ANALYSIS OF FILLET FUNCTION IN WOOD-BASED SANDWICH CONSTRUCTION

by

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ABSTRACT

When a porous honeycomb core is glued to plane facings to make a sandwich construction, glue fillets (concave menisci) are formed around the core cell edges. It is known that glue fillets play an important role in strengthening the bond of the construction, but only few studies on the real function of the fillet have been reported. This thesis investigates the relationships between fillet size and bonding strength in sandwich construction followed by a stress analysis of the fillets.

Sandwich panels with various fillet sizes were produced by means of a glue applicator of original design using a modified phenol-resorcinol resin glue, kraft paper honeycomb cores and Douglas fir plywood facings. Tensile strength tests normal to the sandwich specimens of 1 by 1 inch, and flexure tests on the sandwich beams of 3.75 by 12 inches were performed. Fillet rupture sizes and actual fillet dimensions were measured.

A highly significant correlation was found between fillet size and bonding strength. Larger fillets provided greater bonding strength. When a sandwich was subjected to tensile load, a vertical shear failure took place at the center of the fillet concave meniscus regardless of fillet

size. By assuming the uniformity of fillet shape, the following equation:

$$\tau_B = my + d ,$$

was found to express the relationship between the vertical shear stress τ_B at the fracture point B and the fillet height y at B, where m and d were constants. Too large fillets had tendency to form voids or bubbles within them resulting in lowering strength values.

The appearance of fracture in the glueline in flexure test specimens was similar to that in the tensile test. Most of the sandwich specimens with smaller fillets failed in the glueline, while those with larger fillets mostly failed in core shear. This observation also indicated the superiority of larger fillets in bonding of honeycomb-to-plywood. The cause of glueline failure in the flexure test was deemed to result from a complex system of shear, compression and tensile stresses. However, a mathematical expression describing that system of stresses was not found.

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INTRODUCTION

A laminated construction which consists of two facings or covers and a core is generally referred to as a sandwich construction. The sandwich-panel construction that is a lamination of two thin facings with a thick core and designed to give a high strength-weight ratio is called a structural sandwich construction. According to the Standard of the American Society for Testing and Materials (5), a structural sandwich construction is defined as: "A laminar construction comprising a combination of alternating dissimilar simple or composite materials assembled and intimately fixed in relation to each other so as to use the properties of each to attain specific structural advantages for the whole assembly."

The structural design of sandwich construction may be compared to an I-beam in which flanges carry compressive and tensile loads, while the web carries shear loads when the beam is subjected to a bending moment (25, 39). In structural sandwich constructions the facings correspond to the flanges of the I-beam, while the core functions as the web.

Not all sandwich panels are used for structural purposes. Some are simply designed to act as thermal or acoustical barriers, while others may be intended for weather shields or fire walls (21). The major properties of a sandwich panel are determined by the combination of the facing and core materials. In other words, the choice of the facing and core materials for a sandwich-panel construction depends upon the purpose of the panel use.

Wood-based sandwich constructions have found a wide use in house and building constructions taking advantage of good insulation characteristics, relatively low cost and easy processing (22). Plywood, veneer, hardboard and paperboard are suitable for the facings. Balsawood, paper honeycomb, fibreboard and wood excelsior board have been used as the core materials. Various combinations of wood-based and non-wood-based materials, or combinations of two different wood-based materials can produce either structural or non-structural sandwich constructions.

In any sandwich-panel construction, the facing must be attached to the core by means of bonding or other suitable methods. If the joint between the core and the facing should separate, the panel is useless. A strong joint is particularly important for a structural sandwich construction in which the joint must sustain approximately the same shear stress as the core. While soldering, brazing and welding are applicable to produce all-metal sandwiches of exceptional strength and heat resistance, adhesive bonding is adaptable to almost any combinations of materials. In fact, the development of structural sandwich construction may be credited to the rapid advancement in the adhesive technology after World War II.

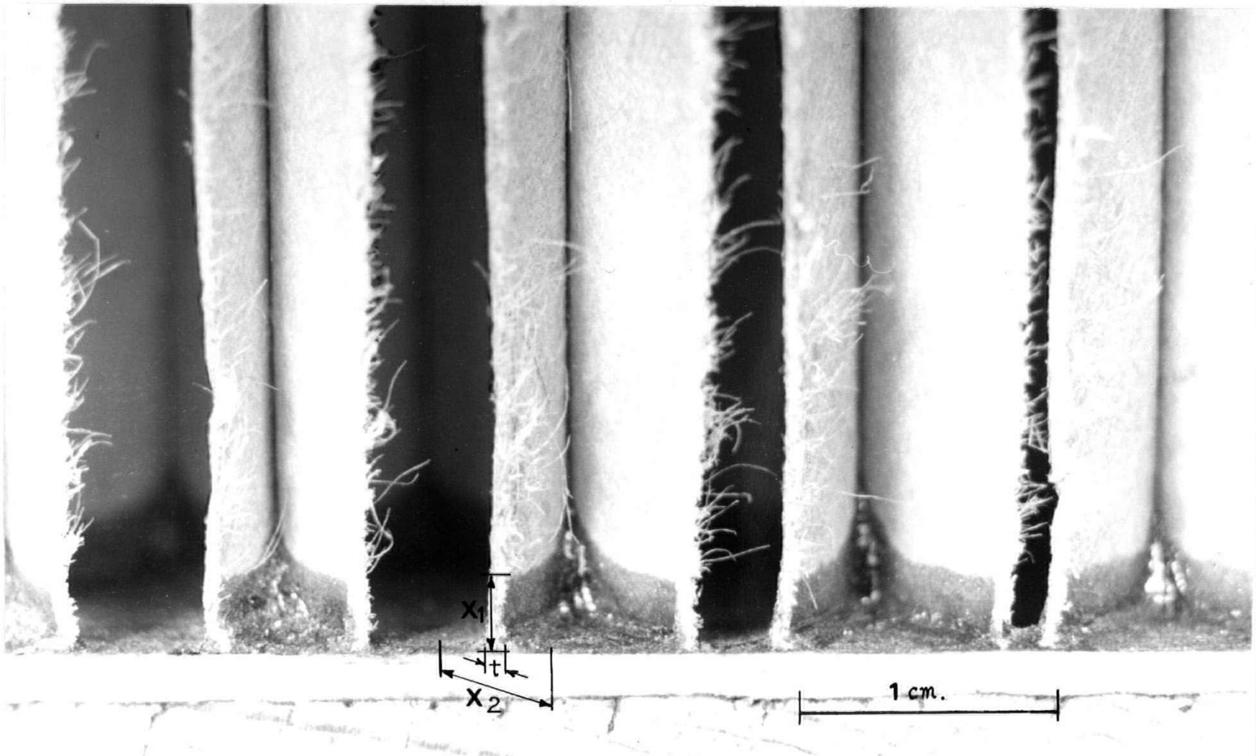
Extensive studies on the structural properties of sandwich construction have been undertaken almost exclusively by the U.S. Forest Products Laboratory for the past two decades (1). The primary objective of these studies was directed towards the application of sandwich construction to aircraft and missiles (16, 17, 26, 28, 30). The Laboratory has published a large number of technical papers on structural sandwich construction, but only a few of the publications have dealt with the relationships between the glueline geometry and the bonding strength.

Recently, the glueline geometry in a sandwich construction has drawn some researchers' attention (11). The recognition of the importance of glueline geometry might have arisen from the practices of efficient use of a given adhesive rather than inventing new adhesives. Under such circumstances, it was found that the most efficient glueline in a sandwich construction should form a "fillet." A fillet, or glue fillet, may be defined as: the glue body that is filling the corner between the core cell wall and the facing (Figure 1). The size and shape of a fillet varies with the type of core cell and the adhesive used. The core cell, in this context, implies small pores of continuous cores, such as balsa, foamed rubbers, and foamed resins, as well as cells of open-celled or gridded type cores such as honeycomb (8).

The main objective of this thesis will be to analyse the fillet function in wood-based sandwich construction in terms of the relationship between glueline geometry, or fillet size, and bonding strength. For this purpose, kraft paper honeycomb was chosen for the core material since its uniformity of cell shape and size simplifies the measurement of fillet size. Plywood was chosen for the facings because it has practical construction applications.

Since fillet shape depends upon glue flow characteristics and the surrounding conditions, the application of several adhesives would induce difficulties in comparing one glue fillet to another. The comparison of filleting effects with glue variations is recognized as a variable of great interest, but was beyond the immediate scope of this study. The sample panels were made with only one kind of adhesive, namely a modified phenol-resorcinol resin adhesive which was easy to handle and sets at room temperatures of 70°F.

In order to test filleting effects on bonding strength, two commonly employed testing methods were called for. Those were "Standard Method of Tension Test of Flat Sandwich Constructions in Flatwise Plane (ASTM Designation: C297-61)" and "Flexure Test of Flat Sandwich Constructions (ASTM Designation: C393-62)." The former covers the procedure for determining the strength in tension flatwise of the bond between core and facings of an assembled sandwich panel. The expression, "tension flatwise," means tension normal to the plane of the sandwich (8). The latter covers a procedure for determining properties of flat sandwich constructions subjected to flatwise flexure in such a manner that the applied moments produce curvature of the plane of a sheet of the sandwich construction. This test may be primarily conducted to determine flexural and shear modulus, and shear strength of the core, or compressive or tensile strength of the facings. However, the test to evaluate core shear strength may also evaluate bonds between core and facings inasmuch as core shear stress values may be lower than actual core shear strength, thus indicating that failure initiated in the bond (4).



X = Fillet height, X = Fillet width, t = Honeycomb wall thickness

Figure 1. Fillets

LITERATURE REVIEW

Hundreds of publications on sandwich construction have been issued,mostly by the U.S. Department of Agriculture, during the past quarter century (16, 17, 24, 26, 27, 28, 30, 38, 42). These publications cover almost all aspects on sandwich construction including the problems of adhesives, cores and testing methods as fundamental studies on mechanical properties. In these series of publications, however, nothing has been mentioned about fillet effects in bonding a porous material like a honeycomb core to another material.

It is not clear when importance of fillet was first recognized, but it seems that the problem was brought up originally in the sandwich panel industry. In 1957, Manning (10), answering a question about application methods of contact type adhesives, mentioned from his experience that he would prefer a spray application to the roller coat for the purpose of building up a fillet on the top edge of the honeycomb core. Although it was not described why a spray application built up a better fillet than a roller coat and what the fillet was like, he explained that formation of this fillet had a very important function or requisite in adhesive performance, because it increased the area of contact, particularly when a contact type glue was used.

Gathering data on sandwich construction, Humke (20) presented a selection guide for sandwich panel materials, in which he pointed out that epoxies and vinylbutyral phenolic adhesives had self-filleting characteristics, while elastomer modified phenolic, neoprene-rubber base, nitrile-rubber base and polyvinyl acetate adhesives had no self-filleting properties. He described that self-filleting or beading was extremely important in honeycomb sandwich, for the bead that clung to the edge of each cell flowed into a firm double fillet when the facing was pressed in place, resulting in added bond area and a stronger structure.

A further discussion about the importance of filleting was presented by Houwink and Salmon (19). "In the most common case, we have a thin foil edge, 0.03 mm., at right angles to cover plate. This core foil edge represents only 1/200 of the total facing material area, yet must resist the same shear stresses as the core. The most efficient adhesives for this application form a fillet, a concave meniscus, between the face sheet and the honeycomb cell wall. Such adhesives become liquid in the curing operation, form the fillet by capillary action, and proceed to cure to a solid state. Those adhesives which do not become truly flowable during curing, are placed in a solvent solution, and roller coated, dipped, or sprayed onto the core to aid formation of fillets."

Recently, Dietz (12) suggested that it was preferable to coat the inner side of plywood faces with glue in addition to applying glue to the core for best results in bonding honeycomb core to plywood skin. He also proposed that it was wise to coat the plywood very lightly and to apply most of the adhesive to the core both for economic reasons and in order to save weight. This is, according to Dietz, the efficient way of making a good fillet with the minimum amount of adhesive.

Grimes (15) studied the effect of filleting on the core properties. First, he made a comparison between two different adhesives on the shear strengths of small and medium fillets. The small fillet (0.09 lbs. per square foot) of modified epoxy adhesive gave the core less "effective strength" and "effective stiffness" than the medium epoxy-phenolic fillet (0.135 lbs. per square foot). This type of comparison, as he recognized, may be unfair in that if the former adhesive were increased in weight to that of the latter, it might possibly provide as good or better filleting and core properties. Comparisons were also made for beam shear, drum peel, and flatwise tensile strengths between two different adhesive weights using the same adhesive. In every comparison the increase of glue weight resulted in the higher strength. Conducting some other experiments, he confirmed that the weight of adhesive within each type was not so important as the fillet size.

Grimes concluded that the fillet size was the most important physical factor in obtaining the maximum strength properties of honeycomb cores and sandwich constructions.

As for the fillet size and actual stresses at the fillet, Grimes assumed that:

(a) stresses occur in a plane perpendicular to the cell wall at approximately its edge,

(b) that the width of the fillet stress plane is a function of cell size and fillet size,

(c) that the length of the fillet plane is equal to b, the cell wall flat width,

(d) that the fillet stress plane total width is

(LF) large fillet r/2
(MF) medium fillet r/3
(SF) small fillet . . . . . r/4, and

(e) that the fillet stress plane area for each flat then becomes

$$\text{(LF)}; \quad A_{fp} = b\ r/2 = r^2 \tan 30° = 0.577r^2$$

(square inch)

$$\text{(MF)}; \quad A_{fp} = b\ r/3 = 0.384r^2$$

$$\text{(SF)}; \quad A_{fp} = b\ r/4 = 0.288r^2,$$

where r is the radius of the inscribed circle of a cell. According to his explanation the flatwise tensile load from the cell wall to the adhesive is passed via shear, and this load then must be transmitted to the face through the fillet plane by tension.

Timoshenko and Goodier (37) have shown the stress distribution pattern at the fillet of a metal plate by the photoelastic method. Although the fillet they showed was not that of the glueline in sandwich construction, the following discussion provides useful suggestions for the study of fillet size and function. These workers confirmed that the maximum stress occurred at the end of a plate of two different widths submitted to centrally applied tension. The ratio of this maximum stress to the average stress in the narrower portion of the plate is called the "stress concentration factor." It depends on the radius R of the fillet to the width d of the plate. Several values of the stress concentration factor obtained experimentally (40) are given in Figure 2. It is seen in the figure that the maximum stress is rapidly increasing as the ratio R/d is decreasing. When R/d = 0.1 the maximum stress is more than twice the average tensile stress.

Investigating ten methods of inspecting bonds between the cores and facings of sandwich panels of the aircraft type, Heebink and Mohaupt (16) reported that none of the tests investigated presented practical and dependable means of inspecting sandwich panels for quality of joints. It also appeared that any combination of these test methods would offer little promise of improvements. These are: (1) visual inspection, (2) special lighting, (3) tapping, (4) supersonic inspection, (5) exposure to vacuum,

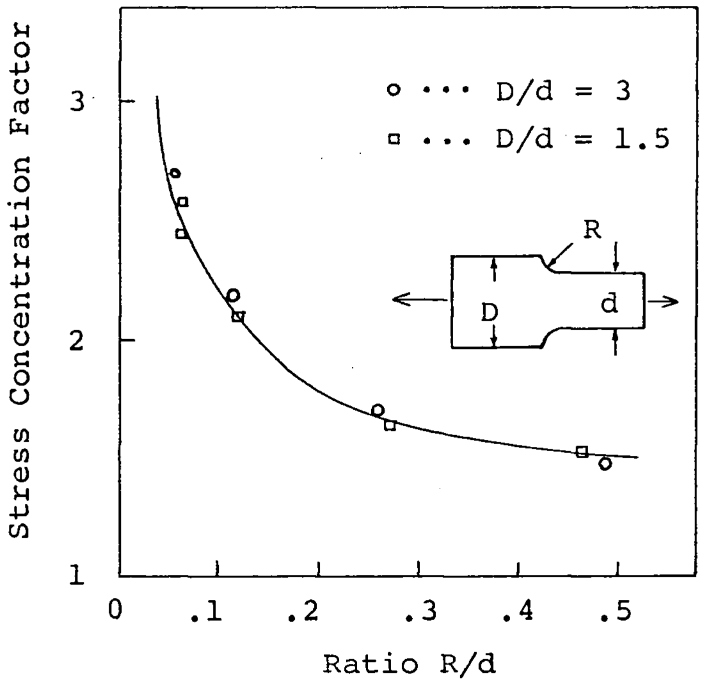


Figure 2   Stress Concentration Factors in Tension

From S. Timoshenko and J.N. Goodier, "Theory of Elasticity," 2nd Ed.

(6) vacuum-cup test, (7) internal pressure test, (8) heating complete panel, (9) local heating, and (10) button-tension test. Heebink and Mohaupt concluded that carefully controlled process specifications, substantiated by sufficient number of destructive tests and supplemented by rigid inspection must be relied upon to insure uniformly high-quality joints in sandwich panels.

Eickner (13) carried out flatwise tensile tests to evaluate the durability of the glue joints in aluminum and end-grain balsa sandwich construction. The principles of the test method and testing apparatus were later employed in the ASTM Designation C297-52 (revised in 1961).

For fabrication of the tension and shear specimens of plywood-faced sandwich panels, the U.S. Forest Products Laboratory (38) recommended the use of room temperature setting resorcinol resin adhesives which should always be applied to both surfaces of the glue joint. Intermediate temperature setting phenol resin adhesives were also recommended if shorter pressing periods were desirable. Further details about specimen size and loading methods proposed in the report were the same as those which were later taken up in the ASTM standard methods (7, 8).

According to Kuenzi (27) the best loading method in flexure test is to apply the concentrated load at the quarter-span points on a beam simply supported at the supports. The reason given is that the maximum moment and the maximum shear stress induced in the beam loaded at the quarter-span points are equal to those induced in the beam on which the load is uniformly distributed. This is easily proved by elementary mechanics. The single concentrated loading at the mid-span of the beam is the simplest way of applying the load. But, this loading produces stress concentration at the loading point as much as twice the corresponding stress concentrations at the supports. Hence, it may happen that the single concentrated loading method cannot detect a fault which is located near the supports (27).

In order to evaluate the shear strength of the core-to-facing bond, however, the abovementioned two-point loading is not appropriate (19). It is known that the central portion between two loading points is not subjected to shear stress. That is, if quarter-span point loading is employed, the glueline shear strength of one half of the span cannot be tested. Houwink and Salmon (19) stated that the usual method of testing the sandwich bond strength in shear is to load a short sandwich beam specimen under three-point loading (i.e. mid-span loading) and to calculate the shear strength from the failing load using the simple beam theory. This method is applicable when the compressive or tensile strength of the facing is not less than the glueline shear strength. If the facing cannot withstand the applied load and if it fails in flexure before failure takes place in the glueline, the strength of the core-to-facing bond cannot be evaluated.

The conventional overlap shear test used to evaluate structural adhesives is not appropriate to measure the strength of adhesive to fillet in sandwich construction (19). In order to evaluate adhesives for bonding core to facings, sandwich panels should be prepared. Following this, the shear strength of gluelines as well as the ability of the total structure to carry a load is determined in beam flexure tests (34). Additional adhesive strength values are obtained from flatwise tensile tests.

MATERIALS AND METHODS

Since the objective of this thesis is to investigate the relationship between fillet size and bonding strength, fillets of different size must be prepared. Variation of fillet size can easily be generated by dipping the edge of the honeycomb in uniformly spread glue layers of various depths. After being dipped in the glue, the honeycomb is placed on the facing and left under the correct pressure until the glue hardens. In the meantime, the glue flows and forms a fillet. From the preliminary experiments it was learned that lateral glue flow on plywood was not satisfactory for making a good fillet. Therefore, in the main test all of the inner sides of the plywood facings were lightly coated with thinned glue of the same type to let the glue on the core flow onto the plywood. The same procedure was followed for the other side of the core and, thus, a sandwich was produced.

