Estimation of corrugated cardboard strength with a new tensile or shear test method

Master Thesis of Mechanical Engineering in the
Graduate School of Engineering,
Nagaoka University of Technology,
Niigata, Japan

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The corrugated cardboard is widely used in manufacturing industries as a packaging and transportation material. Faculty of corrugated cardboard is depended on the fragility, weight, thickness, toughness and so on. The strength of corrugated cardboard changed with the fabrication process, used atmosphere and variety of loading patterns. On the machining process of corrugated cardboard box, the cutting and ruling technology is very important factor. The effects of these factors on the strength of corrugated cardboard have not yet enough been identified.

In general, the corrugated cardboard was composed with three layer of paperboard. One is outside liner and inside liner and the other is corrugated medium. The top of corrugated medium is bonded with glue on outside or inside layer surface. The bonded space was decided by company standard. The evolutional method of bonding strength had not been established. The development of new simple method has been needed.

In this research, to establish the evaluation method of strength of corrugated cardboard material, new practical tensile test and shear test, considering the glue bonding strength, was proposed and the factory of these test method was investigated.

In current studies, it was too hard to evaluate the reproductive tensile and shear strength of corrugated cardboard, because of fabrication method of the cut specimen and the deformation of chuck position. On the shear test, as the direction of parallel chuck changed during loading process, the specimen was rotated. In this research, the new developed method of tensile and shear was accomplished, the reproduced strength could be obtained. The fatigue test was tried on the shear test to investigate the effect of thickness of specimen.

The main results of this research were summarized as follow.

1. A new method of tensile and shear test on corrugated cardboard was developed.

2. The good reproduce strength value obtained using the new method.
3. The effect of corrugated medium on the tensile strength was investigated comparing the strength of inside and outside liner and the tensile strength of this method.
4. On the shear test, the bonding strength of glue area was assumed with changing the number of bonding top. Over 5 bonding top condition, the fracture occurred at the outside and inside liner.
5. On the fatigue test of shear method, even under the 10% of fracture strength, the fracture generated at 33 times.

Chapter 1 Introduction

1.1 Introduction of research

Corrugated cardboard can be defined as "the structure formed by gluing one or more layers of fluted corrugating medium to one or more flat facings of linerboard" [1] (see Fig. 1). It has been used as packing material for more than 100 years, but it still maintains a healthy share of the total market despite increasing competition from plastics. One reason for continued demand for corrugated cardboard packaging is its unique combination of attributes:

- It has a high stiffness to weight ratio. Compared to other rigid packaging materials, corrugated cardboard delivers relatively high stiffness at a relatively low price. This was demonstrated by Steenberg et al. [2] in 1970, and the comparisons are still broadly valid (Fig. 2)
- It has reasonable shock resistance and cushioning properties and the air space in the corrugated structure imparts good thermal insulation.
- It is made from a natural and renewable resource and is fully biodegradable and recyclable. In some European countries over 70% of all corrugated packaging is collected and recycled [3].
- It is versatile and can be used for the diverse packaging requirements of different industries. It can carry a high quality printed image for point of sale marketing and can be used on high speed automated packing lines.

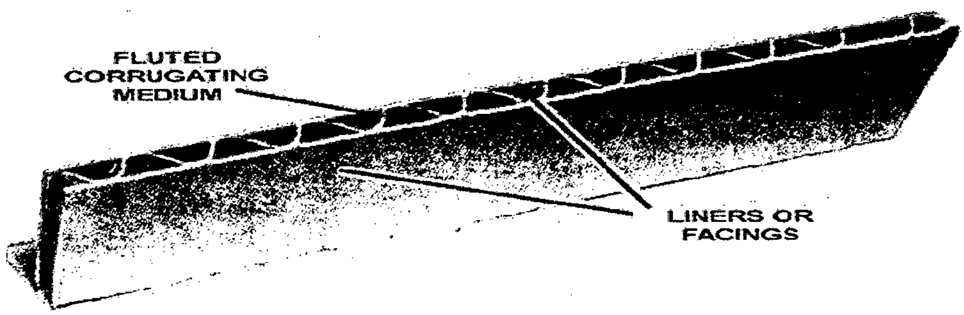


Fig. 1 Section through corrugated cardboard showing the fluted structure

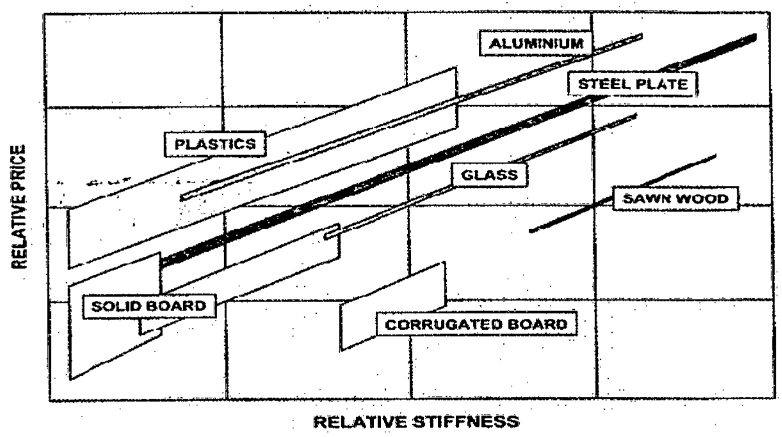


Fig.2 Comparison of relative stiffness and price of various rigid packaging materials. (After Ref. [2])

In 1997, total world paper and board production for all grades was 299 million tones [3]. Of the 145.1 million tone of packaging grades, almost 80 million tones was corrugating materials, which is second only to graphic papers in terms of volume (Fig. 3). Total world shipments of corrugated cardboard in 1999 were 124.9 billion m^2 [4], or almost 125, 00 km^2. By 2001, sufficient corrugated cardboard will be produced annually in the world to totally cover a country the size of England in a continuous layer. Production increased by an average of 3.6% in the years 1995-1999 [4], and the industry is forecast to grow at a rate of about 1% faster than world GDP, or 3.1% per annum, up to 2012 [5].

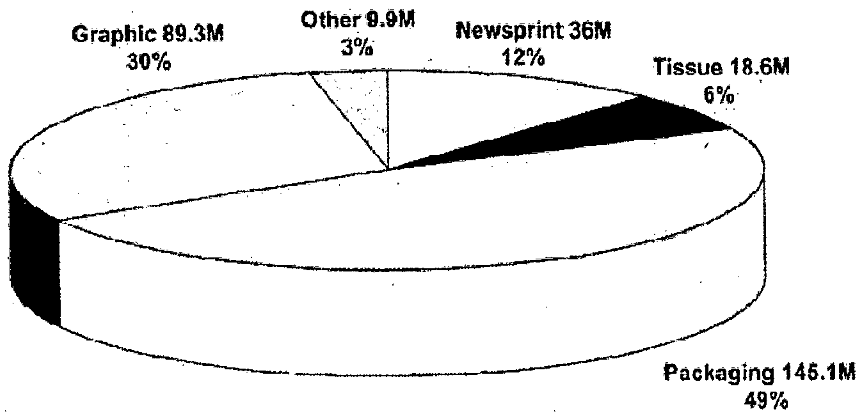


Fig. 3 World paper and board production in millions of tones by grade. (Data from ref. [3].)

1.1.1 The Manufacturing Process

The modern corrugator bears a strong likeness to the original Langston designs [6], with two independently controlled stations to apply the facing (see Fig. 4).

