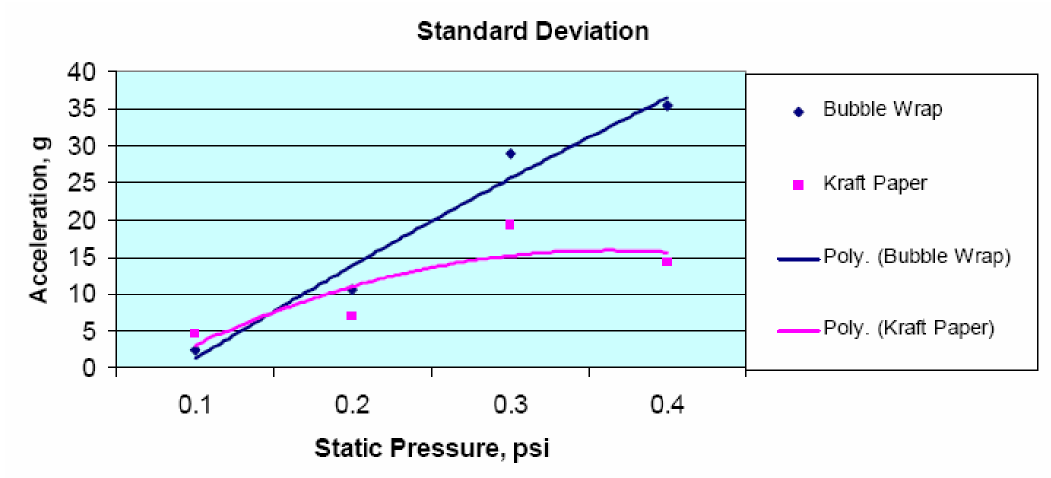
The other application of these folded structures is used for cushioning. The next example also from Basily and Elsayed [3], compares the cushioning effect of Kraft paper sheet folded structure with that of bubble wrap, a popular current cushioning material used today. Cushion curves are used to show the acceleration in levels of g's vs. static stress in psi. This type of graph is frequently used within the packaging industry to show the breaking levels in G of packages. The data is obtained by dropping a plate of predetermined mass onto a cushion of certain height and a calculated area from a given height. Each sample, the bubble wrap and Chevron, are made into 12"x12"x2" pieces. The bubble wrap sample is formed from .5" thick stacks to form a 2" layer and the Chevron used 6"x12" pieces, .5" in height to form a stack of 2". The results are as follows and are conducted by ASTM standard procedures to generate static pressures:




Cushioning curves for bubble wrap and Chevron structure

Figure 8

The results clearly indicate that the 3-D folded kraft is superior to the bubble wrap as a cushioning material. Where the bubble wrap fails to protect the product around 0.13PSI, the 3-D folded kraft protects upwards to 3.25PSI. One of the more important aspects of this test is the standard deviation curve of the bubble wrap and Chevron samples.

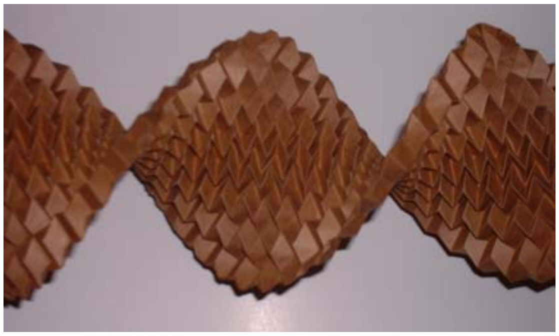



Standard deviations of cushioning materials

Figure 9

The standard deviations for the Chevron sample are smaller than the standard deviations of the bubble wrap. Therefore, the 3-D folded Chevron structure is better able to reproduce consistent results per given stress level than the bubble wrap cushion.

Any sheet material is folded by repeated tessellations of 3-D shapes, which creates unique applications for packaging. The tessellations create the ability to be twisted or contorted in many different ways compared to the honeycomb, which cannot be contorted. The folded paper technology is able to be twisted, wrapped, or bent around objects. This special property gives rise to an almost unlimited number of uses and shapes that can be applied to packaging products. This can contribute to smaller packaging sizes due to its ability to conform to the product itself. The package becomes smaller, lighter, and better protected. The easy maneuverability of the 3-D core will also allow easy rearrangement of packaged product parts into or out of package, or within package after it has already been wrapped in 3-D folded Kraft. Figure 10 is a set of pictures that show how the material can be contorted.



Sample of Chevron being twisted and shaped conically.

Application of 3-D Kraft sheet wrapped around a bottle of wine.

Figure 10

A key factor in selling a package is its aesthetics as a whole, inside and out, along with how well the product is protected. When shopping, a package that is more pleasing to the eye is more likely to be bought, and when buying something fancy or expensive usually the package cushioning material is also aesthetically pleasing (e.g. fragrances or expensive bottled liquors or wines). The new paper folding technology will allow manufacturers to create imprinted patterns, company logo, solid colors, etc. directly on the kraft itself. This will provide a double purpose, both helping the package sell, as well as, protecting the package from impact, shock, compression, or vibration damage. Figure

11 shows applications of the 3-D folded sheets for aesthetics as well as the protecting product.

Flower pattern paper 3-D folded

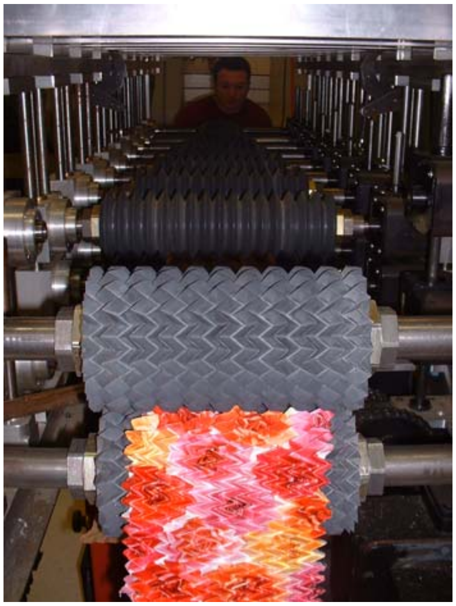
Colored paper wrapped around cologne.

3-D folded Italian flag which could be wrapped around a wine bottle.

Figure 11

These applications of the Chevron pattern used with different pattern papers are serving double purposes: protection and aesthetics. Easily, the Italian flag, the floral or blue paper could be a company logo or some type of text; since the paper is only folded and not stretched, it can return to its original size so no text or picture would be distorted. Figure 12 shows how easily the floral pattern is transformed from a flat sheet into the Chevron pattern. The material used was plain wrapping paper.

Entering machine, flat.



Exiting machine, 3-D folded

Figure 12

3-D folding technology is relatively new and once it is perfected, it will change the packaging industry forever.  Already this new innovation is able to save space, money, material, and can be produced relatively fast and cheap. It out performs all current cushioning materials used in the packaging industry. It uses the same EXACT material as is currently used in Kraft fiberboard, except that the mechanical properties are changed by forming a 3-D structure core out of the material. This theory and machinery can be applied to almost any material not just Kraft paper,  which is in itself is revolutionary because these 3-D structures can be created out of light weight metals or plastics that could be used to make buildings, protect cars during collision, or to make lighter weight planes. This new theory of creating 3-D structure cores has unlimited applications and once implemented and perfected, it will continuously prove over and over its ability of improving our way of life.

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## Figures

Figures 1-3, 5-9 are from references [1] and [3].

Figure 4 is taken from reference [9].

Figures 10-12 are photos taken by author.