Construction of Glue Applicator

In order to produce uniform glue layers of various depths, several methods of making uniform layers of paint and similar materials were explored (2, 3, 6, 32, 33). A TLC coating unit for chromatography was also tried. All of these were designed to meet the requirement of making a uniform layer only once on a particular plate or a sheet. For the purpose of making a uniform glue layer on one plate repeatedly so that a specific glue height could be transferred to the honeycomb core at each application, the above-mentioned apparatus was found to be inconvenient. Consequently, a simple, yet efficient glue applicator of original design was contrived for this experiment.

This glue applicator consists of a set of doctor blades and a base plate (Figures 3, 4). The base plate is a flat plate which is made of a laminated plastic sheet glued on a one-inch-thick plywood sheet with two-stepped side rails fixed on both longitudinal edges of the plate. The side rails are made of laminated plastic strips. The thickness of one step of the rail is that of the laminated plastic strip and actual thickness is 1.4 mm. The doctor blades are ruler-like steel bars and have straight edges. There are four doctor blades prepared so as to produce four different depths of the glue film. Two of the doctor blades have a length that can bridge the lower steps of the side rails across the plate. The other two blades are extended in length to bridge the upper steps. One of the blades of each length is notched at the edge on both ends so that the clearance between the blade edge and the plate bed produces a half thickness of one step of the rail (Figure 4, A) or one-and-one-half thickness of the step (Figure 4, C).

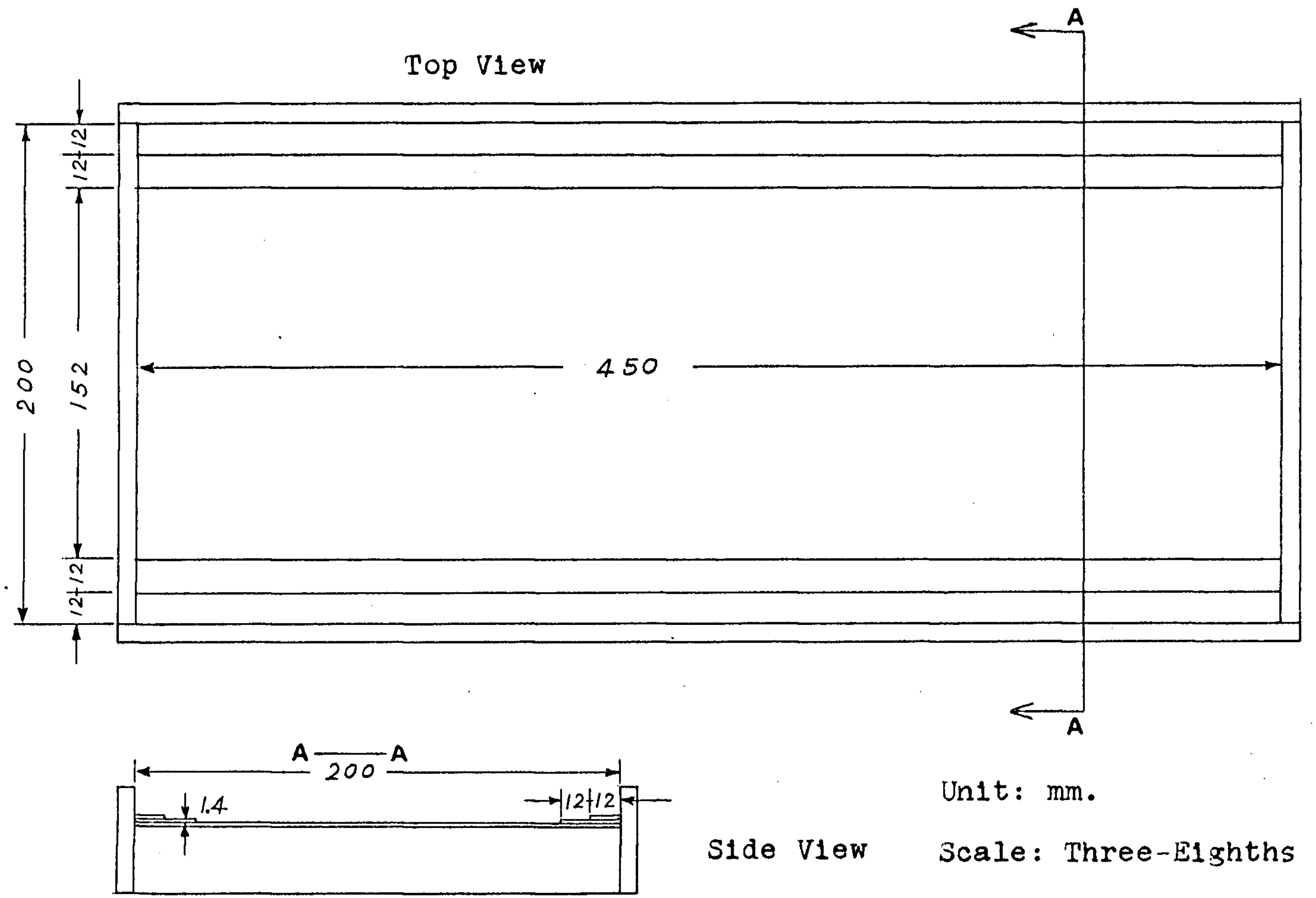


Figure 3. Glue Applicator -- Base Plate

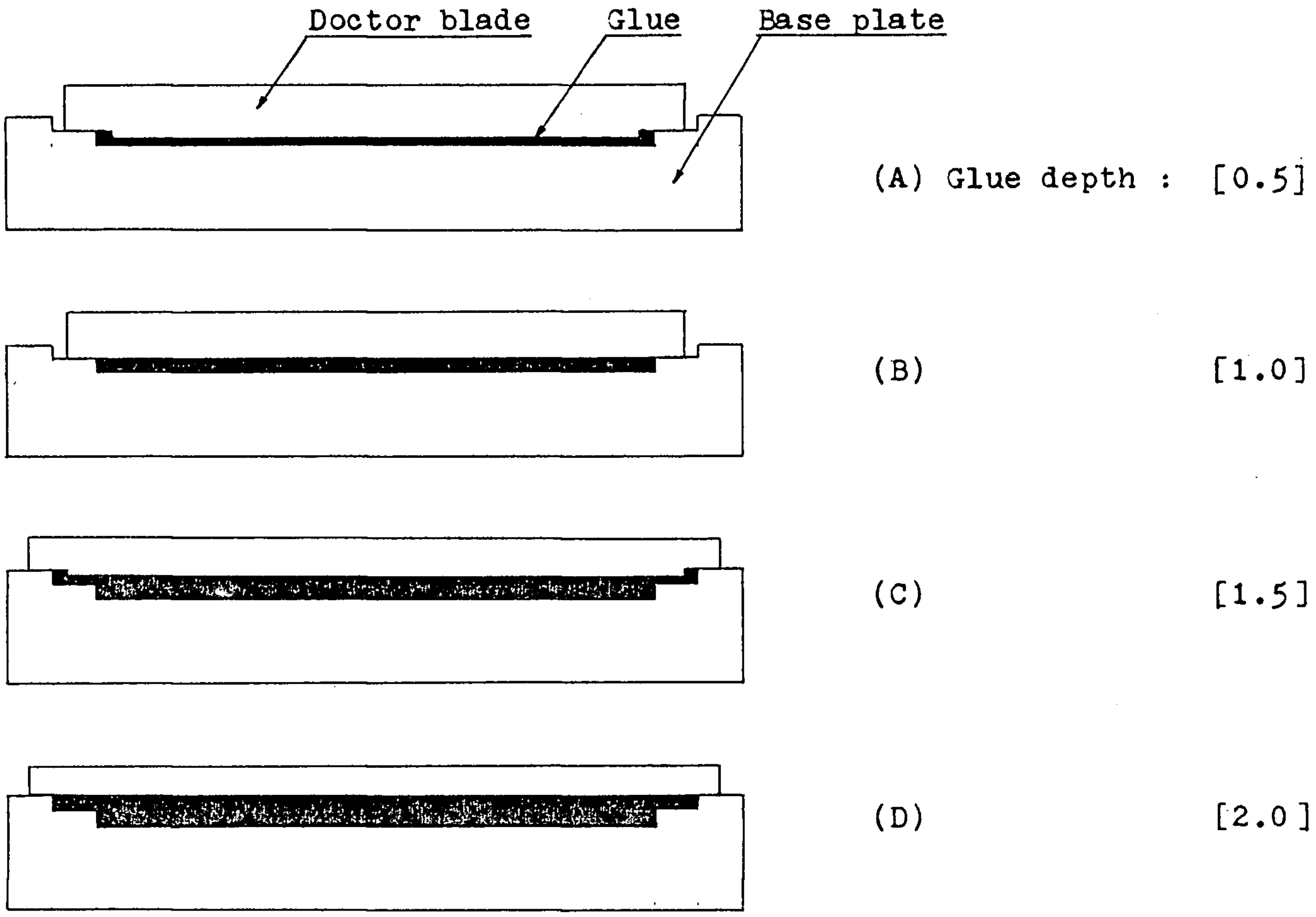


Figure 4. Glue Applicator -- Four Doctor Blades

In order to make a uniform glue layer on the plate, the doctor blade is moved by hand from one end of the plate to the other sliding on the side rails. The clearance between the blade edge and the plate bed controls the glue depth, for the blade edge scrapes off the excess glue poured on the plate and levels the glue layer. The glue depth produced by a half step clearance was referred to as [0.5]. Similarly, the glue depths produced by one step, one-and-one-half step, and two step clearances were referred to as [1.0], [1.5] and [2.0], respectively. These numbers enclosed in brackets are the names of glue depth treatments, and represent neither actual glue depth nor ratios. These symbols were also used for expressing the fillet height groups. For example, the fillet height group [1.0] means those fillets which were made by the glue depth treatment [1.0].

Materials

Facing	Douglas fir plywood; 1/4 inch thick, sanded, good one side.
Core	Kraft paper honeycomb; Hexcell, HNC 3/8 - 80 (18) E, 1 inch thick, 3/8 inch cell size (Figure 5).
Adhesive . . .	Modified phenol-resorcinol resin glue; Pacific Resins, Resorsabond 2600.
Catalyst . . .	Pacific Resins, Parac CR 40.

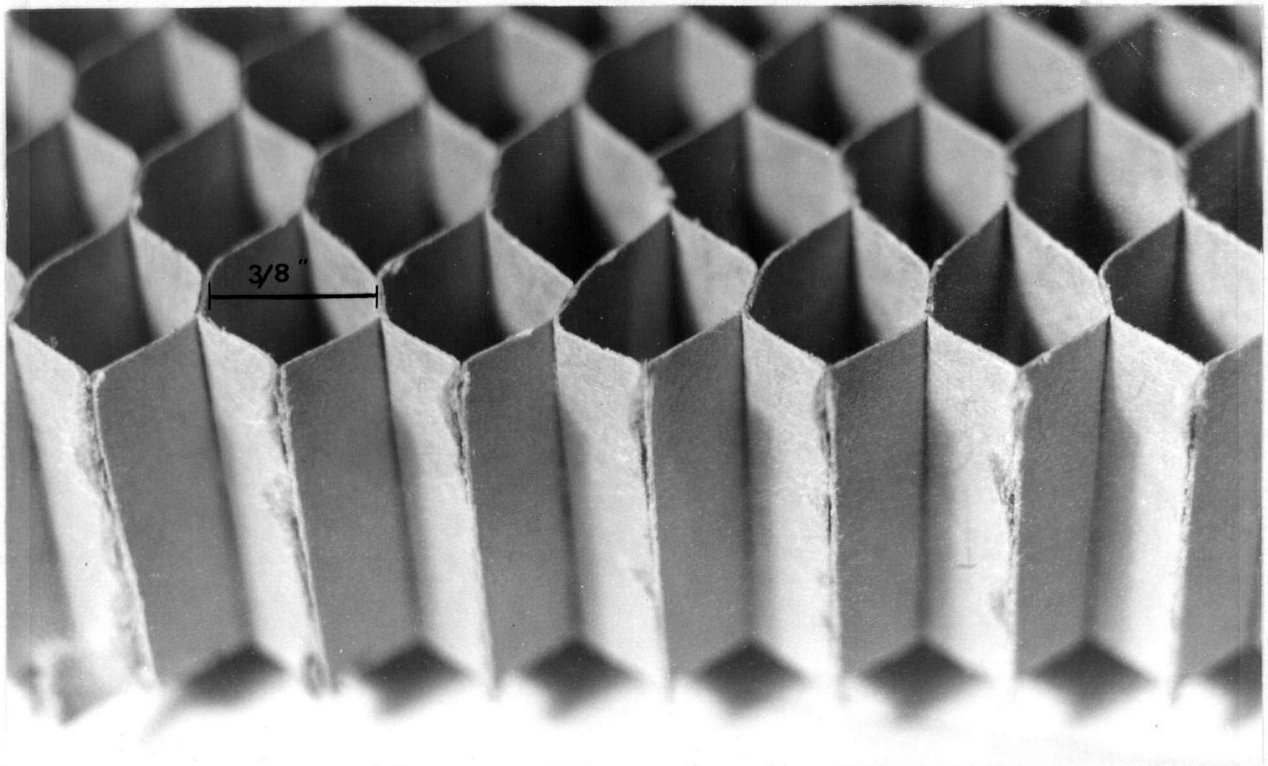


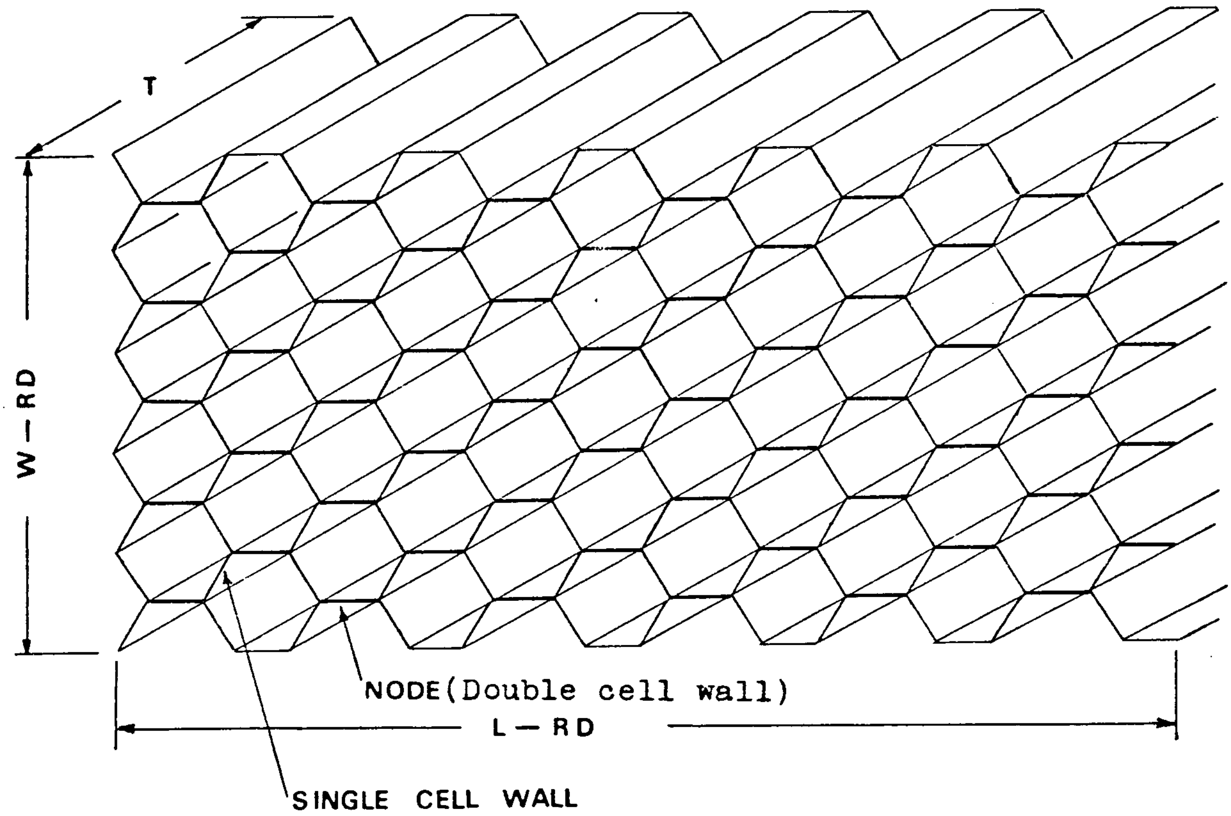
Figure 5. Kraft Paper Honeycomb

Preparation of Sandwich Panels

Plywood was sawn into rectangular pieces of 4 by 14 inches with the face grain direction parallel to the longer dimension. Honeycomb was cut into similar size as the plywood with the transverse ribbon direction (Figure 6) parallel to the length. The sawn plywood and the honeycomb pieces had been kept under the condition of 70 ± 1°F and 50 ± 1% humidity for more than two weeks before they were glued. Prior to bonding the core to the facing, the sanded face of plywood was wetted by brushing it with thinned glue (the mixture of phenol-resorcinol resin, catalyst and water in the ratio of 10:1:5 by weight). The mean coverage was 6.3 grams per square foot in the thinned form. This figure was obtained empirically by a preliminary test.

For the gluing of core-to-facing, the mixture of 10 parts of phenol-resorcinol resin and 1 part of catalyst by weight was used. Twenty-two honeycomb cores for each of the four glue depth treatments were applied with glue by dipping the core into the glue layer until the core edge touched the plate bed. After remaining in the glue for about three seconds the core was carefully pulled up and then placed on a pre-wetted plywood.

Following each application the necessary amount of glue was added to the applicator so that original glue depth was restored. The semi-assemblies of the core and one facing were stacked in such a manner that the core was placed



L - RD = Longitudinal ribbon direction

W - RD = Transverse ribbon direction

T = Honeycomb thickness

Figure 6. Dimensional Nomenclature of Expanded Honeycomb

above the facing and pressed under approximately 50 psi. for more than 12 hours at room temperature. After removing the pressure, these semi-assemblies were treated with the same depth of glue on the other edge of the core. The glue-treated semi-assembly was then placed on a pre-wetted plywood making a sandwich, and pressed in the same way as before. Thus, a uniform fillet shape on both edges of the core was achieved by avoiding the interfering effects of gravity.

Tensile Test Specimen and Test Procedure

Ten test specimens for one fillet height group were made from two randomly chosen sandwich panels by cutting five 1 by 1 inch specimens from one panel. A loading block made of 1 by 1 by 1 inch Douglas fir wood was bonded to each face of the specimens using the same adhesive as in the core-to-facing bonding. The test specimens were subjected to 70 ± 1°F and 50 ± 1% of humidity for more than ten days before the initiation of testing procedures.