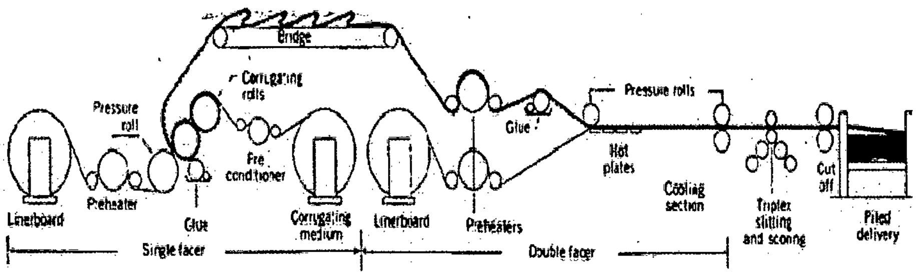
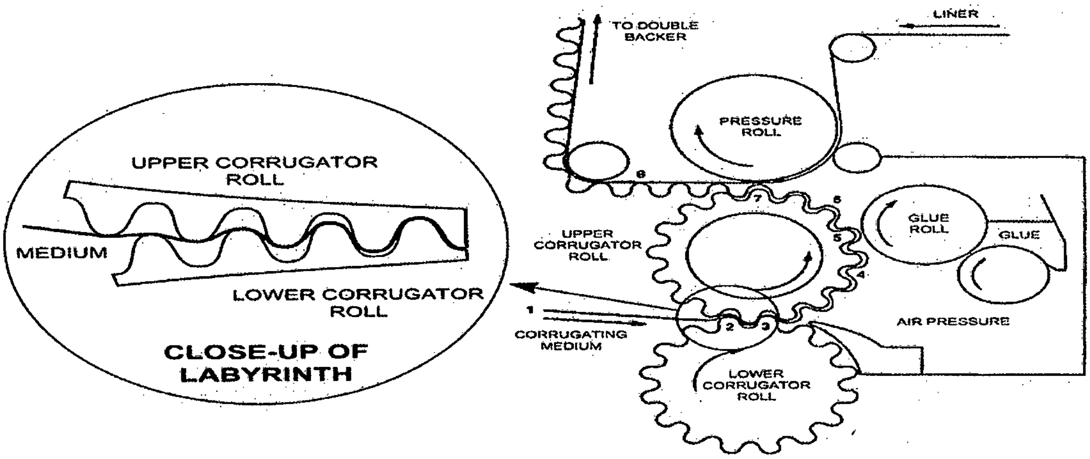


Fig. 4 Modern corrugator for manufacturing corrugated cardboard (Ref. [16]).

The first facing, called the single face (SF) liner, is glued to the medium at the same station that forms the characteristics flutes (Fig. 5). The corrugating medium at is fed from an unwind stand around a preheater roll, then into the labyrinth between two corrugated rolls (locations 2 and 3 in Fig. 5).



Location	Description	Residence Time, ms
1	Preconditioning before the corrugator roll nip	—
2	Labyrinth entering the corrugator roll nip	6.0
3	Labyrinth leaving the corrugator roll nip	1.5
4	Pressure compartment before the glue roll	94.5
5	Glue application	3.0
6	Pressure compartment before the pressure roll	60.0
7	Pressing the liner against the glued flute tips	1.15
8	Formation of the bond after the pressure roll	

Fig. 5 Schematic of the single facer station on a modern corrugator. The table shows approximate residence times at the various stages of the process. (Main diagram adapted from Ref. 62. Inset courtesy of Ian Chalmers, Papro, New Zealand.)

These rolls are steam heated, and the nip pressure is controllable. The medium passes between the rolls, is compressed and thermally softened, and molds to the contours of the corrugated rolls. This process relies on a combination of paper properties such as hot coefficient of friction and ability to stretch and process variable such as web tension, as comprehensively reviewed in the work of Gottsching and Otto [6]-[11] and Whitsitt [12]. The medium is held in place on the corrugator roll by either vacuum or pressure (locations 4 and 6 in Fig. 5) or, on older machines, by the use of mechanical fingers. An adhesive is metered onto the tips of the medium corrugations by an applicator roll (location 5), and the liner is bought into contact with the medium at the pressure roll (location 7). The resulting structure is called single faced board, because it has only one liner glued to the medium. The bond between the two still wet (or "green" as it is known) at this stage but has sufficient tack to hold the structure together. The factors affecting the development of green bond strength are explored in the articles by Batelka [13, 14].

The board is transported to the next station via the bridge, which is a temporary holding facility. This is necessary because the two stations on the corrugator operate independently, and the process would be difficult to control without the provision of a buffer of single face material.

The second layer of liner is added at the double facer, also known as the double backer station. Adhesive is applied to the exposed tips of the corrugating medium, and the second liner is bought into contact under light pressure. The corrugated board then passes over hot plates to cure the adhesive. The final stage is machine direction (MD) slitting and scoring at the triplex station, followed by cross direction (CD) cutting by a rotary cut off knife. These operations produce a blank of the size required for the box making operation. More details of the corrugating operation can be obtained in the book The Corrugator [15]. The corrugated cardboard then passes through several other conversion processes, depending on the nature and complexity of the use (Fig. 6).

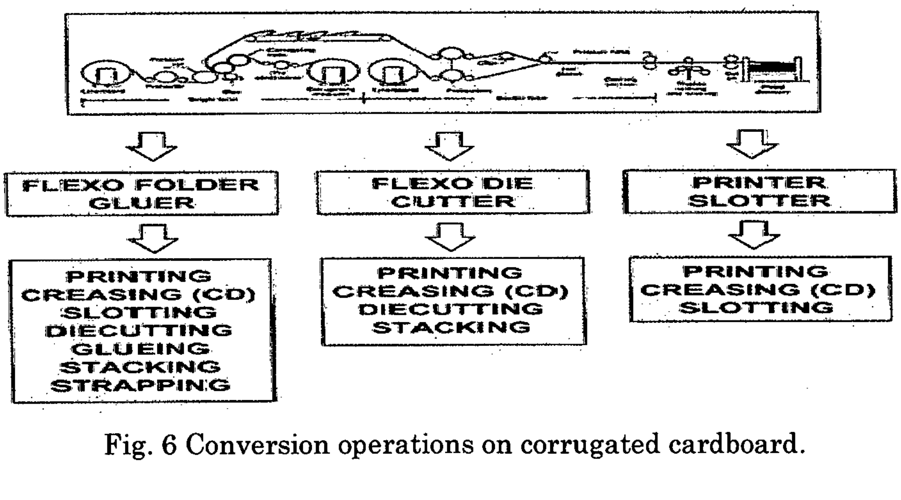


Fig. 6 Conversion operations on corrugated cardboard.

1.1.2 The Structure of Corrugated Cardboard

Corrugated cardboard is a unique construction with a series of connected arches separating the two facings. This provides the structure with rigidity while maintaining an excellent strength to weight ratio. The structure has different properties in its three principal directions (Fig. 7).

The balance of properties in the three principal axes will depend on several characteristics of the materials and structure, including

1. The directional strength of the facings. The paper used for the facings or liners in corrugated cardboard is generically known as linerboard. It is commonly a two layered structure with the greater strength in the direction of manufacture, or machine direction. This is due to the nature of the paper making process, which tends to align fibers in the machine direction.
2. The ability of the medium to keep the facings apart. This will depend on the compressive and shear strength of the flute structure, which also be affected by the strength and integrity of the glue lines between the medium and the liners.
3. The weight per unit area of the facings and medium. Components with higher weight per unit area (grammage) will produce a structure with higher strength. The balance between the grammage of the liners and the medium will also affect structural strength.
4. The geometry of the flutes-the height and number of flutes per unit length (pitch).

Corrugated cardboard can consist of combinations of layer with different liners and flute geometry, such as triple wall structure shown in Fig. 9. It is the ability to change the material and structural attributes that makes corrugated cardboard so versatile as a packaging material.