The loading fixture was made to meet the recommendation given in the ASTM Designation C297-61 (Figure 7). A Tinius Olsen universal testing machine was used to apply a load to the specimens at a constant rate of base movement of 0.02 inch per minute. The maximum strength in tension flatwise, the percentage of facing failure and the fillet size were recorded. Fillet size was measured by vernier calipers

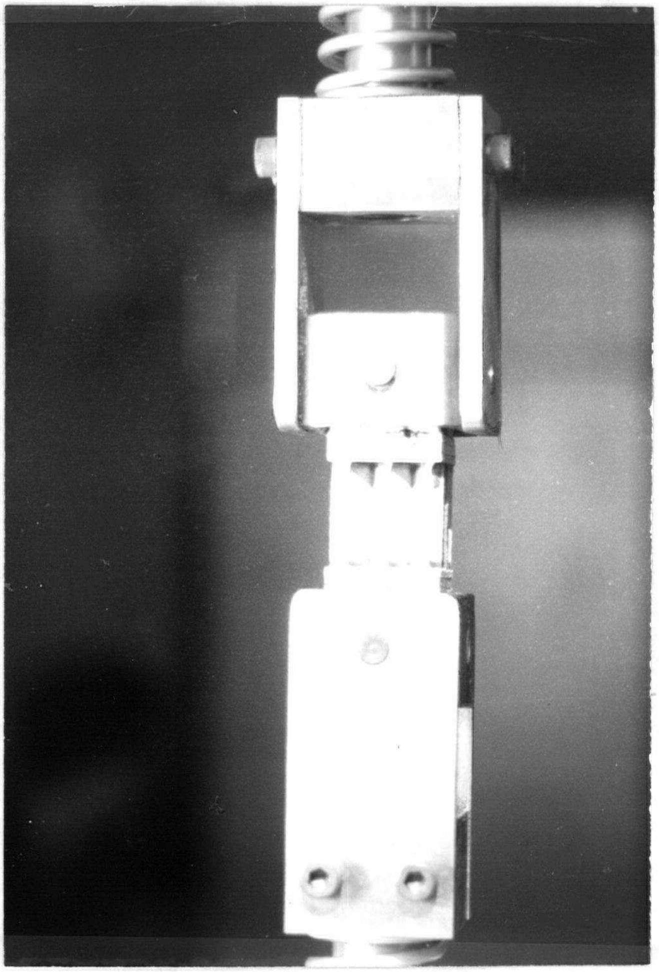


Figure 7. Tensile Test Specimen in Loading Fixture

for the fillet height and width at four random points on the failed side of each specimen after separating the facing from the core. The measurement of fillet width was made for the total width around a single cell wall including the cell wall thickness. Facing failure was expressed by the percentage of the area exposed where the facing plywood was stripped off (maximum of one-ply deep) to the whole facing area.

In order to obtain the strength of adhesive fillet per unit fillet length the ASTM Designation C297-61 (8) is called for.

$$\text{Strength of Adhesive Fillet} = \frac{\text{Flatwise Tensile Strength}}{\text{Fillet Length/Unit Core Area}}$$

where fillet length per unit core area can be found by consideration of the core cell geometry. For cores with hexagonal or square cells it has been found that fillet length per unit core area equals four divided by the cell size.

Proof for a hexagonal cell:

Let the length of a side of hexagon be b (Figure 8), then

Core Cell Size = $\sqrt{3}\,b$, and

Core Cell Area = $\frac{3}{2}\sqrt{3}\,b^2$. Therefore,

$$\text{Fillet Length per Unit Core Area} = \frac{\text{Fillet Length}}{\text{Core Cell Area}}$$

$$= \frac{6b}{\frac{3}{2}\sqrt{3}\,b^2} = \frac{4}{\sqrt{3}\,b} = \frac{4}{\text{Core Cell Size}}\ .$$

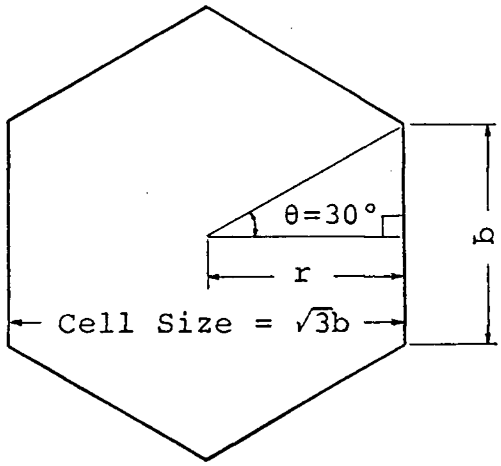


Figure 8 Honeycomb Cell Section

Hence, this fillet length is the length of the core cell edge in contact with the facing.

Flexure Test Specimen and Test Procedure

The remaining twenty sandwich panels from each fillet height group, eighty panels for four fillet height groups in total, were trimmed into 3.75 by 12 inch specimens for flexure test.

Since the objective of the flexure test in this study was to evaluate the shear strength of the glueline between core and facing, it was deemed desirable that the failure should take place in glueline shear rather than in core buckling or shear, or facing tension or compression. A preliminary test was carried out to determine the optimum loading system for the flexure specimens. Usual loading systems for flexure test of sandwich panels are mid-span loading and two-point loading. In the latter, the loading points are generally set at a quarter-span or one-third-span. Mid-span loading has an advantage in testing horizontal shear since the full span is subjected to shear stress, but a failure may occur in the facing, because the modulus of rupture of the facing in bending is maximum at the mid-span (Appendix 3).

In the case of two-point loading, the modulus of rupture of facing in bending decreases as the internal length between the two loading points increases, but the area that is subjected to horizontal shear stress decreases since the portion between the two loading points is not under shear stress. In the preliminary tests, an effort was made to find the minimum internal length between the two loading points where no failure was expected to take place in the facings. As a result, a quarter-span was found to be the most suitable internal length and was employed in this experiment.

The specimen was supported by two round steel bars of 1 inch in diameter at a distance of 1 inch from both ends of the beam. Load was applied by a Tinius Olsen universal testing machine through two round steel bars of the same size as the supporting bars (Figure 9). The rate of movement of the base plate of the testing machine was 0.02 inch per minute. The deflections were measured by a

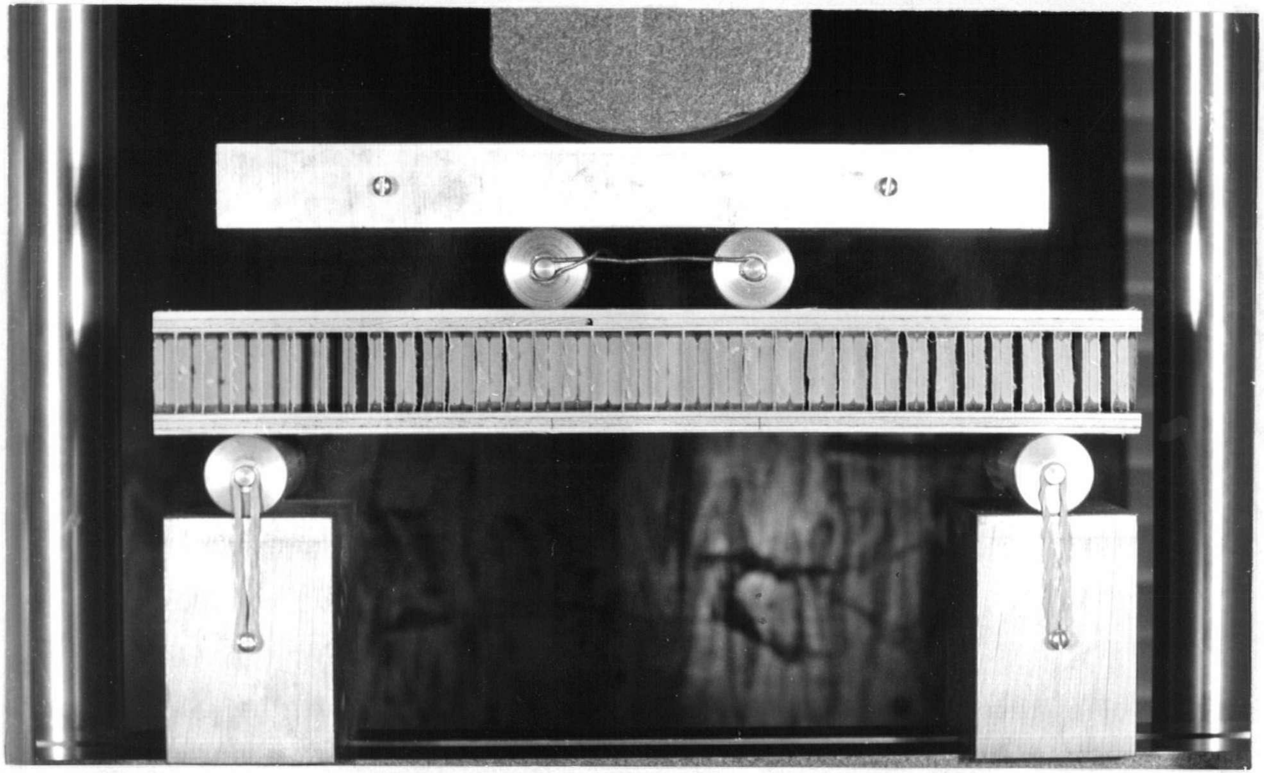


Figure 9. Apparatus for Conducting Flexure Test of Sandwich Construction

dial indicator by means of the machine base plate movement. The maximum load, deflection at fracture and failure characteristics were recorded for each specimen (Table 1).

RESULTS AND ANALYSIS OF DATA

Tensile Test

Tables 2, 3, 4, and 5 show the results of tensile tests for the four fillet height groups [0.5], [1.0], [1.5], and [2.0], respectively. The maximum load applied to the specimen directly gives the tensile strength in psi., since the cross sectional area of the specimen is 1 square inch. The strength of adhesive fillet can be obtained by dividing the tensile strength by the fillet length per unit core area.

For the measurement of the fillet height and width, four single cell walls (Figure 6) and corresponding four fillet lines which were left on the separated plywood were randomly chosen. All measurements were made at the center of single cell wall edges where the effects of core cell geometry due to the surface tension system were considered to be minimum. This is because the factors affecting fillet shape and size at the center of single cell wall edges were deemed to be less variable than those at a double cell wall or around the corner of an hexagonal cell.

The mean value of the four observations in each specimen was computed and recorded in Tables 2, 3, 4, and 5. Standard deviations and other basic figures needed for analysis of variance and correlation analysis are recorded in Tables 8 and 9. As the results show, the glue depth established on the applicator and the resulting fillet height did not agree. But differences between the glue depth and the fillet height mean values were nearly constant throughout all fillet height groups. These facts indicate that there were nearly constant glue elevations on the cell walls due to the surface tension in the liquid-solid system (Table 6).

Five specimens from each fillet height group were randomly selected for the measurement of fracture/fillet width ratio (Table 7). The measurement was made on four single cell traces on the facing of each specimen using vernier calipers reading to 0.05 mm.

1. Fillet Height and Fillet Width Relationship

Analysis of Variance. Using the data given in Table 8, the effects of fillet height treatments on fillet width means were investigated by analysis of variance (Appendix 1-a). The high level of significance of the F value indicates that the fillet width means were not all the same. In order to analyze the relationships between fillet width means, Duncan's New Multiple Range (N.M.R.) Test was carried out (Appendix 1-b).

According to Duncan's N.M.R. Test, there was no significant difference between fillet width means of [1.5] group and [2.0] group at the 5% level. The ranking of fillet width means was; [0.5]<[1.0]<[1.5], [2.0].

Correlation Analysis (Based on data in Table 9).

Fillet height : X_1

Fillet width : X_2

$$SS_{x_1} = 22.4962, \quad SS_{x_2} = 67.3752, \quad SP_{x_1x_2} = 28.99$$

$$b_1 = \frac{SP_{x_1x_2}}{SS_{x_1}} = 1.289, \quad b_0 = \bar{X}_2 - b_1\bar{X}_1 = -0.07$$

Simple regression equation : $X_2 = -0.07 + 1.289X_1$

Coefficient of determination : $r^2 = \dfrac{(SP_{x_1x_2})^2}{SS_{x_1} \cdot SS_{x_2}} = 0.5548$

$$F = \frac{r^2(n - 2)}{1 - r^2} = 47.29^{**} \qquad (n = 40)$$

** indicates significance at the 1% level. That is, the linear relationship between fillet height and fillet width was highly significant (Figure 10).

2. Fillet Height and Tensile Strength Relationship

Analysis of Variance. Using the data given in Table 8, the effects of fillet height treatments on tensile strength means were investigated by analysis of variance (Appendix 2-a). The significance of F value indicates that the tensile strength means were not all the same. In order to analyze the relationships between tensile strength means, Duncan's N.M.R. Test was carried out (Appendix 2-b).

According to Duncan's N.M.R. Test, there were no significant difference in the tensile strength means between [0.5] and [1.0], and between [2.0] and [1.5] at the 5% level. The ranking of tensile strength means was;

$$[0.5],\ [1.0] < [2.0],\ [1.5]$$

Correlation Analysis (Based on data in Table 9).

Fillet height : X_1

Tensile strength : Y

$$SS_{x_1} = 22.4962, \quad SS_y = 7481.6, \quad SP_{x_1y} = 223.54$$

$$b_1 = \frac{SP_{x_1y}}{SS_x} = \frac{223.54}{22.496} = 9.937, \quad b_0 = \bar{Y} - b_1\bar{X}_1 = 38.04$$

Simple regression equation : $Y = 38.04 + 9.94\ X_1$

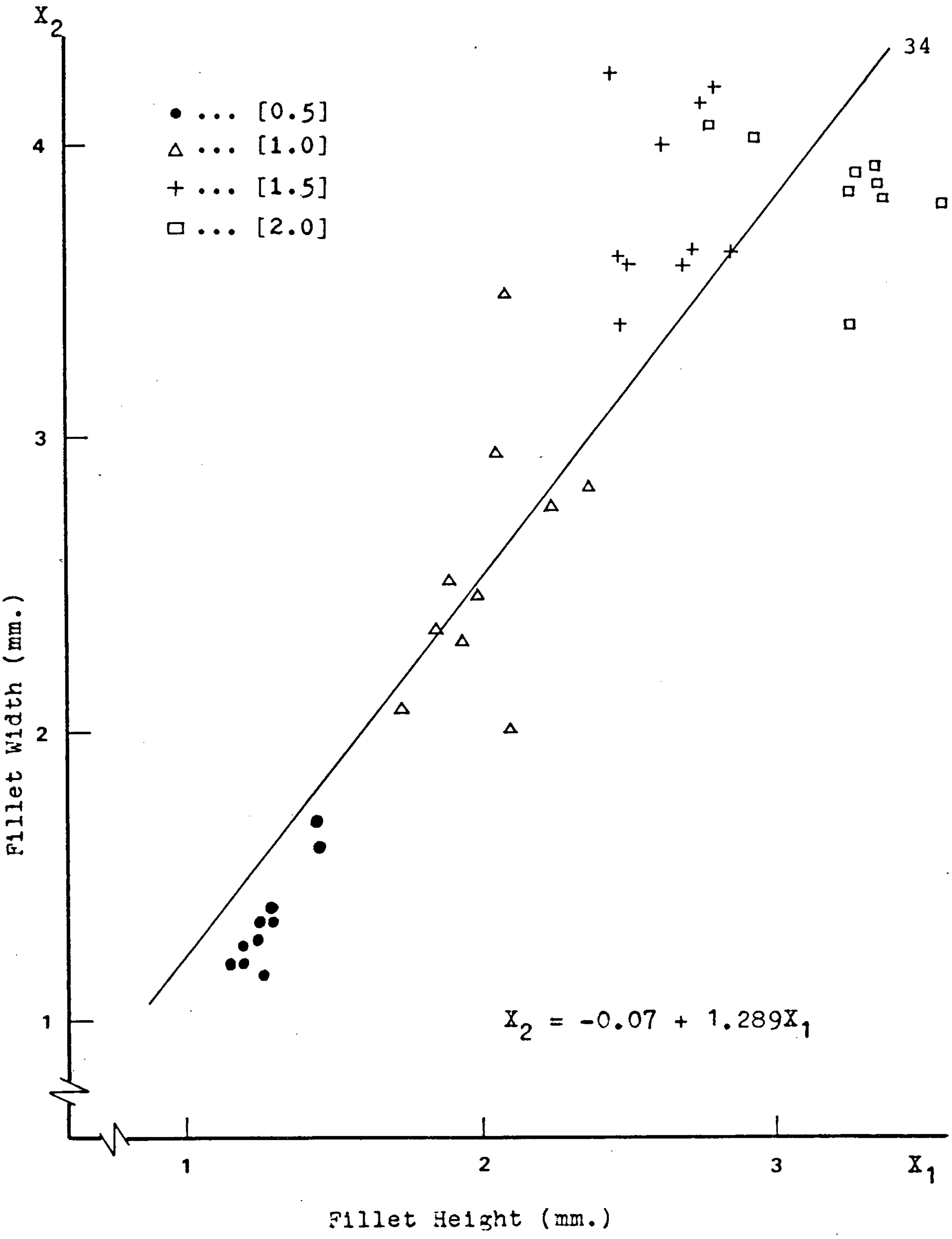


Figure 10. Fillet Height and Fillet Width Relationship in Tensile Test Specimens

Coefficient of determination : $r^2 = \frac{(SP_{x_4y})^2}{SS_{x_1} \cdot SS_y} = 0.2969$

Coefficient of linear correlation : r = 0.545

$F = \frac{r^2(n - 2)}{1 - r^2} = 16.05^{**}$ (n = 40)

** indicates significance at the 1% level. That is, the linear relationship between fillet height and tensile strength was highly significant (Figure 11).

3. Fillet Width and Tensile Strength Relationship

Correlation Analysis (Based on data in Table 9).

Fillet width : X_2

Tensile strength : Y

$SS_{x_2} = 67.375$, $SS_y = 7481.6$, $SP_{x_2y} = 410.26$

$b_1 = \frac{SP_{x_2y}}{SS_x} = 6.089$, $b_0 = \bar{Y} - b_1 \bar{X}_2 = 43.30$

Simple regression equation : $Y = 43.30 + 6.09 X_2$

Coefficient of determination : $r^2 = \frac{(SP_{x_2y})^2}{SS_{x_2} \cdot SS_y} = 0.3339$

Coefficient of linear correlation : r = 0.578

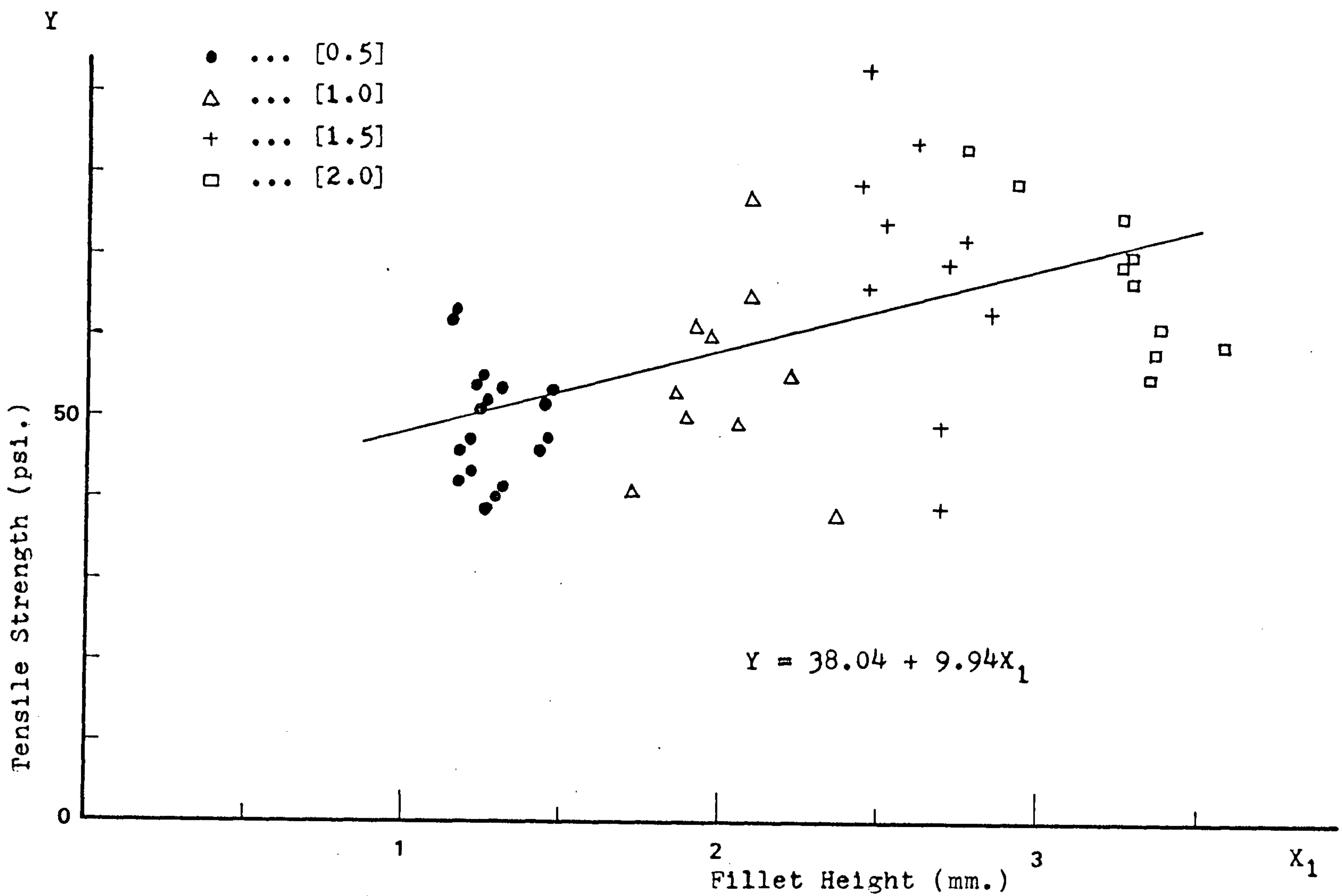


Figure 11. Fillet Height and Tensile Strength Relationship

$$F = \frac{r^2(n - 2)}{1 - r^2} = 19.06^{**} \qquad (n = 40)$$

** indicates significance at the 1% level. That is, the linear relationship between fillet width and tensile strength was highly significant (Figure 12).

4. Deflection at Fracture and Tensile Strength Relationship

Correlation Analysis (Based on data in Table 9).

Deflection : X_3

Tensile strength : Y

$SS_{x_3} = 3.514$, $SS_y = 7481.6$, $SP_{x_3y} = 110.69$

$$b_1 = \frac{SP_{x_3y}}{SS_{x_3}} = 31.50, \quad b_0 = \bar{Y} - b_1 \bar{X}_3 = 38.5$$

Simple regression equation : $Y = 38.5 + 31.5 X_3$

Coefficient of determination : $r^2 = \dfrac{(SP_{x_3y})^2}{SS_{x_3} \cdot SS_y} = 0.466$

Coefficient of linear correlation : $r = 0.683$

$$F = \frac{r^2(n - 2)}{1 - r^2} = 33.16^{**} \qquad (n = 40)$$

** indicates significance at the 1% level. That is the linear relationship between deflection at fracture and

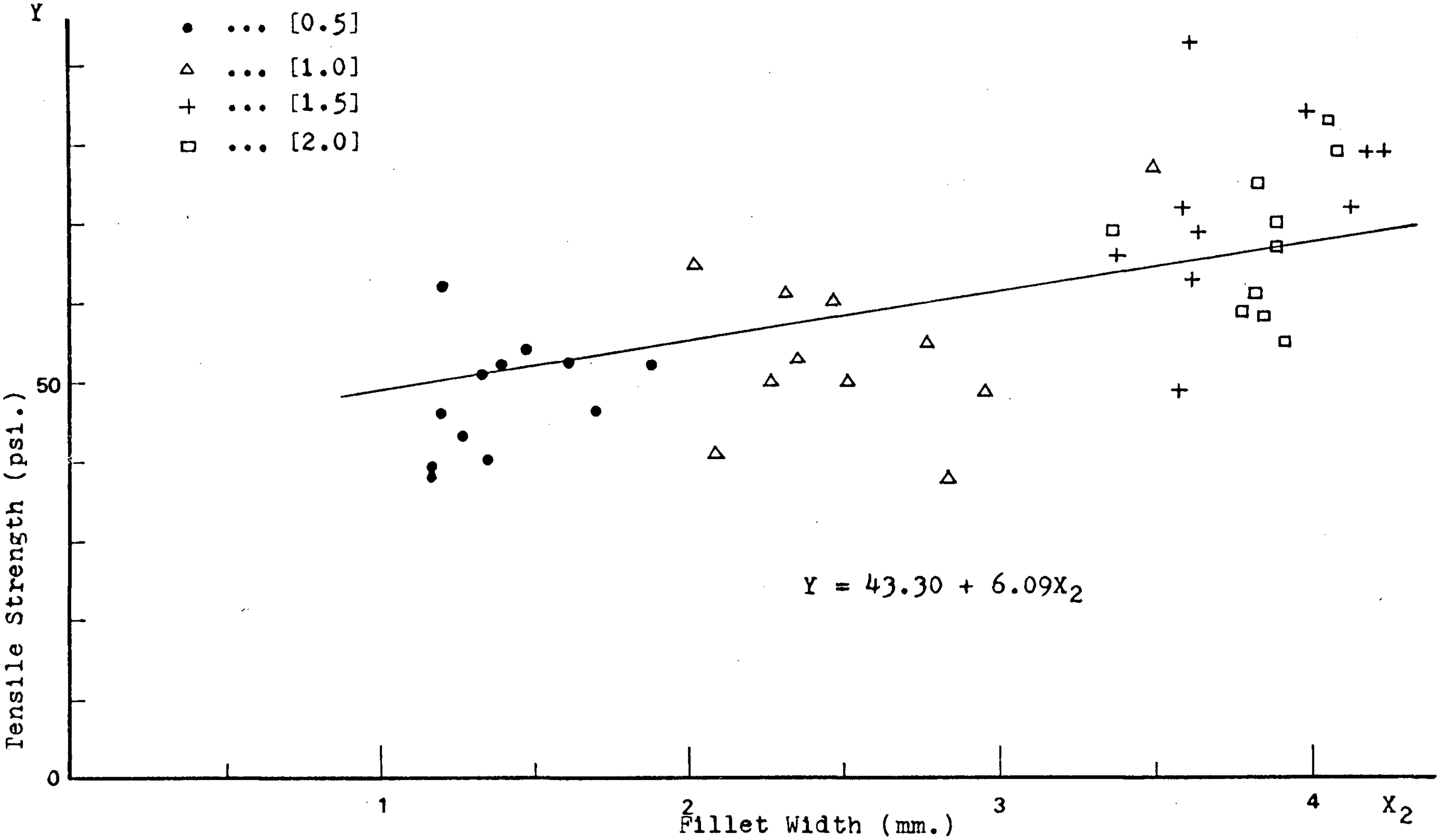


Figure 12. Fillet Width and Tensile Strength Relationship

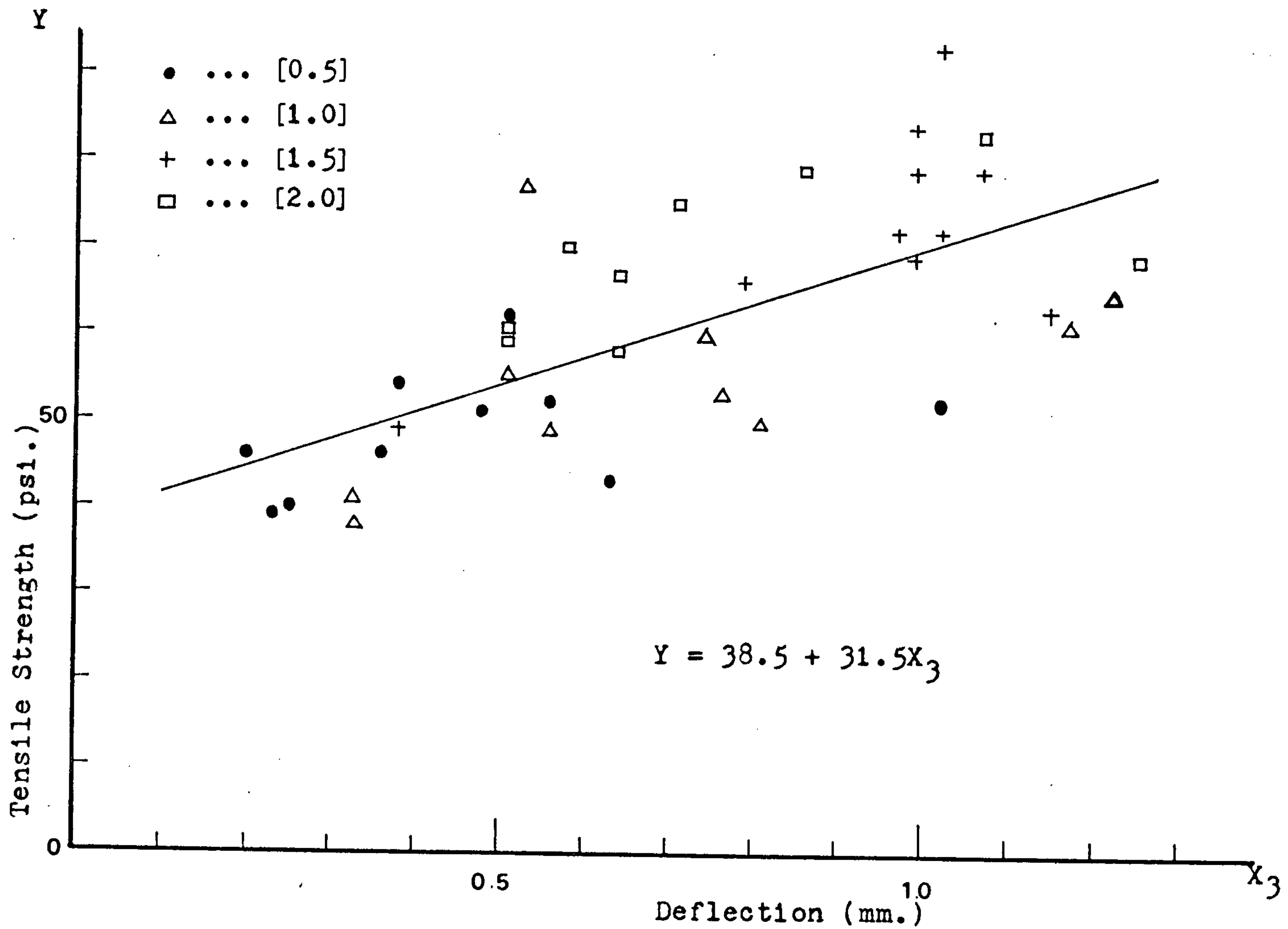


Figure 13. Tensile Strength and Deflection Relationship

tensile strength was highly significant (Figure 13).

5. Facing Failure and Tensile Strength Relationship

Correlation Analysis (Based on data in Table 9).

Facing failure : X_4

Tensile strength : Y

$SS_{x_4} = 1477.1$, $SS_y = 7481.6$, $SP_{x_4y} = 504.4$

Coefficient of determination : $r^2 = \dfrac{(SP_{x_4y})^2}{SS_{x_4} \cdot SS_y} = 0.023$

Coefficient of linear correlation : $r = 0.152$

$F = \dfrac{r^2(n - 2)}{1 - r^2} = 0.89$ n.s. $(n = 40)$

n.s. indicates non-significance at the 5% level. That is, there was no significant correlation between facing failure and tensile strength.

6. Fillet Height and Deflection at Fracture Relationship

Correlation Analysis (Based on data in Table 9).

Deflection : X_3

Fillet height : X_1

$SS_{x_3} = 3.5140, \quad SS_{x_1} = 22.4962, \quad SP_{x_1x_3} = 3.580$

Coefficient of determination : $r^2 = \dfrac{(SP_{x_1x_3})^2}{SS_{x_1} \cdot SS_{x_3}} = 0.162$

Coefficient of linear correlation : $r = 0.403$

$$F = \frac{r^2(n - 2)}{1 - r^2} = 7.35^{*} \qquad (n = 40)$$

* indicates significance at the 5% level. That is, the linear relationship between fillet height and deflection at fracture was significant.

<u>Flexure Test</u>

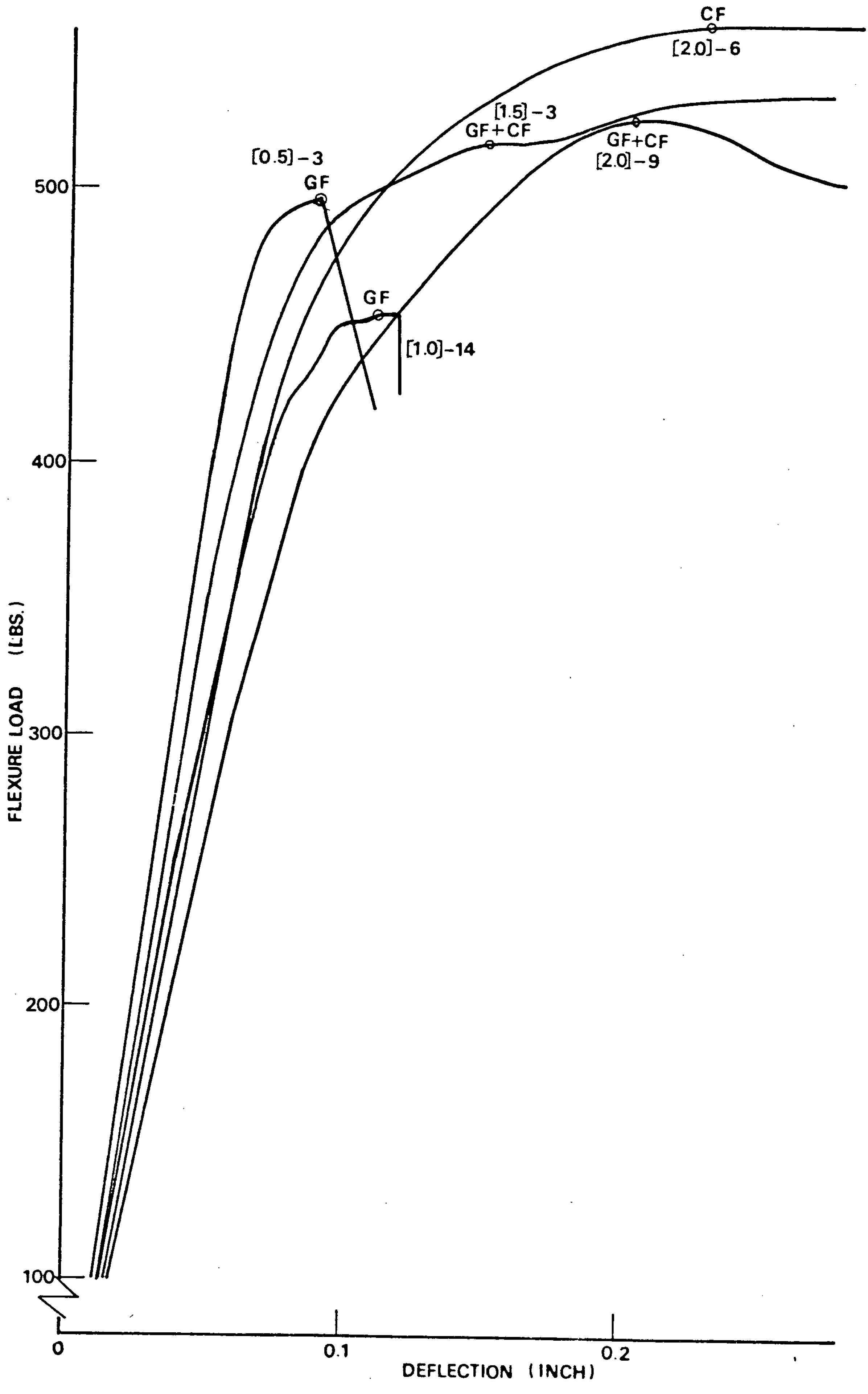
The results of the flexure test for the four fillet height groups, [0.5], [1.0], [1.5], and [2.0] are given in Tables 10, 11, 12 and 13, respectively. The horizontal shear stress in the glueline were calculated by using the equation given in Appendix 3-a.

The types of failure of the specimens at the maximum load P were not all alike. When the failure took place only in the glueline, the load-deflection curve showed a sudden release of stress in the specimen after reaching the maximum load (Figure 14, [0.5]- 3, [1.0]- 14). This type of failure was observed mostly in the small fillet groups,

Figure 14. Selected Load-Deflection Curves in Flexure Tests

CF = Core failure

GF = Glueline failure



CF
[2.0]-6
[1.5]-3
GF+CF
[0.5]-3
GF
GF+CF
[2.0]-9
GF
[1.0]-14
500
400
300
200
100
0
0.1
0.2
FLEXURE LOAD (LBS.)
DEFLECTION (INCH)

[0.5] and [1.0]. When the failure was due partly to the glueline fracture and partly to the core shear or buckling, there was no conspicuous change of stress in the specimen after a glueline fracture was observed, and the deflection proceeded until a rupture occurred in the facing. In such a case the maximum load was recorded at the first point where the glueline failure was observed even if the load increased slightly after that point (Figure 14, [1.5]- 3). In larger fillet groups, especially in [2.0] group, most of the specimens failed in core shear and/or buckling. The gluelines of those specimens were considered to have maintained their strength up to the maximum core shear stress, so the first point from which the load-deflection curve became parallel to the deflection axis was chosen for determination of P (Figure 14, [2.0]- 6).

The measurements of fillet height and fillet width were same as those in the tensile test. The failure types were classified into CF for core failure, GF for glueline failure, and FF for facing failure. When a load was applied on the sandwich beam and if any wrinkles appeared on the honeycomb core walls, it was considered that a failure took place in the core. In most core failures slanting wrinkles appeared on the core walls around the neutral axis of the sandwich beam at the outer sides of the loading points. In some cases core buckling, which appeared as slight folds near the glueline, accompanied the core shear failures.

The glueline failure was observed as a slide of the facing delamination from the core. Minor peeling damages of the surface of facings which sometimes accompanied the delaminations were regarded as a part of the glueline failure. Facing failures were such that either top or bottom facing was ruptured by bending at or near the center of two loading points.

Five specimens from each fillet height group except [2.0] were selected for the measurement of fracture/fillet width ratio (Table 14). From [2.0] group the three specimens which failed in the gluelines were selected for the same purpose. The method of measurement was as same as that in the tensile test specimens.

1. Fillet Height and Fillet Width Relationship

Analysis of Variance. Using the data given in Table 15, the effects of fillet height treatments on fillet width means were investigated by analysis of variance (Appendix 4-a). The high level of significance of the F value indicates that the fillet width means were not all the same. In order to analyze the relationships between fillet width means, Duncan's N.M.R. Test was carried out (Appendix 4-b).