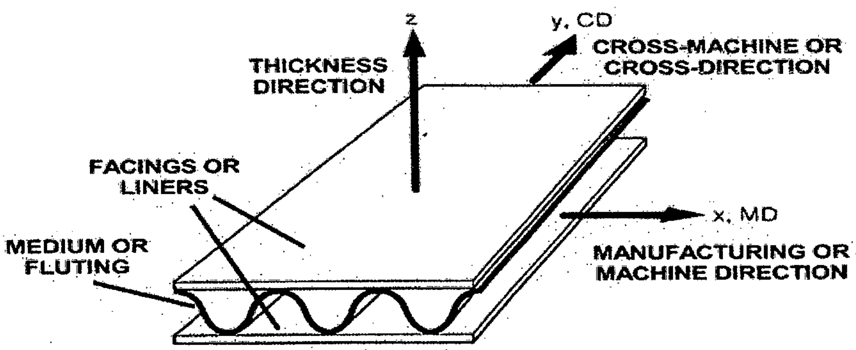


Fig. 7 Corrugated cardboard structure showing the three principal axes. (Adapted from Ref. 17)

1.1.3 Characterization of Corrugated Cardboard

Corrugated cardboard can be characterized by

- Flute geometry
- Linerboard and medium grammage
- Linerboard and medium furnish
- Number of layers

A primary characteristic of corrugated cardboard is the height and pitch of the corrugations of the medium of fluting (Fig. 8). The four most common flute types are described in Table 1.

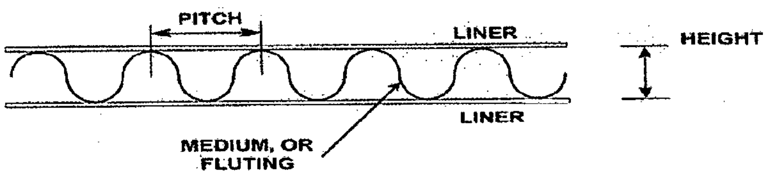


Fig. 8 Geometrical properties of medium corrugations.

The take up factor is a measure of the linear length of the medium per unit length of corrugated cardboard. For example, one meter A-flute cardboard will contain 1.54m of corrugating medium because of the fluted structure. The flutes are lettered in the order which they were introduced.

A- flute cardboard has the greatest thickness and consequently the highest bending stiffness. Because the take up factor is also high, the cardboard has greater resistance to a compressive load applied in the direction of the flute. These two factors combine to give better box compression strength. However, the cardboard is more susceptible to damage during manufacture and service life due to its poor resistance to a load applied perpendicular to the liner surface. The large spacing between the flutes can also lead to problems with flexographic printing.

B- flute cardboard has relatively high resistance to perpendicular loading but lower thickness and bending stiffness and consequently produces boxes with lower compression strength. It is more resistant to perpendicular loading due to the greater number of flutes per unit length, which also yield a smoother surface with better flexographic printability. B-flute uses about 14% less corrugating medium than A-flute due to the lower take up factor.

C- flute was introduced as a compromise between the A and B flutes and has a good balance of the critical properties.

D- flute designation is not assigned to a flute style.

E- flute is not commonly used for shipping containers but the large number of flutes per unit length impart a smooth surface for high quality printing. Consequently, it is used in display boxes where appearance is placed at a premium.

Table 1 Geometrical Properties of the Four Common Flute Profiles

Flute type	Flute spacing (mm)	Flutes per meter	Flute height (mm)	Take-up factor
A	8.3-10	110±10	4.67	1.54
C	7.1-8.3	130±10	3.61	1.43
B	6.1-6.9	165±10	2.46	1.32
E	3.2-3.6	295±15	1.15	1.27

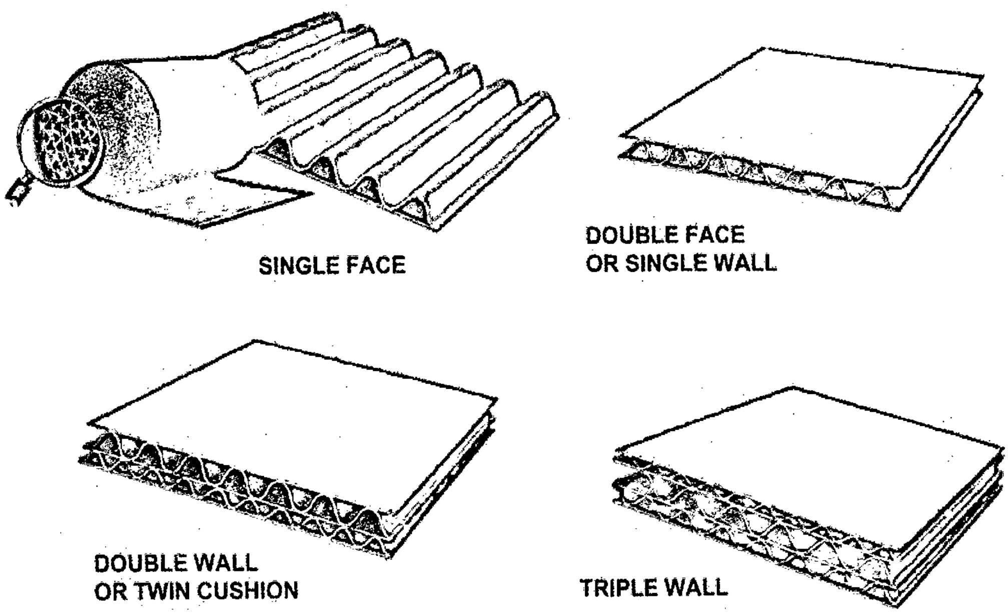


Fig. 9 Layered configurations of corrugated cardboard. (Courtesy Fibre Box Assocation, Rolling Meadows, IL.)

There has been a trend toward smaller flutes station and can run them together to make structures with more than one layer (Fig. 9). Each of the layers, or walls, can have its own combination of flute type, component grammage, and furnish. In 1999, almost 89% of all manufactured corrugated cardboard was single-wall, with 9.5% double-wall, about 1% single-face, and 0.6% triple-wall (source: Fibre Box Association).

1.1.4 Developments in Corrugated Cardboard

There has been a trend toward smaller flutes compare with the established carton-board grades, and the growth in this market was very strong toward end of the 1990s. Mini-flutes are E-flute and smaller variants (Table 2). They are used for packaging where high quality printing is required and structural strength is of secondary importance. In the late 1990s this market was growing by 7% per year and was expected to increase to 10% per year in the early twenty-first century [18].[20]

Table 2 Mini-flute Grades of Corrugated Cardboard

Flute type	Flute spacing (mm)	Flutes per meter	Flute height (mm)	Take-up factor
E	3.2–3.6	295±15	1.15	1.27
F	2.3–2.5	422±15	0.76	1.25
G	1.6–1.8	584±25	0.53	1.2
N	1.8	555±25	0.40	1.2