According to Duncan's N.M.R. Test, fillet width means ranked as:

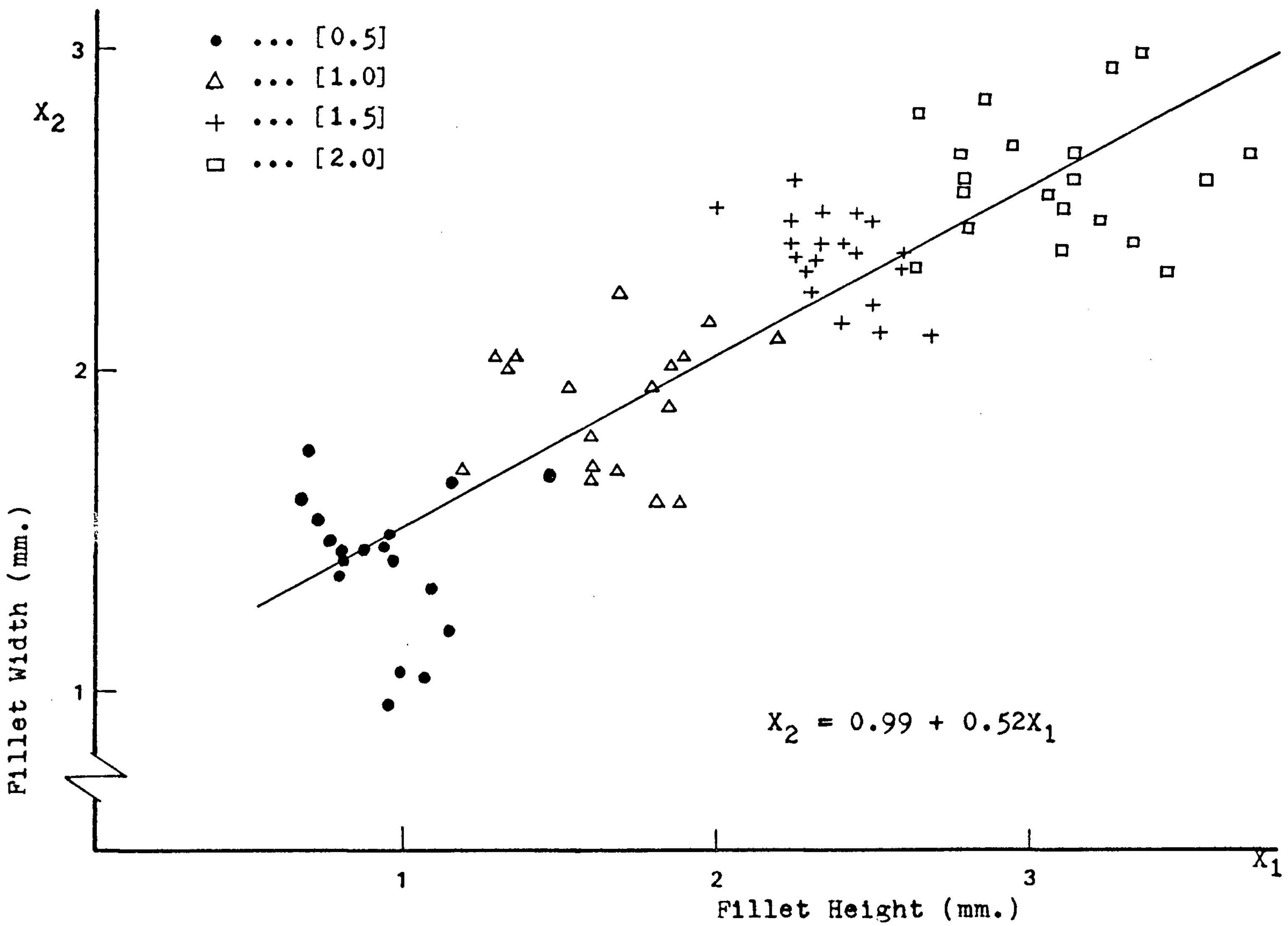


Figure 15. Fillet Height and Fillet Width Relationship in Flexure Test Specimens

$$[0.5] < [1.0] < [1.5] < [2.0]$$

at the 1% level of significance.

Correlation Analysis (Based on data in Table 15).

Fillet height : X_1

Fillet width : X_2

$$SS_{x_1} = 56.782, \quad SS_{x_2} = 19.935, \quad SP_{x_1x_2} = 29.790$$

$$b_1 = \frac{SP_{x_1x_2}}{SS_{x_1}} = 0.5246, \quad b_0 = \bar{X}_2 - b_1 \bar{X}_1 = 0.99$$

Simple regression equation : $X_2 = 0.99 + 0.52\ X_1$

Coefficient of determination : $r^2 = \dfrac{(SP_{x_1x_2})^2}{SS_{x_1} \cdot SS_{x_2}} = 0.784$

Coefficient of linear correlation : $r = 0.886$

$$F = \frac{r^2(n - 2)}{1 - r^2} = 284^{**} \qquad (n = 80)$$

** indicates significance at the 1% level. That is, there was a highly significant linear relationship between fillet height and fillet width. As the fillet height increased, so did the fillet width (Figure 15).

2. Fillet Height and Shear Strength Relationship

Analysis of Variance. Using the data given in Table 15, the effects of fillet height treatments on shear strength means were investigated by analysis of variance (Appendix 5-a). The significance of F value indicates that the shear strength means were not all the same. In order to analyze the relationships between shear strength means, Duncan's N.M.R. Test was carried out (Appendix 5-b).

There was a significant difference in shear strength means between height treatments of [1.0] and [0.5] at the 5% level according to Duncan's N.M.R. Test, but it was not highly significant at the 1% level. The difference between the two groups, [1.0] and [0.5] as one group, [1.5] and [2.0] as another, was highly significant at the 1% level.

Correlation Analysis (Based on data in Table 15).

Fillet height : X_1

Shear strength : Y

$$SS_{x_1} = 56.782, \quad SS_y = 1487.96, \quad SP_{x_1y} = 156.99$$

$$b_1 = \frac{SP_{x_1y}}{SS_{x_1}} = 2.765, \quad b_0 = \bar{Y} - b_1 \bar{X}_1 = 46.9$$

Simple regression equation : $Y = 46.9 + 2.77 X_1$

Coefficient of determination : $r^2 = 0.2917$

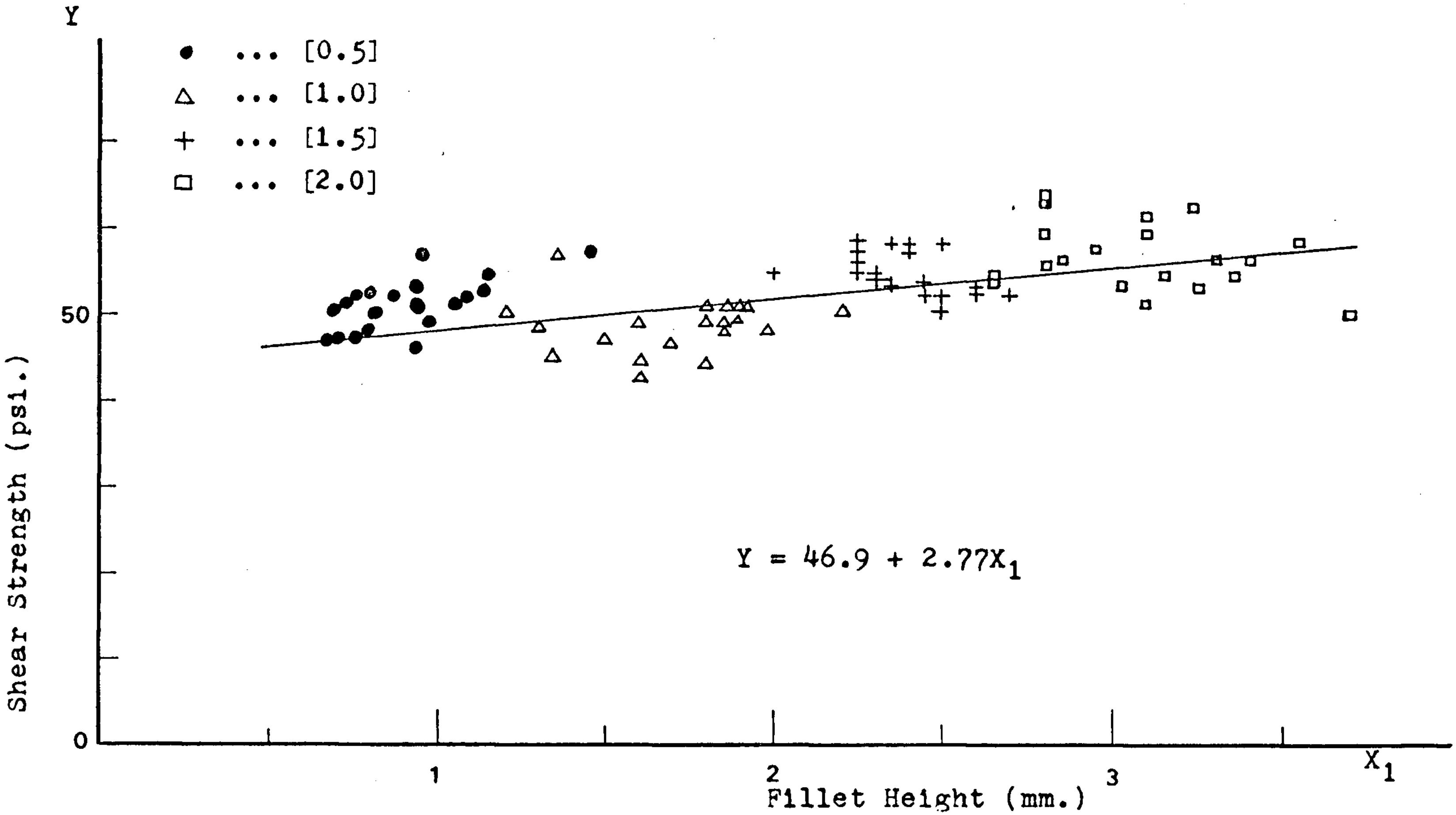


Figure 16. Fillet Height and Shear Strength Relationship

Coefficient of linear correlation : $r = 0.540$

$F = 32.13^{**}$ (n = 80)

** indicates significance at the 1% level. That is, the linear relationship between fillet height and shear strength was highly significant (Figure 16).

3. Fillet Width and Shear Strength Relationship

Correlation Analysis (Based on data in Table 15).

Fillet width : X_2

Shear strength : Y

$SS_{x_2} = 19.935$, $SS_y = 1487.96$, $SP_{x_2y} = 92.61$

$$b_1 = \frac{SP_{x_2y}}{SS_{x_2}} = 4.646, \quad b_0 = \bar{Y} - b_1 \bar{X}_2 = 43.6$$

Simple regression equation : $Y = 43.0 + 4.65 X_2$

Coefficient of determination : $r^2 = 0.2895$

Coefficient of linear correlation : $r = 0.538$

$F = 15.48^{**}$ (n = 80)

** indicates significance at the 1% level. That is, the linear relationship between fillet width and shear strength was highly significant (Figure 17).

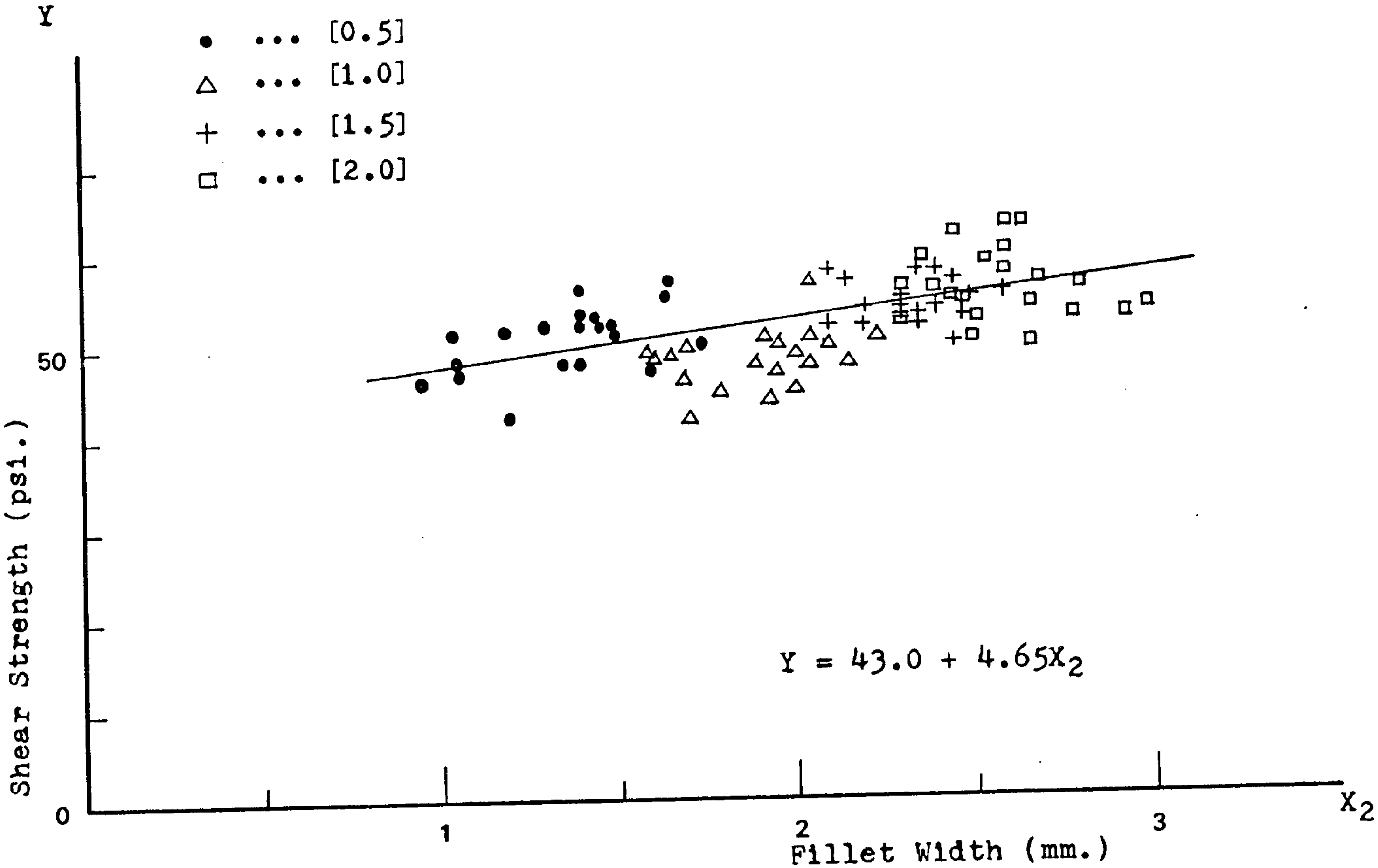


Figure 17. Fillet Width and Shear Strength Relationship

4. Deflection at Fracture and Shear Strength Relationship

Correlation Analysis (Based on data in Table 15).

Deflection at fracture : X_3

Shear strength : Y

$SS_{x_3} = 141.889$, $SS_Y = 1487.96$, $SP_{x_3Y} = 280.378$

$$b_1 = \frac{SP_{x_3Y}}{SS_{x_3}} = 1.976, \quad b_0 = \bar{Y} - b_1 \bar{X}_3 = 45.8$$

Simple regression equation : $Y = 45.8 + 1.98\ X_3$

$$\text{Coefficient of determination : } r^2 = \frac{(SP_{x_3Y})^2}{SS_{x_3} \cdot SS_Y} = 0.3723$$

Coefficient of linear correlation : $r = 0.61$

$F = 46.24^{**}$ (n = 80)

** indicates significance at the 1% level. That is, the linear relationship between deflection at fracture and shear strength was highly significant.

5. Fillet Height and Deflection Relationship

Analysis of Variance. Using the data given in Table 15, the effects of fillet height treatments on deflection means at fracture were investigated by analysis of variance (Appendix 6-a). The significance of F value indicates that the deflection means at fracture were not all the same. In order to analyze the relationships between deflection means, Duncan's N.M.R. Test was carried out (Appendix 6-b).

According to Duncan's N.M.R. Test, there was no significant difference between the deflection means of [0.5] group and [1.0] group at the 1% level. The ranking of the deflection means was; [0.5], [1.0] < [1.5] < [2.0].

Correlation Analysis (Based on data in Table 15).

Fillet height : X_1

Deflection : X_3

$SS_{x_1} = 56.782$, $SS_{x_3} = 141.889$, $SP_{x_1x_3} = 74.222$

$$b_1 = \frac{SP_{x_1x_3}}{SS_{x_1}} = 1.307, \quad b_0 = \bar{X}_3 - b_1 \bar{X}_1 = 0.6838$$

Simple regression equation : $X_3 = 0.73 + 1.307\ X_1$

Coefficeint of determination : $r^2 = 0.6838$

Coefficient of linear correlation : $r = 0.827$

$F = 168.68^{**}$ $(n = 80)$

** indicates significance at the 1% level. That is, the linear relationship between deflection and fillet height was highly significant (Figure 18).

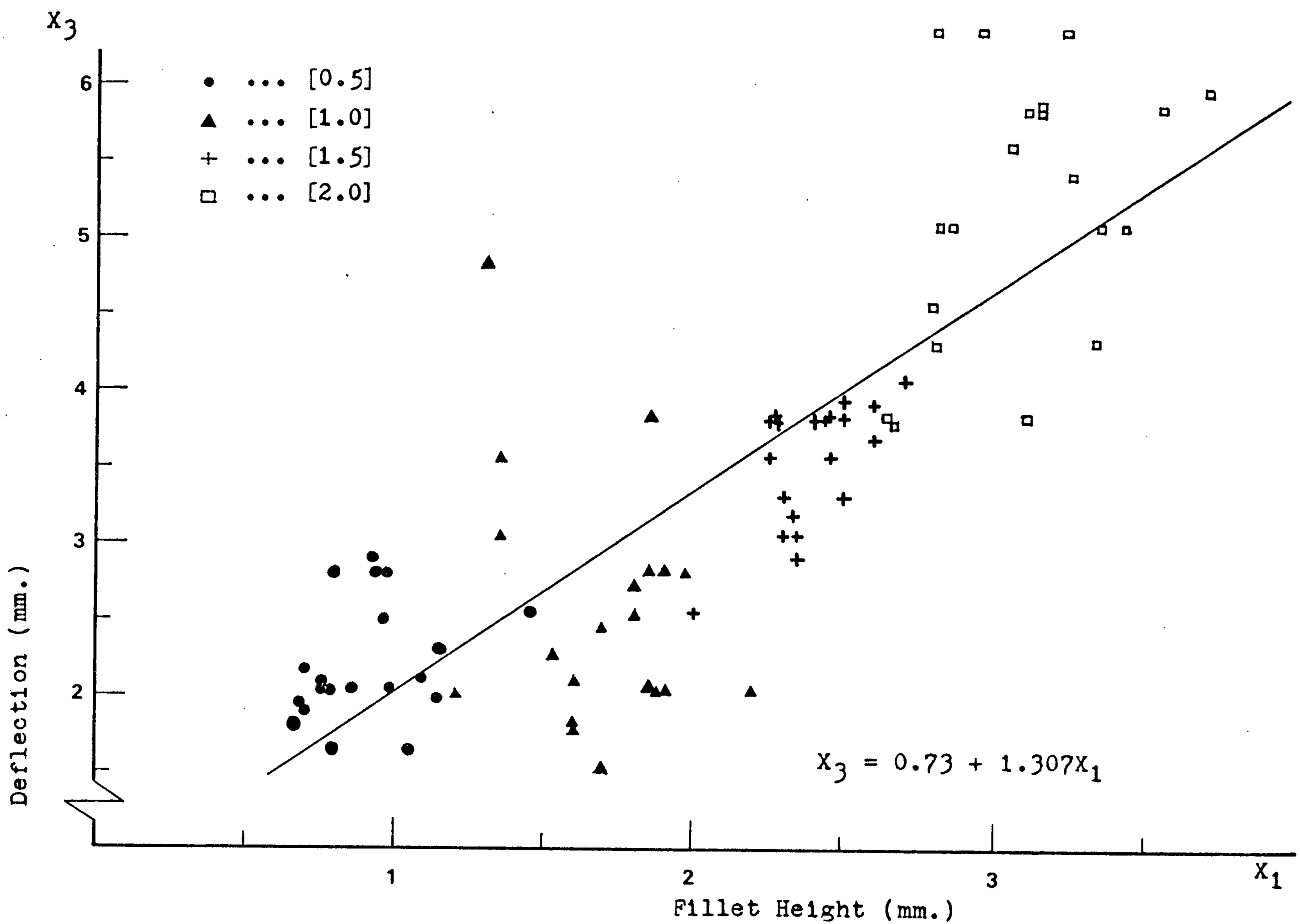


Figure 18. Fillet Height and Deflection Relationship in Flexure Test Specimens

DISCUSSION

Fillet Geometry

For the tensile test specimens, there was no significant difference in fillet width between the fillet height treatments of [1.5] and [2.0]. For the flexure test specimens, however, each of the four height treatments was significantly different in fillet width. Considering the fact that the tensile test specimens of one fillet height group were cut from only two original sandwich panels, while the flexure test specimens of one fillet height group were made from twenty different sandwich panels, the inference based on the flexure test specimens will be more reliable as far as general discussion on fillet height and fillet width relationship is concerned.

As was shown in the previous chapter, there was a highly significant linear correlation between fillet height and fillet width in both types of specimen when all the observations were considered to be independent. However, if the treatment means of fillet height and fillet width in the flexure test specimens are taken into consideration, a parabolic curve

$$X_1 = -0.06\ X_2^2 + \frac{0.5(X_2 - t)}{2}\ ,\ 0.8 \leq X_2 \leq 2.9$$

can be fitted, where X_1 and X_2 denote the fillet height and the fillet width, respectively, and t denotes the thickness of the honeycomb paper. The boundary conditions of X_2 were obtained by extending the sequence of experimental data of X_2's to both limits (Appendix 7).

The minimum fillet width ($X_2 = 0.80$) and height ($X_1 = 0.30$) given in Appendix 7 are explained in the following discussion. When a honeycomb cell wall edge is placed on a liquid glue surface (glue depth = 0.00), the glue will be pulled up on the cell wall by the surface free energy until the equilibrium in liquid-solid system is reached. This height will be 0.3 mm. When this cell wall is placed on the pre-wetted plywood, the glue attached around the cell wall edge will flow sideways by the surface tension and the mechanical force of the cell wall movement toward the facing. The total width of these flows on both sides of the cell wall will be 0.8 mm. Then, the fillet width on one side of the cell wall excluding the cell wall thickness is 0.3 mm.

If the cell wall is dipped into the glue for 1.40 mm. for example, the cell wall becomes wetted to a height of 1.40 + 0.30 = 1.70 mm. The fillet width in that case will be 1.90 mm. Similarly, the maximum width of the fillet can be estimated as $X_2 = 2.90$ by extending the sequence to the upper limit. As this point the fillet height will be 4.5 mm. or higher. This means that the fillet width will not become larger than 2.9 mm. even though the fillet height may be larger than 4.5 mm.

Grimes (16) suggested that a large fillet is defined as one whose width is equal to r/2, where r is the core cell size; similarly the width of medium fillet is r/3, and the width of small fillet is r/4. Since the radius of honeycomb cell used in this thesis is 3/8 inch, or 4.7 mm., large fillet width becomes r/2 = 2.4 mm., medium fillet width is r/3 = 1.6 mm., and small fillet width is r/4 = 1.2 mm. The fillet width on one side of the cell wall, i.e. $(X_2 - 0.25)/2$, for the four fillet height groups are;

[0.5] : (1.37 - 0.25)/2 = 0.56

[1.0] : (2.58 - 0.25)/2 = 1.17

[1.5] : (3.80 - 0.25)/2 = 1.78

[2.0] : (3.84 - 0.25)/2 = 1.80 .

Therefore, according to the classification by Grimes, the fillets in [1.5] and [2.0] belong to the medium fillet group, while [1.0] belongs to the small fillet. The fillet width in [0.5] group is approximately one-half of the small fillet width.

Fillet geometry at a joint of honeycomb and plywood cannot be determined by the fillet height and width only. The shape of fillet is also an important factor. When a glue-treated honeycomb was placed on a plywood surface the fillet surface was convex at first, but it changed into concave with the passage of time. This may be partly due to the change of surface tensions between the liquid and solids that was induced by the glue diffusion into the honeycomb wall and plywood. The shrinkage of the glue body which took place as a result of glue solidification is probably contributing to the change of surface shape, too. Although no numerical measurement was made for determining the curve of fillet surfaces, it was assumed for further analysis that every concave curve was forming a part of a circle as illustrated in Figure 19 - (A).

The type of adhesive used in this experiment was a modified phenolic-resorcinol resin as was mentioned earlier. This was a commercially blended adhesive and no detail of the formula was obtainable, nevertheless it is assumed that the adhesive consisted of a resole based phenolic and resorcinol formaldehyde resins from its property of water solubility (43, 54). If so, the glue should contain some water for a dispersing agent. A small amount of water is also released by the condensation polymerisation reaction in both phenolic and resorcinol resins (32).

Only scant experimental proof exists for the reason of bubble or void formation in a solidified glue of any type (8), but water is one of the likely main causes of void formation. Some fillets in the specimens of [2.0] group had a relatively large cavity beneath the thin glue skin which was forming the outward surface of the fillet. This fact may explain the reason why fillet shear strength of [2.0]

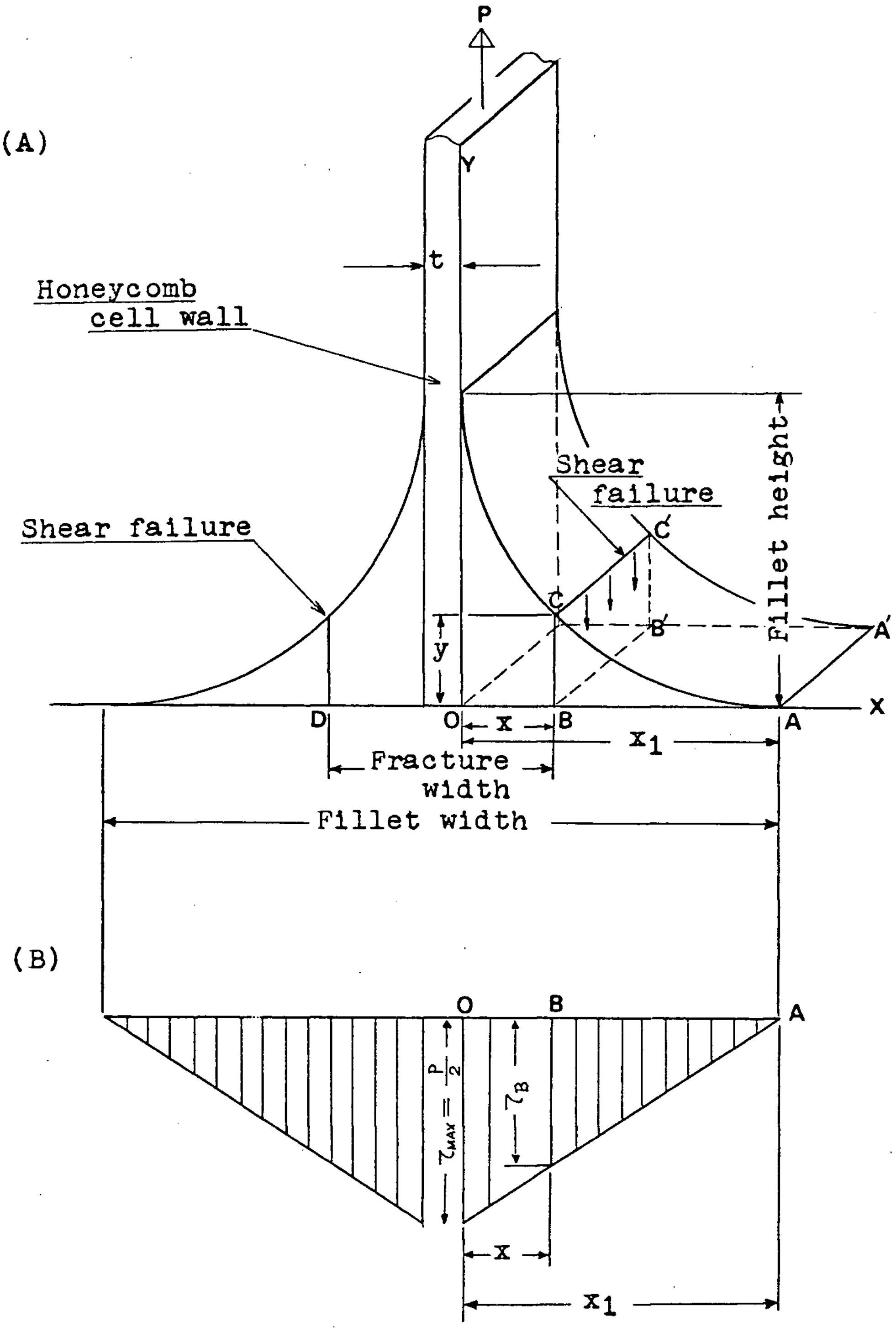


Figure 19. Dimensional Nomenclature on Fillet Section and Shear Stress Distribution

was not larger than that of [1.5] in spite of the larger size in fillet height and width, for voids and bubbles in a solidified adhesive layer are the major factors which cause weakening of total glueline strength (8).

Tensile Strength

A significant difference in tensile strength was found between the low fillet groups of [0.5], [1.0] and the high fillet groups of [1.5], [2.0], as stated earlier. Between [1.5] and [2.0], there was no significant difference in either fillet width or tensile strength. Hence, these two can be treated as one group. In spite of the significant difference in fillet width between [0.5] and [1.0], there was no significant difference in tensile strength between them.

By observing the fracture lines in the specimens after the tensile test, it was found that most of the fracture took place by tensile failure in the joint of paper honeycomb and plywood plus shear failure in the fillet. The shear fracture was approximately perpendicular to the facing. In order to examine how fillets are contributing to the total glueline strength the stress distribution and rupture point should be known. Fillet shape is assumed to be symmetrical with respect to the cell wall, and analysis will be carried out for fillet on one side of the cell wall.

For the purpose of mathematical expression, the facing surface is taken as X-axis and the cell wall is taken as Y-axis (Figure 19 - A). If a tensile load P per unit fillet length is applied to the cell wall, the glueline OA will be subjected to the tensile stress:

$$\sigma = \frac{x_1 P}{2x_1 + t} \qquad \text{.... [1]}$$

At the same time vertical shear stress is distributed in the fillet as shown in Figure 19 -(B). The magnitude of the shear stress at point B, x-distance from O, is

$$\tau_B = \frac{P}{2} \cdot \frac{x_1 - x}{x_1} \qquad \text{.... [2]}$$

If the concave face of a fillet is assumed to be a quarter portion of a circle with radius x_1, then the fillet height y at B is expressed by:

$$y = x_1 - \sqrt{2x_1 x - x^2} \qquad \text{.... [3]}$$

Let R be the ratio of fracture width* X_f to the fillet width X_w, then

$$x = (R\,\bar{X}_2 - t)/2 \qquad \text{.... [4]}$$

and $$x_1 = (\bar{X}_2 - t)/2 \qquad \text{.... [5]}$$

* The distance between the shear failure points, B and D (Figure 19 - A).

Substituting the values of R (Table 7) and $\bar{X}_2$ (Table 8) into [4] and calculating the ratio, x/x_1, it is found that x/x_1 becomes constant for all fillet height groups;

i.e. $x = 0.3\ x_1$ .... [6]

Substituting [6] into [3], it is determined that

$$y = 0.3\ x_1$$
$$y = x \qquad \text{.... [7]}$$

This result shows that the shear failure point on the fillet surface was the center of the concave (the point C in Figure 19 - A).

Substituting [6] into [2],

$$\tau_B = 0.35\ P\ .$$

Since P is proportional to $\bar{Y}$, τ_B is proportional to $\bar{Y}$, too. Therefore, τ_B can be expressed as:

$$\tau_B = k\bar{Y} \qquad \text{.... [8]}$$

where k is a constant. In order to examine whether or not the shear strength of fillet is proportional to y, the hypothesis $\tau_B = my$, where m is a constant, will be tested.

From [8], $\tau_B = my = k\bar{Y}$,

then $y = \frac{k}{m}\bar{Y}$,

or $\frac{y}{\bar{Y}} = c$, where c is a constant.

But, the results of calculation of $\frac{y}{\bar{Y}}$ x 100 for [0.5], [1.0], [1.5] and [2.0] were 0.344, 0.632, 0.731 and 0.795, respectively. That is,

$$\frac{y}{\bar{Y}} \neq c ,$$

then $\tau_B \neq my$

or, the shear strength of the fillet at point B was not proportional to the fillet height at B. Moreover, $\frac{y}{\bar{Y}}$ increased as either fillet width or fillet height increased. The value $\frac{y}{\bar{Y}}$ x 100 is a parameter which indicates the weakness of fillet under the vertical shear stress.

Although the shear strength was not directly proportional to y, it did not indicate the lack of linear relationship between the shear strength and y. Suppose there is a linear relationship between them, then

$$\tau_b = my + d \qquad \text{.... [9]}$$

where d is a constant. Substituting [9] into [8],

$$\frac{y + \frac{d}{m}}{\bar{Y}} = \frac{k}{m} .$$

Taking $\frac{d}{m} = 0.22$* and substituting the values of $\bar{Y}$ and y for each fillet height group, the values of $\frac{k}{m}$ are found to be nearly constant (Appendix 8). This substantiates the hypothesis [9].

These results reveal that, when a tensile load normal to a sandwich facing is given, a fillet rupture occurs in vertical shear at the center of the fillet concave face and in tension at or near the joint between adhesive and the facing, and that the shear strength of the fillet increases as the fillet height increases under the relationship:

$$\tau_B = my + d, \quad \text{where } 0 < m < 1 \quad \text{and} \quad d > 0 .$$

The absence of significant difference in tensile strength between [1.5] and [2.0] may be owing to the lack of significant difference in fillet size between them. The absence of significant difference in tensile strength between [0.5] and [1.0] cannot be explained.

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* From [1.0] and [1.5],

$$\frac{0.348 + d/m}{54.9} = \frac{0.531 + d/m}{72.6} \therefore d/m = 0.22$$

Although there was a highly significant correlation between deflection at fracture and tensile strength, glue fillets are not considered as the main factor contributing to the deflection. The elongation in the composite of plywood and paper honeycomb may be the main factor. The proposed reasons are:

(a) The magnitude of deflection was greater than the fillet height. The fillet cannot elongate so much as its height, since it is so brittle that it breaks by shear before it elongates that much.

(b) It is supposed that stresses in either plywood or honeycomb did not exceed the proportional limit. That is, the deflection of plywood or honeycomb was proportional to the tensile load. Hence the linear correlation between the tensile strength and the deflection of the specimen was highly significant.

The type of facing failure was such that the plywood edge split parallel to the grain to the depth of the inner face ply. The average percentages of facing failure were 1.2% for [0.5] as the lowest and 9.2% for [1.0] as the highest. Since these values are comparatively low, i.e. less than 10%, the facing failure is not considered as a significant factor for the analysis of fillet functions. This fact is also supported by the correlation analysis.

Shear Strength

According to the data published by Hexcel, Inc. the shear strength of the honeycomb used for this thesis was 70 psi. (perpendicular to ribbon direction). By using the formula for determination of core shear stress (4), the maximum load for flexure test is approximated as follows:

$$S = \frac{P_1}{(h + c)b} ,$$

where $S = 70$ psi., $h = 1.5$ inch, $c = 1.0$ inch, $b = 3.75$ inch and P_1 = load in lbs. by mid-span loading.

$$P_1 = S(h + c)b = 656.25 \text{ (lbs.)} .$$

This means that the sandwich panel specimen will fail by core shear if the flexure load exceeds 656 lbs. by mid-span loading. The value of P will increase to some extent ($P_2 = 685$) under the loading method practised in this thesis (Appendix 9). As the data show (Tables 10, 11, 12, 13) no flexure load exceeded 600 lbs, nevertheless most of the specimens of larger fillet groups, i.e. [1.5] and [2.0], failed in core shear before glueline failure took place. This might be due to the lack of extra caution taken during pressure control for the higher fillet groups.

When paper honeycomb is wetted by glue it becomes much softer than in the dry condition. The paper honeycomb treated with the deeper glue spread had a larger wet and soft portion than those treated with shallower spreads. Therefore, the higher fillet groups had a greater chance for buckling if the same pressing load is given to the all fillet groups during the curing process. The pressure was approximately 50 psi. regardless of the glue height group. However, the pressure gauge was not sufficiently sensitive in control below 100 psi., hence the sandwich panels of the higher fillet groups might have been overpressed beyond their proportional limits in the wet condition. Even though the failure were invisible, once the paper honeycomb was overpressed it would not be able to show its inherent strength when a shear or compressive load was subsequently applied.

In spite of the core failures in the higher fillet groups, highly significant correlations were found between fillet height and shear strength, and between fillet width and shear strength. The mean shear strength of [1.0] was less than that of [0.5] at the 5% level of significance. The cause for this particular case is unknown. If the fillet height groups are classified into small and medium fillet, as discussed in the first section of this chapter, there remains no difficulty in the interpretation of the statistical data. That is, the horizontal shear strength in sandwich construction is affected by the fillet size. The larger fillet carries more shear stress than does the smaller fillet.

The appearance of the failure in the glueline was similar to that in the tensile test. The ratio x/x_1 for the fillet height groups of [0.5], [1.0], [1.5] and [2.0] are calculated as 0.24, 0.27, 0.28 and 0.27, respectively. If it is assumed that the concave face of the fillet was the quarter portion of a circle with radius x_1, then the fracture is considered to have taken place by breaking the fillet vertically at the middle points of the concave face on both sides of the cell wall and the glue-plywood joint between them. The latter was due to the shear force, while the former was regarded as a result of the combination of compression, tension and shear forces. More accurately, the glue-plywood joint was also carrying tensile stress because of the deflection (14).

SUMMARY AND CONCLUSION

When the modified phenolic-resorcinol resin glue was used for bonding kraft paper honeycomb to plywood to make a sandwich construction, fillets were formed around the joints of honeycomb and plywood. Fillet size was measured in terms of its height and width. It was found that the cores treated with heavier glue spread produced higher and wider fillets, and the correlation between fillet height and width was highly significant. The surface shape of fillet was convex at first, but it changed into concave as glue solidification proceeded. This phenomenon was true regardless of fillet size. However, some fillets in large fillet groups, especially in [2.0] group, had a relatively large void underneath a thin glue surface. It is well known that voids in a solidified adhesive layer are one of the major factors to decrease the total glueline strength. This fact will probably apply to fillet as well. Hence a too large fillet may suffer a weakening effect from void formation.

In the tensile test most of the fractures were observed at the glue-plywood joint by the tensile failure and at the middle of the fillet concave face by the vertical shear. This tendency was encountered regardless of the fillet height group.

The vertical shear strength at the fracture line in a fillet can be expressed as:

$$\tau_B = my + d \quad ,$$

where τ_B is the shear strength at the fracture point B, y is the fillet height at B, m and d are constants. This means that the vertical shear strength of a fillet at the fracture point B increases as the fillet height at B increases by the ratio of m. The value of m, which is greater than zero and less than one, can be obtained empirically. The value of d is approximately equal to 0.22 x m. If there exists a void in the fillet, however, m will assume a much smaller value than the calculated value based on the analysis. It was also noted that, in the use of paper honeycomb as the core for a structural sandwich construction, the right pressure for the assembly should be carefully studied since the core, when it is wet with glue, tends to fail in shear or compressive buckling more easily than when it is dry.

In general, a larger fillet withstands bigger load. But, as far as the adhesive used in this thesis is concerned, the rate of increase of fillet strength decreases as the fillet size increases. It was previously pointed out that too large a fillet is apt to produce voids within it, resulting in lowering strength values. Such a fillet diminishes the characteristic strength of its size. Therefore, too large a fillet is not efficient for good bonding, not only for economical reasons, but also by technical interference.