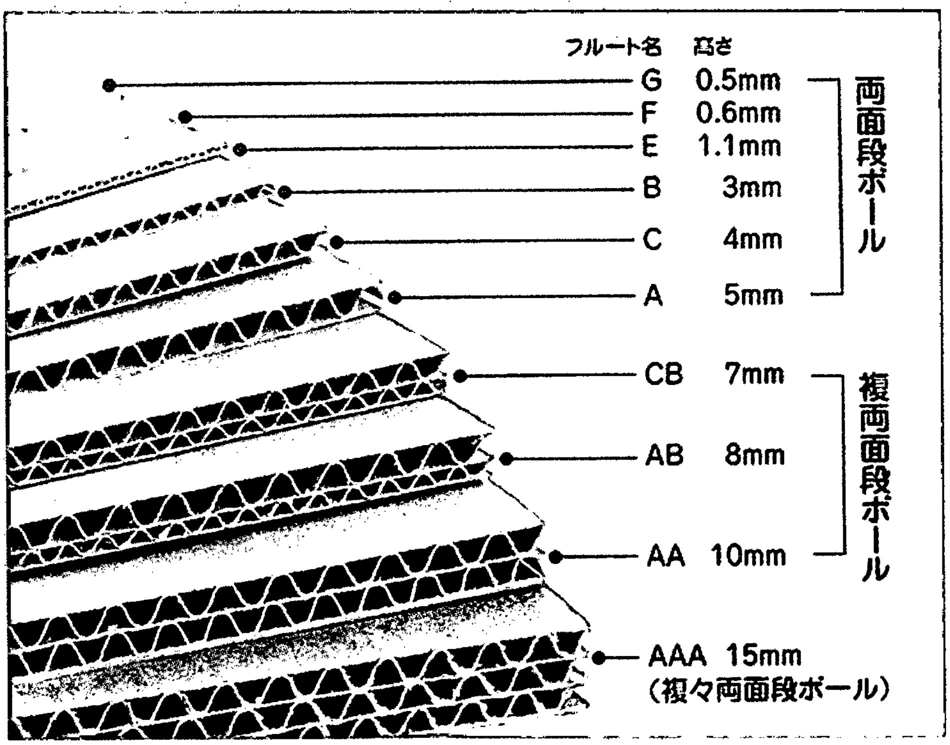


Fig. 10 Type of Corrugated Medium (Ref [19]).

1.2 Research Background

Corrugated medium is made using large corrugation machines. To create corrugated medium, the paper is subjected to high pressure steam, which softens the fibers. The fibers are bent to create the required thickness of flute between the paperboard sheets.

Next, pressure is applied to the top and bottom of the corrugated medium to increase the strength of the material. The flat liner boards are brushed with an adhesive on one side and then the corrugated medium sheet is sandwiched between the two layers of flat liner board. That is inside liner and outside liner. Adequate adhesion between inside liner, outside liner and corrugated medium provide the foundation strength for the usefulness of corrugated cardboard.

1.3 Aim of study

Corrugated cardboard is governed by the strength properties of the corrugated medium, which is determined partly by material properties and partly by geometry. The material properties of influence are basis weight, fiber strength and fiber bonding. Geometry properties of influence here are flute shape and flute size.

This research is concern and focus on introducing new method and measuring the strength of corrugated cardboard due to adhesive bond. Measurement the strength of corrugated cardboard using tensile and shear test provides an important parameter in defining the structural properties of cardboard and for determining the strength of corrugated cardboard panels for end use applications.

1.4 Organization

This study has been organized into four chapters. Each chapter provides the information as follow:

Chapter 1: *Introduction.* We elaborately introduce the general background of corrugated cardboard and describe the problems related to tensile and shear test. Research aim of study is identified.

Chapter 2: *Tensile Test.* This chapter concentrates on introducing the new method of tensile test applied on corrugated cardboard. It also discusses the suitable size and pattern for tensile test using this method.

Chapter 3: *Shear Test.* This chapter concentrates on shear test applied on corrugated cardboard. It also discusses the long life application for corrugated cardboard using shear test.

Chapter 4: *Discussion and Conclusions.* This chapter summarized the major contribution of this research. It then provides recommendations for further studies.

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Chapter 2 Tensile Test

2.1 Background

Current Japan Industrial Standards (JIS) that is related to this study is stated as below:

1. JIS P8113 Paper and board-Determination of tensile properties-Part 2: Constant rate of elongation method [1]. This standard IS only tensile test for liner of corrugated cardboard.
2. JIS K7113 Testing method for tensile properties of plastics. This standard IS only tensile test for plastics.
3. JIS K6251 Rubber, vulcanized or thermoplastics- Determination of tensile stress-strain properties [2]. This IS only to determine the adhesive bond for plastics.

2.2 Aim of Study

Aim of this study is stated below:

1. To introduce a new method that is involved in specimen pattern and size of tensile test apply on corrugated cardboard.
2. To study the adhesive bond on corrugated cardboard using the tensile test.

Fig.1 shows the current problems when tensile test is applied on corrugated cardboard. Problems that have been recognized are as follows:

1. size and pattern of specimen.
2. solves the problem at chuck position.

Fig. 1 Current problems of corrugated cardboard during tensile test (size, pattern of specimen and gripped zone).

2.3 Pre-test

Regarding JIS P8113, the size of specimen had been cut and two rods of aluminum were inserted through corrugated cardboard shows in fig.2. However, the result shows the size and pattern the fracture occurred at chuck position.

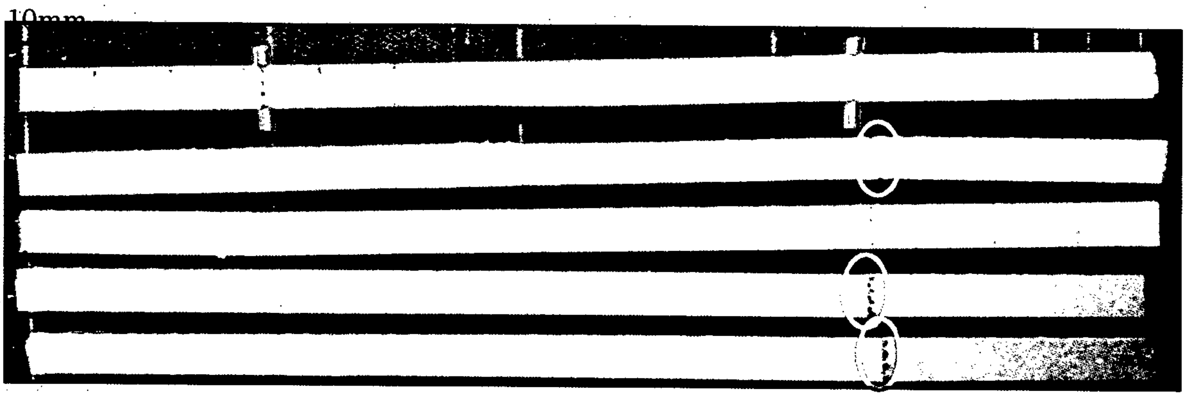

Fig. 2 Result of corrugated cardboard regarding from JIS P8113.

Next, the experiment is done with the same pattern of corrugated cardboard but with shorter length. Thus, five rods of experiment were inserted through corrugated cardboard shows in fig.3. However, the result shows that the fracture is still at chuck position.

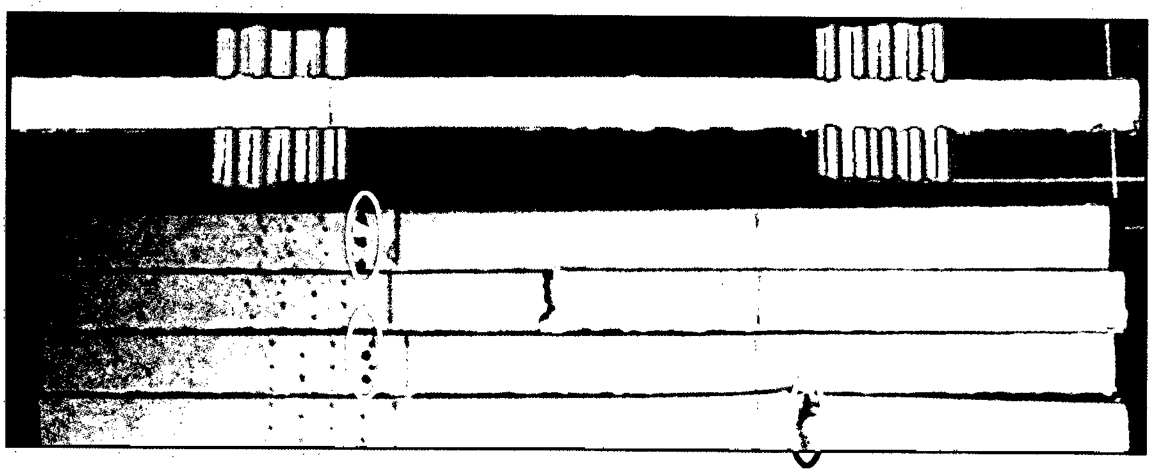

Fig.3 Result for second pre-test.