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TABLES

Table 1. Partial Results of Preliminary Test for Determination of Loading System

	Fillet Height [2.0]		Blank	
	Max. Load	Failure	Max. Load	Failure
Two-Point Loading $\ell' = 1/4$	547 lbs.	Glueline shear	563 lbs.	Facing tension
Mid-Span Loading $\ell' = 0$	457 lbs.	Facing tension	380 lbs.	Facing tension

Table 2. Results of Tensile Test for Fillet Height Group [0.5]

Sample No.	Tensile Strength psi.	Deflection mm.	Fillet Height mm. 1	2	3	4	Mean	Fillet Width mm. 1	2	3	4	Mean	F.F. %
1	39	0.23	1.20	1.40	1.40	1.05	1.26	1.45	1.10	1.15	0.95	1.16	0
2	40	0.25	0.95	1.45	1.50	1.25	1.29	1.30	1.20	1.50	1.40	1.35	0
3	46	0.20	1.10	1.35	1.20	1.10	1.19	1.10	1.25	1.25	1.20	1.20	0
4	51	0.48	0.90	1.55	1.25	1.30	1.25	1.35	1.50	1.30	1.20	1.34	0
5	46	0.36	1.45	1.45	1.45	1.40	1.44	1.75	1.75	1.60	1.65	1.69	0
6	43	0.63	1.45	1.15	1.00	1.15	1.19	1.40	1.10	1.25	1.30	1.26	0
7	52	0.56	1.45	1.35	1.25	1.10	1.29	1.30	1.25	1.60	1.40	1.39	0
8	52	1.02	1.30	1.50	1.70	1.30	1.45	1.55	1.50	1.70	1.65	1.60	0
9	62	0.51	0.95	1.30	1.20	1.15	1.15	1.20	1.20	1.20	1.20	1.20	12
10	54	0.38	1.20	1.40	1.35	1.00	1.24	1.45	1.50	1.35	1.60	1.48	0
Mean	48.5	0.462					1.275					1.367	1.2

F.F. = Facing Failure

Table 3. Results of Tensile Test for Fillet Height Group [1.0]

Sample No.	Tensile Strength psi.	Deflection mm.	Fillet Height mm. 1	2	3	4	Mean	Fillet Width mm. 1	2	3	4	Mean	F.F. %
1	77	0.53	2.00	2.20	2.20	2.00	2.10	4.60	3.20	3.35	2.80	3.49	8
2	65	1.22	2.00	2.25	2.20	1.95	2.10	1.85	2.35	1.80	2.05	2.01	10
3	50	0.81	1.80	2.15	2.20	2.45	1.90	2.50	2.40	2.55	2.60	2.51	12
4	41	0.33	1.80	1.60	2.00	1.50	1.73	2.20	2.00	2.05	2.05	2.08	24
5	60	0.74	2.20	1.85	1.95	1.95	1.99	2.80	2.40	2.35	2.30	2.46	8
6	61	1.17	1.90	1.75	2.00	2.10	1.94	2.50	2.40	2.10	2.25	2.31	6
7	49	0.56	2.15	2.30	1.90	1.90	2.06	2.90	3.25	2.85	2.80	2.95	12
8	53	0.76	1.85	2.00	1.80	1.80	1.86	2.55	2.25	2.00	2.60	2.35	8
9	55	0.51	1.75	2.50	2.20	2.50	2.24	2.95	2.65	2.90	2.55	2.76	0
10	38	0.33	2.50	2.50	2.20	2.30	2.38	3.05	3.00	2.40	2.85	2.83	4
Mean	54.9	0.696					2.030					2.575	9.2

F.F. = Facing Failure

Table 4. Results of Tensile Test for Fillet Height Group [1.5]

Sample No.	Tensile Strength psi.	Deflection mm.	Fillet Height mm.					Fillet Width mm.					F.F.
			1	2	3	4	Mean	1	2	3	4	Mean	%
1	66	0.79	2.35	2.55	2.60	2.35	2.46	3.60	3.25	3.70	2.95	3.38	0
2	63	1.15	2.65	2.95	2.90	2.95	2.86	3.80	3.50	3.45	3.70	3.61	12
3	69	0.99	2.95	2.95	2.60	2.40	2.73	3.25	3.65	4.20	3.40	3.63	14
4	49	0.38	2.50	2.80	2.95	2.55	2.70	3.95	3.30	3.30	3.75	3.58	0
5	72	0.97	3.00	2.95	2.40	2.70	2.76	3.85	3.80	4.50	4.35	4.13	12
6	79	0.99	2.55	2.85	3.10	2.75	2.81	3.75	3.70	4.30	5.00	4.19	8
7	79	1.07	2.50	2.35	2.50	2.45	2.45	4.45	4.45	3.65	4.40	4.24	0
8	93	1.02	2.50	2.35	2.35	2.70	2.48	4.05	3.40	3.20	3.80	3.61	12
9	84	0.99	2.50	2.65	2.70	2.65	2.63	3.55	4.00	4.35	4.05	3.99	16
10	72	1.02	2.70	2.40	2.60	2.35	2.51	3.60	3.70	3.35	3.70	3.59	0
Mean	72.6	0.937					2.639					3.795	7.4

F.F. = Facing Failure

Table 5. Results of Tensile Test for Fillet Height Group [2.0]

Sample No.	Tensile Strength psi.	Deflection mm.	Fillet Height mm.					Fillet Width mm.					F.F. %
			1	2	3	4	Mean	1	2	3	4	Mean	
1	83	1.07	3.15	2.60	2.50	2.90	2.79	4.20	4.00	3.55	4.45	4.05	0
2	75	0.71	3.45	3.20	3.45	2.95	3.26	3.95	3.65	3.85	3.85	3.83	0
3	70	0.58	3.20	3.20	3.50	3.25	3.29	3.95	4.00	3.80	3.80	3.89	8
4	79	0.86	2.85	3.00	3.20	2.70	2.94	3.90	4.25	3.70	4.20	4.01	0
5	59	0.51	3.40	3.80	3.90	3.20	3.58	3.95	3.80	3.60	3.80	3.79	14
6	69	1.25	3.30	3.15	3.40	3.20	3.26	3.45	3.25	3.05	3.70	3.36	0
7	61	0.51	3.55	3.60	3.15	3.20	3.38	3.10	3.20	4.35	4.60	3.81	4
8	55	0.61	3.50	3.25	3.20	3.45	3.35	4.00	3.85	3.40	4.40	3.91	3
9	58	0.64	3.60	3.35	3.50	3.00	3.36	3.80	4.25	3.65	3.70	3.85	1
10	67	0.64	3.40	3.25	3.35	3.15	3.29	4.25	3.60	4.10	3.60	3.89	6
Mean	67.6	0.738					3.250					3.839	3.6

F.F. = Facing Failure

Table 6. Glue Depth and Fillet Height in Tensile Test Specimens

Fillet Height Group	Glue Depth	Fillet Height	Difference
[0.5]	0.7 mm.	1.28 mm.	0.58 mm.
[1.0]	1.4	2.03	0.63
[1.5]	2.1	2.64	0.54
[2.0]	2.8	3.25	0.45

Table 7. Fracture/ Fillet-Width Ratio in Selected Tensile Test Specimens

	No.	1			2			3			4			Mean
		X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	$R=X_f/X_w$
[0.5]	1	55	17	0.310	55	20	0.364	54	24	0.444	40	24	0.600	0.430
	2	56	21	0.374	47	20	0.425	54	24	0.444	56	25	0.446	0.422
	3	60	28	0.466	76	28	0.369	54	23	0.426	50	26	0.520	0.445
	5	70	25	0.357	65	32	0.494	65	27	0.414	71	30	0.423	0.421
	6	40	20	0.500	50	21	0.420	54	20	0.371	47	22	0.469	0.440
	Mean													0.432
[1.0]	1	130	30	0.231	137	40	0.292	105	32	0.306	105	45	0.428	0.314
	3	110	42	0.382	108	45	0.416	105	35	0.368	115	42	0.365	0.383
	6	88	30	0.341	80	30	0.375	93	35	0.376	89	45	0.393	0.371
	7	113	35	0.310	109	32	0.294	125	45	0.360	119	30	0.252	0.304
	8	90	29	0.322	95	32	0.338	100	28	0.280	97	36	0.372	0.328
	Mean													0.340
[1.5]	3	145	41	0.282	145	40	0.276	142	50	0.352	137	41	0.300	0.302
	4	174	52	0.300	156	54	0.346	121	40	0.330	145	53	0.366	0.336
	5	158	56	0.354	137	64	0.466	143	60	0.420	158	49	0.310	0.387
	6	165	45	0.273	150	49	0.327	131	54	0.414	125	41	0.328	0.336
	10	125	47	0.375	119	44	0.470	136	49	0.360	144	50	0.347	0.388
	Mean													0.350
[2.0]	1	163	53	0.325	140	42	0.300	165	49	0.297	128	40	0.312	0.309
	2	138	50	0.362	133	45	0.345	157	50	0.339	129	57	0.442	0.372
	3	138	50	0.362	148	40	0.270	150	43	0.286	141	50	0.354	0.318
	4	168	54	0.321	158	45	0.285	165	53	0.321	175	49	0.280	0.302
	8	140	56	0.400	140	55	0.393	130	51	0.392	145	56	0.386	0.417
	Mean													0.344

Note: X_w = Fillet width in 1/1000 inch

X_f = Width of fracture in fillet in 1/1000 inch.

Table 8. Auxiliary Table for Statistical Analysis of Tensile Test Results - (A)

		Fillet Height X_1	Fillet Width X_2	Deflection X_3	Facing Failure X_4	Tensile Strength Y	df
[0.5]	ΣX	12.75	13.67	4.62	12	485	
	ΣX^2	16.3467	18.9699	2.6708	144	239.71	
	$(\Sigma X)^2$	162.5625	186.8689	21.3444	144	235225	
	SS	0.0904	0.2830	0.5364	129.6	448.5	
	S	0.10	0.18	0.24	3.8	7.1	9
	$\bar{X}$	1.275	1.367	0.46	1.2	48.5	
[1.0]	ΣX	20.03	25.75	6.96	92	549	
	ΣX^2	41.5318	68.0859	5.7110	1208	31335	
	$(\Sigma X)^2$	412.0900	663.0625	48.4416	8464	301401	
	SS	0.3228	1.7796	0.8668	361.6	1194.9	
	S	0.19	0.44	0.31	6.3	11.5	9
	$\bar{X}$	2.030	2.575	0.696	9.2	54.9	
[1.5]	ΣX	26.39	37.95	9.37	74	726	
	ΣX^2	69.8577	144.8807	9.1979	948	54042	

Table 8. (Continued)

		X_1	X_2	X_3	X_4	Y	df
[1.5]	$(\Sigma X)^2$	696.4321	1440.2025	87.7969	5476	527076	
	SS	0.2145	0.8604	0.4182	400.4	1334.4	
	S	0.15	0.31	0.22	6.7	12.2	9
	$\bar{X}$	2.639	3.795	0.937	7.4	72.6	
[2.0]	ΣX	32.50	38.39	7.38	36	676	
	ΣX^2	106.0840	147.6961	5.9990	322	46496	
	$(\Sigma X)^2$	1056.2500	1473.7921	54.4644	1296	456976	
	SS	0.4590	0.3169	0.5526	192.4	798.4	
	S	0.23	0.19	0.25	4.6	9.4	9
	$\bar{X}$	3.250	3.839	0.74	3.6	67.6	
Total.	ΣX	91.94	115.76	28.33	214	2436	
	ΣX^2	233.8202	379.6326	23.5787	2622	155844	
	CF	211.3240	312.2574	20.0647	1144.9	148352.4	
	SS	22.4962	67.3752	3.5140	1477.1	7481.6	
	S	0.79	1.37	0.31	6.41	14.42	36
	$\bar{X}$	2.30	2.89	0.71	5.35	60.90	

Note: SS = Sum of squares, S = Standard deviation, CF = Correction factor = $(\Sigma X)^2/40$

Table 9. Auxiliary Table for Statistical Analysis of Tensile Test Results - (B)

	X_1X_2	X_1X_3	X_1Y	X_2Y	X_3Y	X_4Y 1)
[0.5]	17.5674	5.9775	617.38	664.50	230.60	744
[1.0]	52.6600	14.0223	1115.03	1427.11	398.22	4860
[1.5]	100.2334	24.7352	1909.75	2769.10	695.56	5678
[2.0]	124.6050	23.9656	2180.53	2599.33	511.60	2255
Total	295.0658	68.7006	5822.69	7460.04	1835.98	13537
CF 2)	266.07	65.117	5599.146	7049.78	1725.29	13032.6
SP 3)	28.99	3.580	223.54	410.26	110.69	504.4

Note: 1) Symbols from Table 8
2) Correction factor
3) Sum of products

Table 10. Results of Flexure Test for Fillet Height Group [0.5]

No.	Max. Load lbs.	Shear Strength psi.	Deflection mm.	Fillet Height (mm.) 1	2	3	4	Mean	Fillet Width (mm.) 1	2	3	4	Mean	Type of Failure
1	540	56.9	2.54	1.30	1.45	1.40	1.70	1.46	1.85	1.65	1.75	1.40	1.66	GF
2	475	50.0	1.91	0.60	0.70	0.65	0.80	0.69	2.00	2.00	1.40	1.55	1.74	GF
3	496	52.2	2.29	1.05	1.00	1.25	1.25	1.14	1.15	1.00	1.55	1.00	1.18	GF
4	500	52.6	2.87	0.90	1.00	0.95	0.85	0.93	1.25	1.60	1.20	1.70	1.44	GF
5	443	46.6	1.83	0.60	0.70	0.65	0.70	0.66	1.60	1.70	1.65	1.40	1.59	GF
6	485	51.1	2.16	0.85	0.50	0.80	0.70	0.71	1.45	1.60	1.45	1.60	1.53	GF+CF
7	455	47.9	2.03	0.95	0.80	0.60	0.75	0.78	1.30	1.30	1.45	1.35	1.35	GF
8	475	50.0	2.80	0.70	0.75	0.90	0.80	0.79	1.35	1.60	1.35	1.35	1.43	GF+CF
9	495	52.1	2.03	0.70	0.80	0.75	0.75	0.75	1.30	1.30	1.65	1.60	1.46	GF
10	482	50.7	1.63	1.00	1.10	1.00	1.10	1.05	1.45	1.10	0.75	0.80	1.03	GF
11	535	56.3	2.46	0.80	1.00	0.95	1.10	0.96	1.45	1.45	1.25	1.45	1.40	GF
12	466	49.1	2.03	1.00	0.95	0.95	1.00	0.98	1.10	1.20	0.90	1.00	1.05	GF
13	518	54.5	1.98	1.35	1.15	1.15	0.95	1.15	1.70	1.70	1.70	1.45	1.64	GF+CF
14	493	51.9	2.11	0.95	0.95	1.25	1.15	1.08	1.45	1.35	1.20	1.25	1.31	GF+CF
15	492	51.8	2.03	0.90	0.60	1.00	0.95	0.86	1.25	1.30	1.45	1.70	1.43	GF
16	445	46.8	1.91	0.70	0.70	0.70	0.60	0.68	1.10	1.20	1.15	1.25	1.19	GF
17	439	46.2	2.80	0.80	0.85	1.00	1.10	0.94	1.05	0.85	1.00	0.90	0.95	GF
18	490	51.6	2.80	0.65	1.00	1.00	1.10	0.94	1.45	1.50	1.50	1.45	1.48	GF+CF
19	446	46.9	2.03	0.80	0.70	0.80	0.70	0.75	0.95	1.10	1.00	1.20	1.06	GF
20	500	52.6	1.65	0.60	0.85	0.85	0.85	0.79	1.45	1.35	1.45	1.40	1.41	GF
Mean	483.5	50.89	2.19					0.90					1.37	

Note: CF = Core failure
GF = Glueline failure
FF = Facing failure.

Table 11. Results of Flexure Test for Fillet Height Group [1.0]

No.	Max. Load lbs.	Shear Strength psi.	Deflection mm.	Fillet Height (mm.)					Fillet Width (mm.)					Type of Failure
				1	2	3	4	Mean	1	2	3	4	Mean	
1	467	49.2	2.16	1.50	1.75	1.50	1.65	1.60	1.35	1.70	1.85	1.70	1.65	GF
2	469	49.4	3.81	1.80	1.90	1.95	1.80	1.86	2.35	1.90	1.70	2.10	2.01	GF+CF
3	470	49.5	2.82	1.60	2.10	2.00	1.85	1.89	1.75	1.80	1.30	1.45	1.58	CF
4	441	46.4	1.53	1.90	1.75	1.50	1.60	1.69	1.25	1.95	1.70	1.80	1.68	GF
5	480	50.5	2.04	1.85	1.90	1.85	1.90	1.88	2.00	1.90	2.00	1.90	1.95	GF
6	424	44.6	1.78	1.20	1.80	1.60	1.80	1.60	1.65	1.70	2.15	1.65	1.79	GF
7	485	51.1	2.42	1.65	1.65	1.60	1.85	1.69	2.15	2.15	2.35	2.25	2.23	GF+CF
8	453	47.7	2.80	2.30	1.90	1.90	1.80	1.98	2.40	2.15	2.10	1.95	2.15	GF
9	480	50.5	2.04	1.85	1.85	1.90	2.00	1.90	2.00	2.10	2.05	2.00	2.04	GF
10	447	47.1	2.28	1.40	1.70	1.45	1.55	1.53	1.80	2.20	1.65	2.15	1.95	GF
11	478	50.3	2.04	2.00	2.25	2.25	2.30	2.20	2.15	2.15	2.05	2.00	2.09	GF
12	464	48.9	2.67	1.80	1.80	1.65	2.00	1.81	1.30	1.55	1.80	1.70	1.59	GF
13	402	42.3	1.83	1.50	1.45	1.65	1.80	1.60	1.65	1.60	2.05	1.45	1.69	GF
14	455	47.9	2.80	1.80	1.70	1.90	2.00	1.85	1.80	2.70	2.00	1.70	1.88	GF
15	480	50.5	2.04	1.90	1.85	1.90	1.80	1.86	1.90	1.85	1.95	2.00	1.93	GF
16	422	44.4	2.54	1.60	1.95	1.65	1.95	1.79	1.75	2.00	2.00	2.00	1.94	GF+CF
17	460	48.4	4.82	1.10	1.40	1.30	1.40	1.30	1.75	2.05	2.15	2.20	2.04	CF+FF
18	470	49.5	2.04	1.00	0.80	1.60	1.35	1.19	1.85	1.60	1.65	1.65	1.69	GF+CF
19	540	56.8	3.05	1.35	1.10	1.60	1.40	1.36	2.00	2.05	2.15	1.95	2.04	GF
20	425	44.7	3.56	1.30	1.25	1.35	1.45	1.34	2.15	1.90	2.00	2.00	2.01	CF
Mean	460.6	48.48	2.55					1.70					1.90	

Note: CF = Core failure
GF = Glueline failure
FF = Facing failure.

Table 12. Results of Flexure Test for Fillet Height Group [1.5]

No.	Max. Load lbs.	Shear Strength psi.	Deflection mm.	Fillet Height (mm.) 1	2	3	4	Mean	Fillet Width (mm.) 1	2	3	4	Mean	Type of Failure
1	502	52.8	2.92	2.15	2.40	2.35	2.50	2.35	2.40	2.20	2.65	2.65	2.48	GF
2	518	54.5	2.54	2.00	2.45	1.80	1.80	2.01	2.35	2.55	2.30	2.75	2.49	GF
3	517	54.4	3.81	2.00	2.15	2.35	2.50	2.25	2.80	2.50	2.00	2.25	2.39	GF+CF
4	555	58.4	3.81	1.90	2.15	2.40	2.60	2.26	2.30	2.45	2.25	2.35	2.34	GF+CF
5	545	57.4	3.56	1.90	2.40	2.35	2.35	2.25	2.30	2.65	2.25	2.60	2.45	GF+CF
6	519	54.6	3.04	2.35	2.60	2.05	2.20	2.30	2.30	2.00	2.30	2.60	2.30	GF+CF
7	547	57.6	3.81	2.70	2.40	2.20	2.35	2.41	2.55	2.40	2.40	2.15	2.38	CF
8	472	49.7	3.81	2.50	2.25	2.60	2.65	2.50	2.45	2 30	2.60	2.45	2.45	GF+CF
9	548	57.7	3.04	2.15	2.20	2.45	2.55	2.34	2.60	2.15	2.40	2.35	2.38	GF+CF
10	541	56.9	3.81	2.30	2.25	2.30	2.80	2.41	2.10	2.10	2.20	2.15	2.14	GF+CF
11	500	52.6	3.91	2.35	2.40	2.85	2.85	2.61	2.20	2.25	2.40	2.40	2.31	GF+CF
12	550	57.9	3.94	2.65	2.50	2.45	2.50	2.53	2.10	2.05	2.10	2.20	2.11	CF
13	514	54.1	3.30	2.45	2.35	2.20	2.25	2.31	2 25	2.40	2.45	2.20	2.33	CF
15	495	52.1	3.81	2.30	2.75	2.25	2.50	2.45	2.45	2.20	2.25	2.50	2.35	CF
16	505	53.2	3.68	2.60	2.75	2.55	2.50	2.60	2.20	2.45	2.40	2.35	2.35	GF+CF
17	527	55.5	3.81	2.30	2.30	2.10	2.35	2.26	2.40	2.30	3.00	2.60	2.58	CF
18	510	53.7	3.56	2.60	2.30	2.50	2.45	2.46	2.45	2.35	2.80	2.30	2.48	CF
19	495	52.1	3.30	2.60	2.70	2.45	2.25	2.50	2.05	2.30	2.45	1.95	2.19	CF
20	493	51.9	4.06	2.85	2.75	2.50	2.65	2.69	2.45	1.95	1.85	2.15	2.10	GF
Mean	518.2	54.54	3.54					2.39					2.34	

Note: CF = Core failure
GF = Glueline failure
FF = Facing Failure.