After that, I tried to change the specimen pattern into dumbbell pattern by using die cutting shows in fig. 4. Unfortunately, the result was devastating. After the die cutting, process the original thickness of corrugated cardboard was damaged (fig. 5).

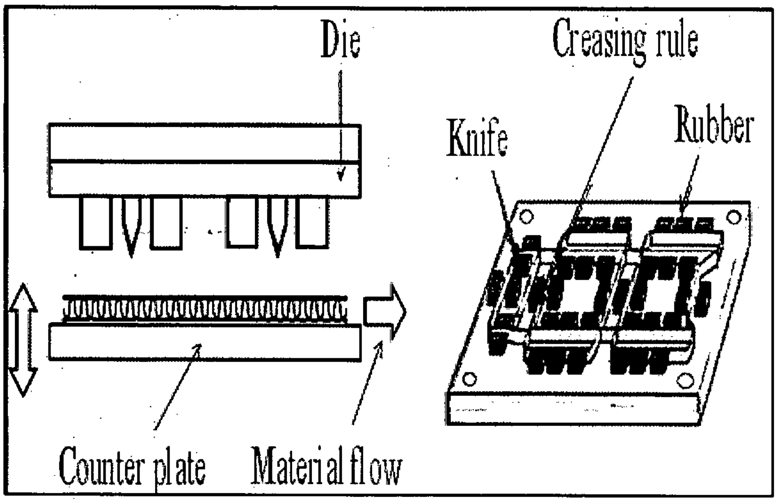

Fig. 4 Die cutting processing

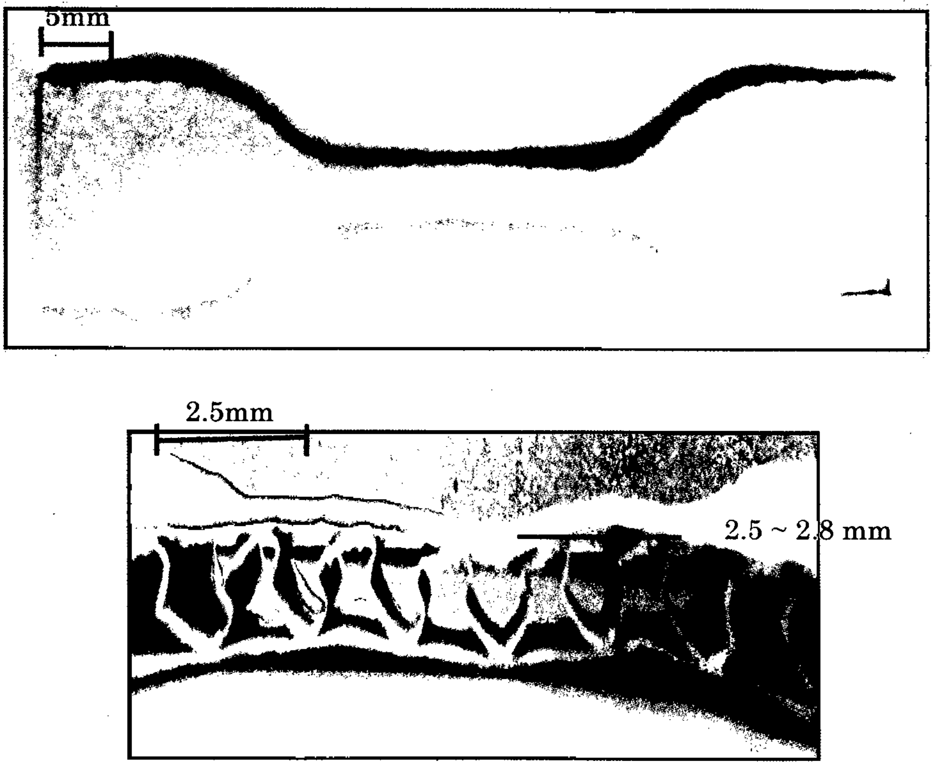

Fig. 5 Result after using die cutting and the thickness of corrugated cardboard after deformed.

A new instrument was designed in order to be used inside INSTRON (2716-015) shows in fig. 6. The result after applying the new instrument in INSTRON (2716-015) is showed in fig. 7. The end result failed to get not a deformed corrugated cardboard.

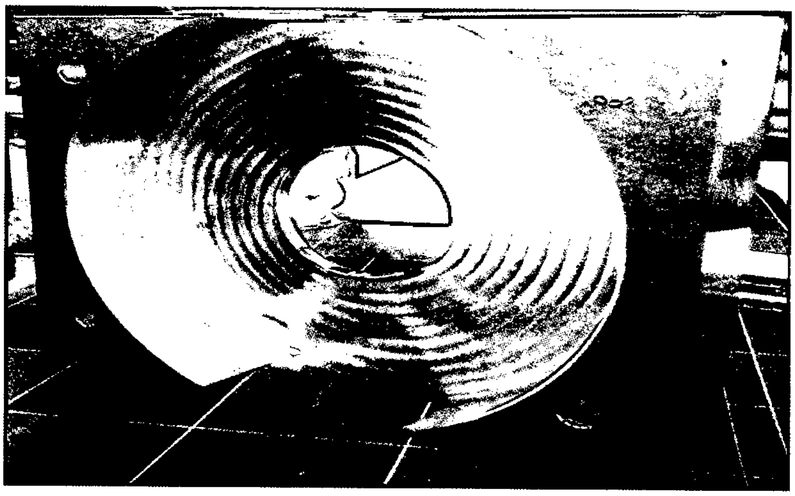

Fig. 6 The new instrument was designed and applied on INSTRON (2716-015).

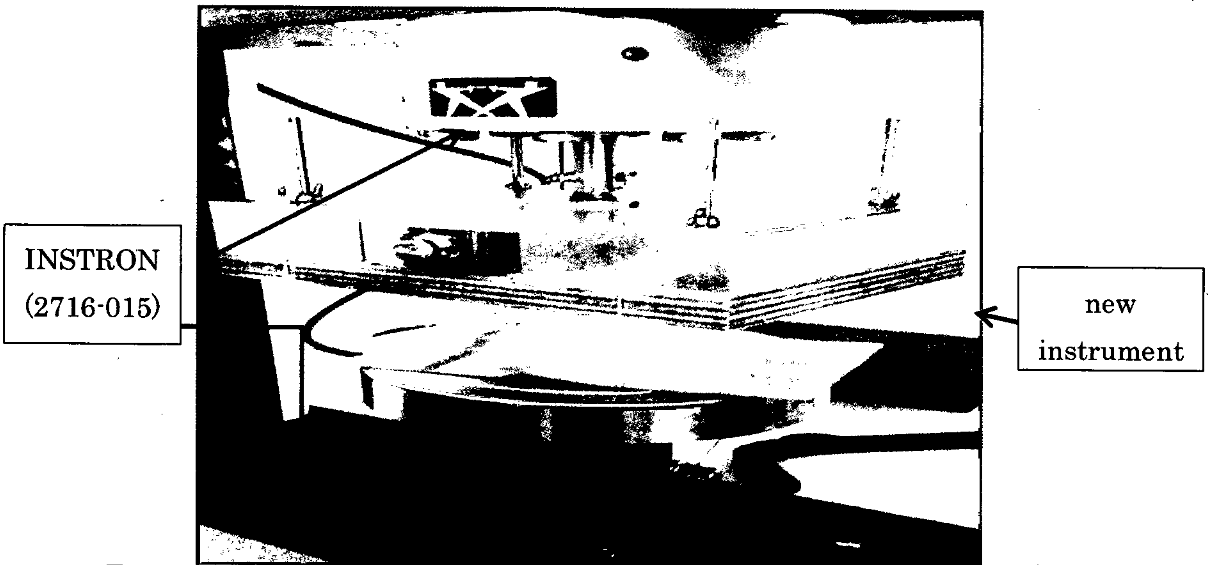

Fig. 7 Result after using new instrument inside INSTRON (2716-015).

In order, to get not deformed corrugated cardboard by using the new instrument, I tried to insert rod of wood and plastic shows in fig. 8. However, by using both materials, it is too hard to be cut by INSTRON (2716-015). The result was devastating

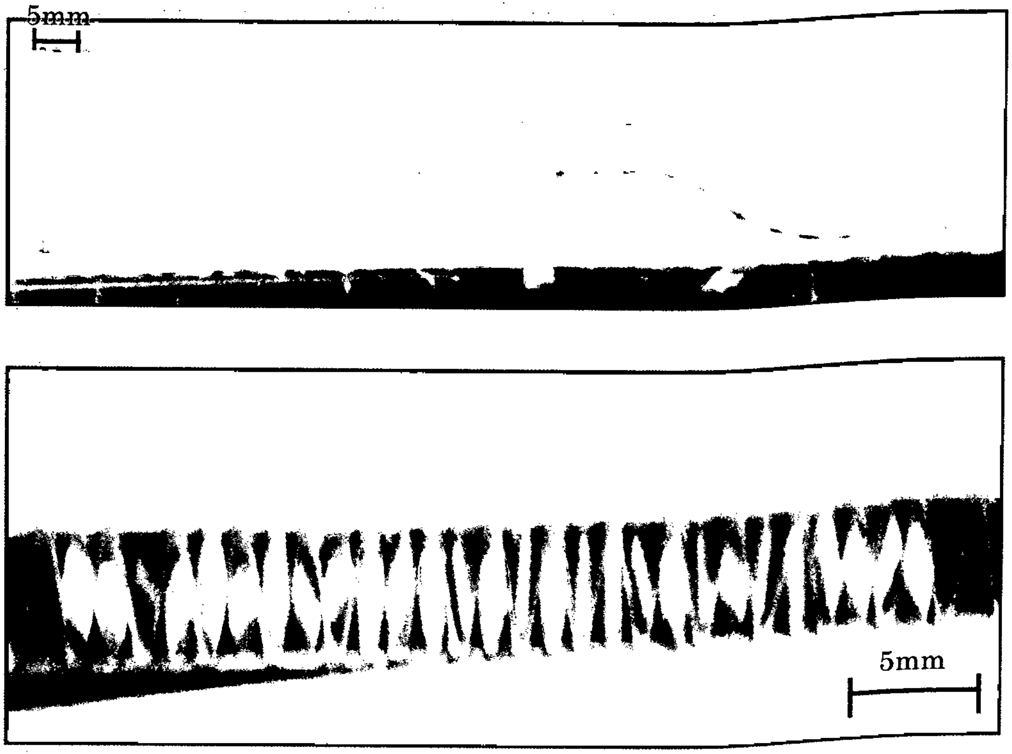

Fig. 8 Result after inserted rods of wood and plastic.

Finally, with the cooperation from Yoshizawa Company the specimen had successfully been cut. By using 3 dimension cutting machine shows in fig. 9.

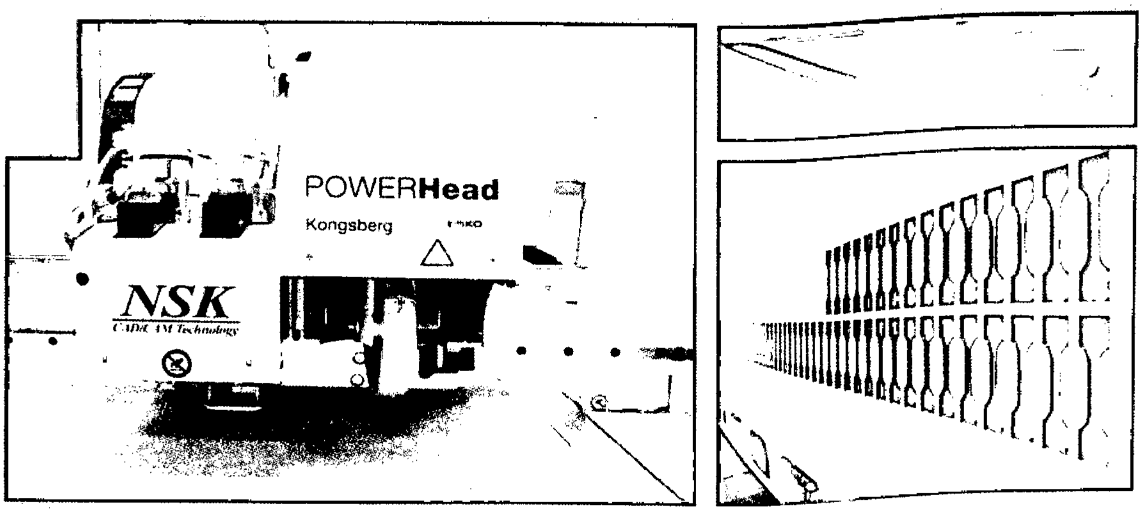

Fig. 9 The 3 dimension cutting machine.

2.4 Method 1

A flute was used as the material. The sectional properties material of A flute is shows in fig. 10.

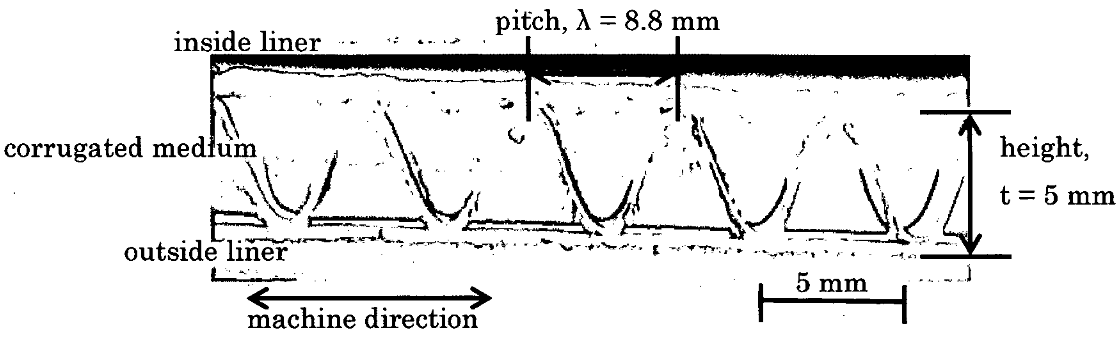

Fig. 10 Sectional properties material of A flute.

2.4.1 Comparison between liner and corrugated cardboard

- □ The corrugated cardboard were been cut into size and pattern shows in fig. 11.
- □ Two rods of aluminum were inserted through the corrugated medium like fig. 11. The size of rod of aluminum shows in fig. 12.
- □ Using INSTRON (2716-015) to make the tensile test for corrugated cardboard (fig. 13). It was repeated for 10 times.

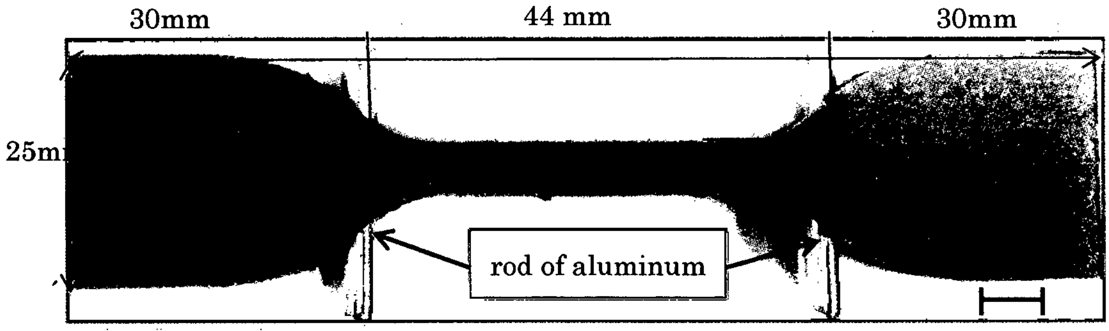

Fig.11 Size of specimen for dumbbell pattern of corrugated cardboard.

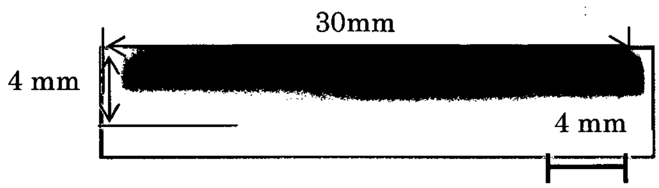

Fig. 12 Size of the rod of aluminum

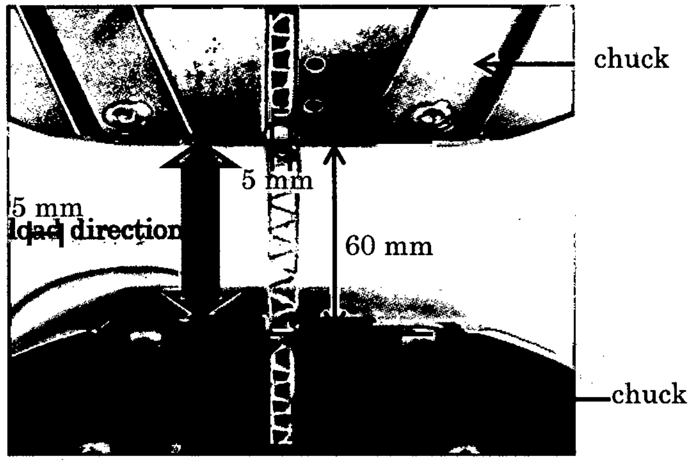

Fig. 13 specimen inside INSTRON (2716-015).

2.4.2 results

Fig. 14 shows the result for 10 times of tensile test on corrugated cardboard. The stress of corrugated cardboard was calculated by eq. 1 for every method.

stress = (load) / (thickness) X (2 liner) eq. (1)

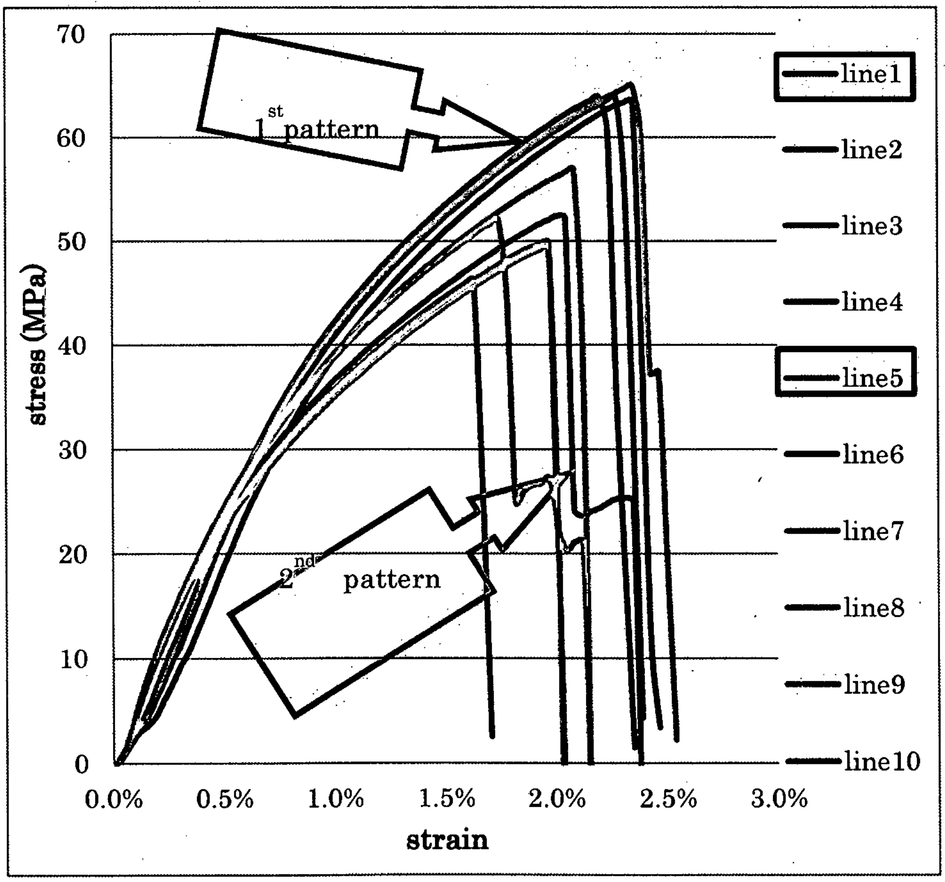

Fig. 14 Result of corrugated cardboard on tensile test

Fig.14 shows that two patterns of graphs were achieved during tensile test on corrugated cardboard. The average yield breaking was 56.3 MPa and the average strain breaking was 1.7%. 1st pattern of graph is without the effect of corrugated medium. 2nd pattern of graph is with the effect of corrugated medium. 1st pattern of graph (fig. 15) and 2nd pattern of graph (fig. 16) shows the detail for every pattern of graph.

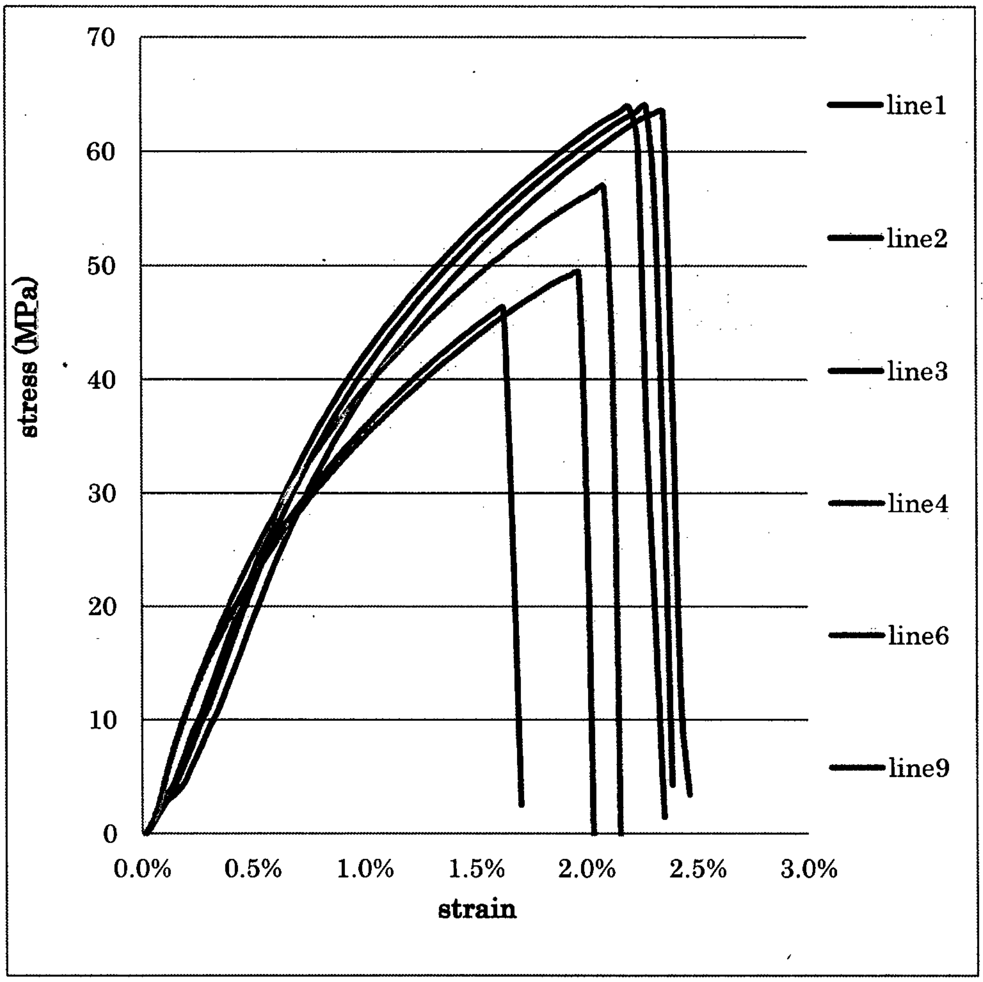

Fig. 15 The result for 1st pattern of graph

From fig.15, the average yield breaking was 57.3 MPa and average strain breaking was 1.8%. 6 among 10 times of result were this pattern.

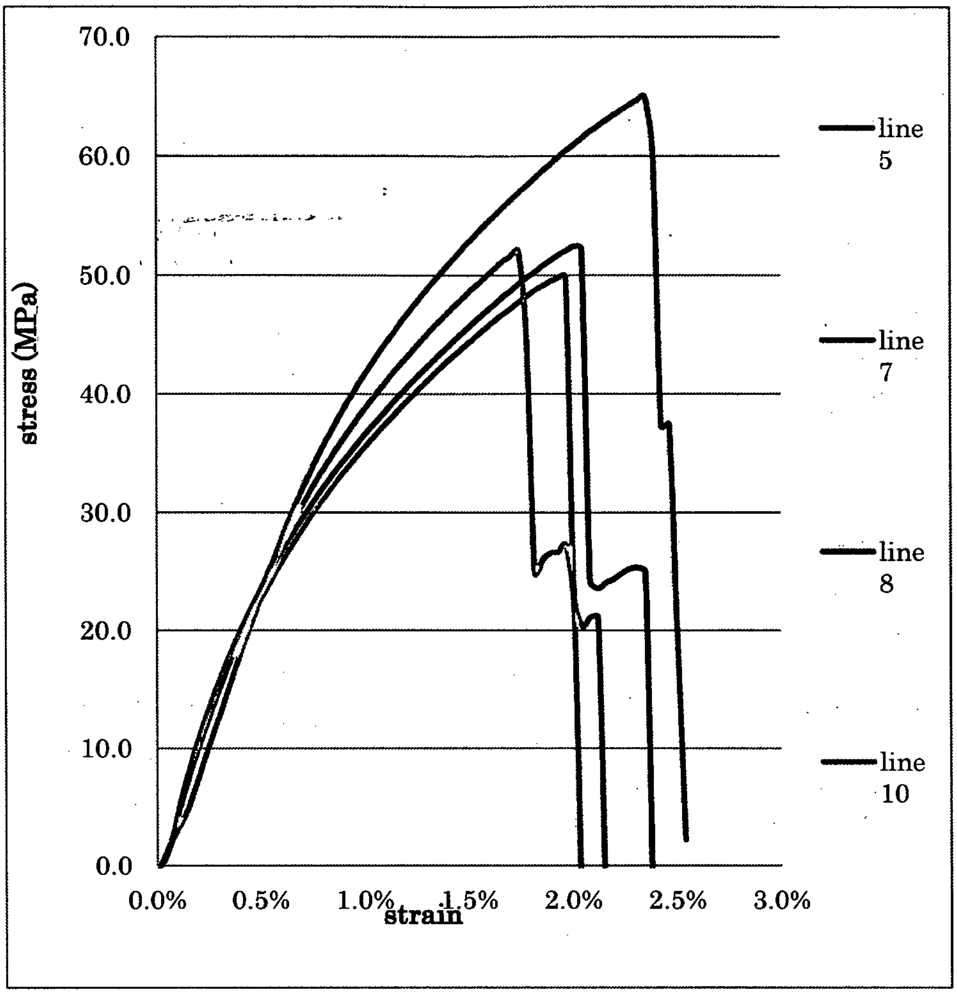

Fig. 16 The result for 1st pattern of graph

From fig.16, the average yield breaking was 54.8 MPa and average strain breaking was1.8%. 4 among 10 times of result were this pattern. This shows that for the average yield breaking the 1st pattern of graph was bigger than the 2nd pattern of graph. However, the average strain breaking for both patterns was the same. Next, fig. 17 to fig. 20 was the result pictures for 1st pattern of graph (line 1) from fig. 15.

Fig. 17 line 1 from right view.

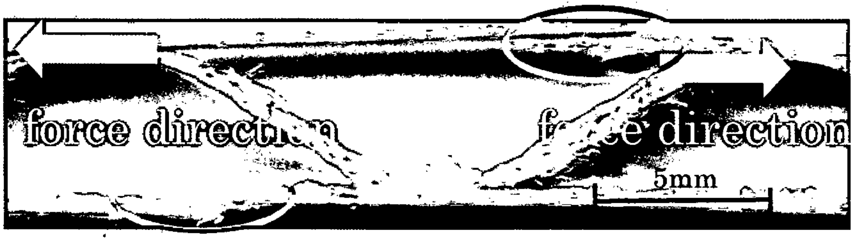

Fig. 18 line 1 from left view.

Fig. 19 line 1 from upper view.

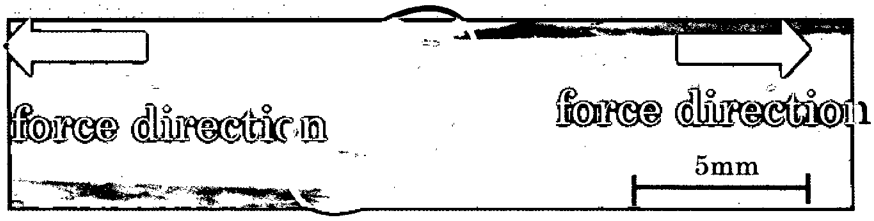

Fig. 20 line 1 from below view.

Fig. 17 and fig. 18 show that the fracture occurred at both; inside and outside liner. Thus both results show that fracture occurred far from the adhesive bond. Fig. 19 and fig. 20 show the result that fracture occurred not in the straight line. This is because the effect of corrugated medium does not appear. This result also shows the same pattern of fracture if we apply tensile test on liner on 45 degree. Fig. 21 to fig. 24 is the result of the pictures for 2nd pattern of graph (line 5) from fig. 15.

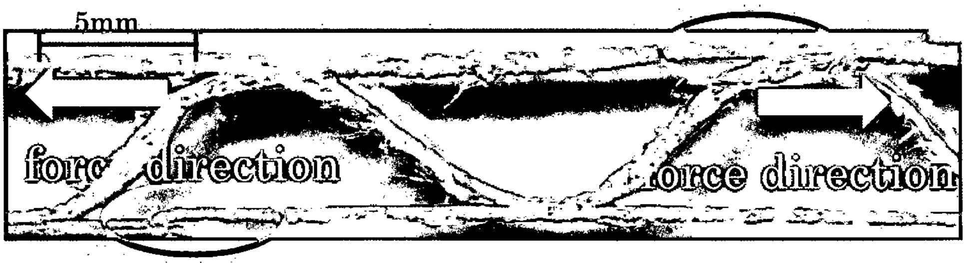

Fig. 21 line 5 from right view.