Table 13. Results of Flexure Test for Fillet Height Group [2.0]

No.	Max. Load lbs.	Shear Strength psi.	Deflection mm.	Fillet Height (mm.)					Fillet Width (mm.)					Type of Failure
				1	2	3	4	Mean	1	2	3	4	Mean	
1	595	62.6	6.35	2.95	3.05	2.55	2.65	2.80	2.50	2.45	2.80	2.55	2.58	CF
2	482	50.7	3.81	2.95	3.15	3.30	3.05	3.11	2.25	2.45	2.85	2.40	2.49	CF
3	590	62.1	6.35	3.00	3.00	3.85	3.05	3.23	2.00	2.50	2.50	2.80	2.45	CF
4	500	52.6	3.79	2.60	2.55	2.65	2.85	2.66	3.00	2.60	2.90	2.60	2.78	GF+CF
5	575	60.5	5.85	3.20	3.15	3.05	3.20	3.15	2.35	2.70	2.65	2.60	2.58	CF
6	560	58.9	5.85	3.20	3.80	2.55	2.90	3.11	2.35	2.05	2.35	2.70	2.36	CF
7	517	54.4	5.85	3.20	3.10	2.85	3.45	3.15	2.60	2.70	2.60	2.75	2.66	CF
8	508	53.5	3.81	3.05	2.60	2.40	2.50	2.64	2.15	2.20	2.55	2.35	2.31	GF+CF
9	526	55.4	5.08	2.25	2.90	3.00	3.10	2.81	2.05	2.75	2.70	2.20	2.43	GF+CF
10	539	56.7	6.35	3.05	3.00	2.85	2.90	2.95	2.85	2.75	2.90	2.20	2.68	CF
11	500	52.6	5.59	2.65	3.45	2.70	2.45	3.06	2.15	2.85	2.95	2.15	2.53	CF
12	560	58.9	4.32	2.55	2.80	2.95	2.90	2.80	2.65	2.70	2.45	2.35	2 54	CF
13	550	57.9	5.85	3.50	3.50	3.65	3.60	3.56	2.65	2.80	2.65	2.20	2.58	CF
14	536	56.4	4.32	3.40	3.10	3.40	3.40	3.33	2.45	2.40	2.25	2.40	2.38	CF
15	595	62.6	4.57	2.75	2.80	2.60	3.00	2.79	2.60	2.80	2.75	2.40	2.64	CF
16	515	54.2	5.08	3.20	3.35	3.40	3.50	3.36	3.00	2.90	3.20	2.80	2.98	CF
17	470	49.5	5.96	3.85	3.70	3.90	3.40	3.71	2.35	3.30	2.70	2.30	2.66	CF
18	530	55.8	5.04	3.55	3.75	3.20	3.20	3.43	2.35	1.60	2.80	2.40	2.29	CF+FF
19	505	53.2	5.40	3.60	2.80	3.20	3.45	3.26	2.60	3.10	2.90	3.10	2.93	CF
20	530	55.8	5.08	2.95	2.90	2.90	2.70	2.86	2.70	3.00	2.75	2.85	2.83	CF+FF
Mean	534.2	56.22	5.22					3.09					2.58	

Note: CF = Core failure
GF = Glueline failure
FF = Facing failure.

Table 14. Fracture/Fillet-Width Ratio in Selected Flexure Test Specimens

	No.	1			2			3			4			Mean
		X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	X_w	X_f	X_f/X_w	X_f/X_w
[0.5]	4	63	23	0.37	75	30	0.40	57	24	0.42	55	25	0.45	0.41
	5	50	23	0.46	49	21	0.43	53	25	0.47	49	24	0.49	0.46
	9	65	19	0.29	65	22	0.34	65	20	0.31	65	24	0.37	0.33
	2	70	25	0.33	81	35	0.43	65	25	0.39	50	20	0.40	0.39
	1	75	28	0.37	65	22	0.34	69	25	0.37	75	25	0.33	0.37
														0.39
[1.0]	4	76	26	0.34	75	30	0.40	80	30	0.38	80	25	0.31	0.36
	11	70	27	0.39	68	25	0.37	70	18	0.26	73	25	0.34	0.34
	12	73	24	0.33	75	28	0.37	70	25	0.36	75	20	0.27	0.34
	13	70	24	0.34	80	30	0.38	76	30	0.40	70	27	0.39	0.38
	14	79	34	0.43	80	40	0.50	75	32	0.43	85	40	0.47	0.46
														0.38
[1.5]	1	110	40	0.36	99	37	0.37	97	45	0.46	100	36	0.36	0.39
	2	102	38	0.37	95	38	0.40	99	45	0.45	100	40	0.40	0.41
	6	90	25	0.28	125	43	0.34	100	35	0.35	95	29	0.31	0.32
	9	97	45	0.46	112	45	0.40	95	34	0.36	116	33	0.29	0.38
	10	121	35	0.29	125	30	0.24	85	32	0.38	120	42	0.35	0.32
														0.36
[2.0]	4	200	70	0.35	170	37	0.22	195	50	0.26	139	48	0.35	0.30
	8	100	40	0.40	128	30	0.23	145	50	0.35	110	46	0.42	0.35
	9	75	27	0.36	163	62	0.38	150	45	0.30	93	37	0.40	0.35
														0.34

Note: X_w = Fillet width in 1/1000 inch

X_f = Width of fracture in fillet in 1/1000 inch.

Table 15. Auxiliary Table for Statistical Analysis of Flexure Test Results

		Fillet Height X_1	Fillet Width X_2	Deflection X_3	Shear Strength Y	df
[0.5]	ΣX	18.09	27.33	48.89	1017.8	
	ΣX^2	17.1361	38.3119	99.1713	51972.50	
	$(\Sigma X)^2$	327.2481	746.9289	1926.3321	1035916.84	
	SS	0.7737	0.9655	2.8547	176.66	
	S	0.20	0.23	0.39	3.05	19
	$\bar{X}$	0.90	1.37	2.19	50.9	
[1.0]	ΣX	33.92	37.93	51.07	969.7	
	ΣX^2	58.7832	72.6421	142.3241	47202.53	
	$(\Sigma X)^2$	1150.5664	1438.6849	2608.1449	940318.09	
	SS	1.2549	0.7079	11.9169	186.63	
	S	0.26	0.19	0.79	3.13	19
	$\bar{X}$	1.70	1.90	2.55	48.5	
[1.5]	ΣX	47.82	46.83	70.70	1090.8	
	ΣX^2	114.8128	109.9895	253.1512	59604.96	

Table 15. (Continued)

		X_1	X_2	X_3	Y	df
[1.5]	$(\Sigma X)^2$	2286.7524	2193.0489	4998.49	1189844.64	
	SS	0.4752	0.3371	3.1267	112.73	
	S	0.16	0.13	0.41	2.44	19
	$\bar{X}$	2.39	2.34	3.54	54.5	
[2.0]	ΣX	61.77	51.68	104.30	1124.3	
	ΣX^2	192.4819	134.2492	558.2140	63481.05	
	$(\Sigma X)^2$	3815.5329	2670.8224	10878.49	1264050.49	
	SS	1.7053	0.7081	14.7895	278.53	
	S	0.30	0.19	0.88	3.83	19
	$\bar{X}$	3.09	2.58	5.22	56.2	
Total	ΣX	161.60	163.77	269.96	4202.6	
	X^2	383.2140	355.1929	1052.8686	222261.04	
	$(\Sigma X)^2$	26114.5600	26820.6129	72878.4016	17661846.76	
	SS	56.7820	19.9351	141.889	1487.96	
	S	0.86	0.51	1.37	4.42	76
	$\bar{X}$	2.02	2.05	3.37	52.5	

Note: SS = Sum of squares, S = Standard deviation

APPENDICES

APPENDIX 1

Tables of Analysis of Variance and Duncan's New Multiple Range Test for Fillet Width means in Tensile Test Specimens

a. Analysis of Variance

Source	df	SS	MS	F
Height Treatment	3	64.135	21.378	237.53**
Error	36	3.240	0.090	
Total	39	67.375		

** indicates significance at the 1% level.

b. Duncan's New Multiple Range Test

Tr.	$\overline{X}_2$	$TV_{.05}$	$SSR_{.05}$	D_1	D_2	D_3	$TV_{.01}$	$SSR_{.01}$	D_1	D_2	D_3
[2.0]	3.839	3.114	0.2958	+			4.126	0.3919	+		
[1.5]	3.795	3.018	0.2863	+	+		4.015	0.3814	+	+	
[1.0]	2.575	2.870	0.2762	-	+	+	3.851	0.3658	-	+	+
[0.5]	1.367										

$$n = 10, \quad S_{\overline{x}} = \sqrt{\frac{EMS}{n}} = 0.095$$

[0.5]	[1.0]	[1.5]	[2.0]
1.367	2.575	<u>3.795</u>	<u>3.839</u>

Means underlined by the same line did not differ significantly(P = .01).

APPENDIX 2

Tables of Analysis of Variance and Duncan's New Multiple Range Test for Tensile Strength Means in Tensile Test Specimens

a. Analysis of Variance

Source	df	SS	MS	F
Height Treatment	3	3715.4	1238.5	11.81**
Error	36	3776.2	104.9	
Total	39	7491.6		

** indicates significance at the 1% level.

b. Duncan's New Multiple Range Test

Tr.	$\overline{Y}$	$TV_{.05}$	$SSR_{.05}$	D_1	D_2	D_3	$TV_{.01}$	$SSR_{.01}$	D_1	D_2	D_3
[1.5]	72.6	3.114	10.09	+			4.126	13.36	+		
[2.0]	67.6	3.018	9.78	+	+		4.015	13.00	+	+	
[1.0]	54.9	2.870	9.30	-	+	-	3.851	12.47	-	+	-
[0.5]	48.5										

$$n = 10, \quad S_{\overline{Y}} = \sqrt{\frac{EMS}{n}} = 3.239$$

[0.5] [1.0] [2.0] [1.5]
<u>48.5 54.9</u> <u>67.6 72.6</u>

Means underlined by the same line did not differ significantly (P = .01).

APPENDIX 3

Basic Equations

a. Modulus of Rupture of Facing in Bending (30)

$$\sigma_b = \frac{M\,y}{I}$$

$$M = \frac{P}{4}(\ell - \ell')$$

$$y = \frac{1}{2}h$$

$$I = \frac{b(h^3 - c^3)}{12}$$

$$\sigma_b = \frac{\frac{1}{4}P(\ell - \ell')\,\frac{1}{2}h}{\frac{b(h^3 - c^3)}{12}} = \frac{3Ph(\ell - \ell')}{2b(h^3 - c^3)}$$

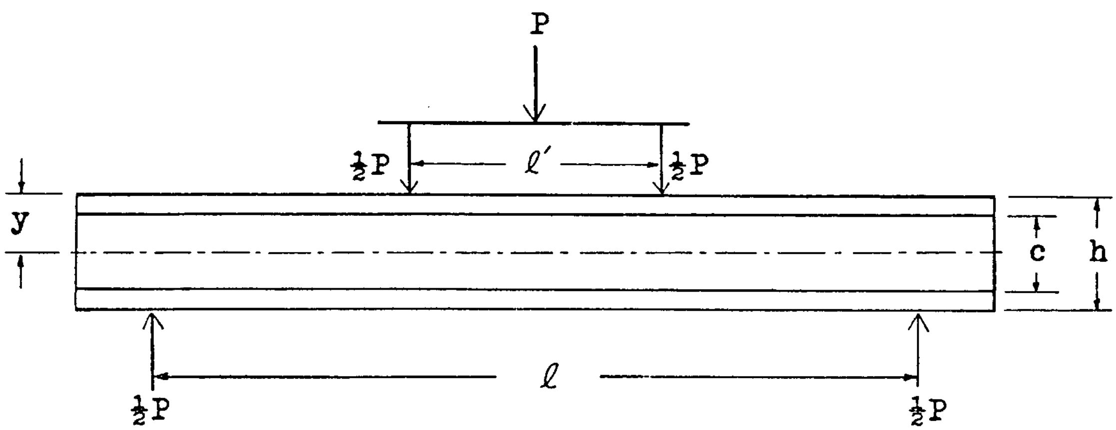
where σ_b : modulus of rupture in bending (psi.)

M : bending moment (in. lb.)

I : moment of inertia (in.^{4})

b : width of beam (in.)

P : load (lbs.)



APPENDIX 3 (Continued)

b. Horizontal Shear Stress in Glueline (37)

$$\tau_h = \frac{VQ}{Ib}, \qquad V = \frac{1}{2}P, \qquad Q = \frac{1}{8}\, b(h^2 - c^2)$$

$$\tau_h = \frac{\frac{1}{2}P(b/8)(h^2 - c^2)}{\frac{b(h^3 - c^3)}{12}\, b} = \frac{3P(h^2 - c^2)}{4b(h^3 - c^3)}$$

where τ_h : horizontal shear stress (psi.)

V : total shear at the section (lbs.)

Q : statical moment of the area above the plane upon which the unit shear is computed, taken about the neutral axis of the beam (in.^{3}).

APPENDIX 4

Tables of Analysis of Variance and Duncan's New Multiple Range Test for Fillet Width Means in Flexure Test Specimens

a. Analysis of Variance

Source	df	SS	MS	F
Height Treatment	3	17.216	5.739	160.3**
Error	76	2.719	0.0358	
Total	79	19.935		

** indicates significance at the 1% level.

b. Duncan's New Multiple Range Test

Tr.	$\overline{X}_2$	$TV_{.05}$	$SSR_{.05}$	D_1	D_2	D_3	$TV_{.01}$	$SSR_{.01}$	D_1	D_2	D_3
[2.0]	2.58	3.066	0.129	+			4.013	0.169	+		
[1.5]	2.34	2.969	0.125	+	+		3.905	0.164	+	+	
[1.0]	1.90	2.821	0.118	+	+	+	3.746	0.157	+	+	+
[0.5]	1.37										

$$n = 20, \quad S_{\bar{x}} = \sqrt{\frac{EMS}{n}} = 0.042$$

According to Duncan's N.M.R. Test, fillet width means ranked as:

$$[0.5] < [1.0] < [1.5] < [2.0]$$

at the 1% level of significance.

APPENDIX 5

Tables of Analysis of Variance and Duncan's New Multiple Range Test for Shear Strength Means in Flexure Test Specimens

a. Analysis of Variance

Source	df	SS	MS	F
Height Treatment	3	733.42	244.47	24.62**
Error	76	755.54	9.93	
Total	79	1487.96		

** indicates significance at the 1% level.

b. Duncan's New Multiple Range Test

Tr.	$\overline{Y}$	$TV_{.05}$	$SSR_{.05}$	D_1	D_2	D_3	$TV_{.01}$	$SSR_{.01}$	D_1	D_2	D_3
[2.0]	56.22	3.066	2.160	+			4.013	2.827	+		
[1.5]	54.54	2.969	2.092	+	+		3.905	2.751	+	+	
[0.5]	50.89	2.821	1.987	-	+	+	3.746	2.639	-	+	-
[1.0]	48.48										

$$n = 20, \quad S_{\overline{Y}} = \sqrt{\frac{EMS}{n}} = 0.7045$$

At the 5% level of significance; [1.0] [0.5] [1.5] [2.0]
48.5 50.9 54.5 56.2

At the 1% level of significance; [1.0] [0.5] [1.5] [2.0]
48.5 50.9 54.5 56.2

Means underlined by the same line did not differ significantly.

APPENDIX 6

Tables of Analysis of Variance and Duncan's New Multiple Range Test for Deflection Means in Flexure Test Specimens

a. Analysis of Variance

Source	df	SS	MS	F
Height Treatment	3	109.59	36.53	85.95**
Error	76	32.30	0.425	
Total	79	141.89		

** indicates significance at the 1% level.

b. Duncan's New Multiple Range Test

Tr.	$\overline{X}_3$	$TV_{.05}$	$SSR_{.05}$	D_1	D_2	D_3	$TV_{.01}$	$SSR_{.01}$	D_1	D_2	D_3
[2.0]	5.22	3.066	0.448	+			4.013	0.585	+		
[1.5]	3.54	2.969	0.433	+	+		3.905	0.570	+	+	
[1.0]	2.55	2.821	0.412	+	+	-	3.746	0.546	+	+	-
[0.5]	2.19										

$$n = 20, \quad S_{\overline{x}} = \sqrt{\frac{EMS}{n}} = 0.146$$

[0.5] [1.0] [1.5] [2.0]
<u>2.19 2.55</u> 3.54 5.22

Means underlined by the same line did not differ significantly (P = .01).

APPENDIX 7

Sequences of Fillet Width Means

(Unit : mm.)

	Ext.	Empirical				Ext.	
Glue Depth	0.00	0.70	1.40	2.10	2.80	3.50	4.20
$\bar{X}_1$	0.30	0.90	1.70	2.39	3.09	3.80	4.50
$\bar{X}_2$	0.80	1.37	1.90	2.34	2.58	2.80	2.90
$\frac{\bar{X}_2 - t}{2}$	0.30	0.60	0.85	1.05	1.20	1.30	1.35
1st difference	0.30	0.25	0.20	0.15	0.10	0.05	
2nd difference		0.05	0.05	0.05	0.05	0.05	

$\bar{X}_1$ = Fillet height

$\bar{X}_2$ = Fillet width

t = Honeycomb cell wall thickness (0.2 mm.)

Ext. = Extrapolated

APPENDIX 8

Values of k/m for the Four Fillet Height Groups

	$\bar{Y}$	$x_1 = (\bar{X}_2 - t)/2$	$y = 0.3x_1$	100 k/m
[0.5]	48.5	0.557	0.167	0.81
[1.0]	54.9	1.161	0.348	1.03
[1.5]	72.6	1.771	0.531	1.04
[2.0]	67.6	1.793	0.538	1.13

$$\frac{k}{m} = \frac{y + 0.22}{\bar{Y}}$$

APPENDIX 9

Core Shear Stress under Two-Point Loading

When two loading points are located at a distance of 3/8-span from each support, core shear stress is calculated as follows (4):

$$S = \frac{P_2}{(h + c)b} k ,$$

where S = core shear stress (psi.)

h = sandwich thickness = 1.5 inch

c = core thickness = 1 inch

b = sandwich width = 0.375 inch

P_2 = flexure load (lbs.)

$k = 1 - e^{-B}$, and

$$B = \frac{3a_2 \ (c + f)}{16f} \sqrt{\frac{6G}{Ecf}}$$

f = facing thickness = 0.25 inch

E = modulus elasticity of the facing = 1,800,000 psi.(36)

G = effective core shear modulus = 8,000 psi.

Hence $B = 2.98$

and $k = 1 - e^{-2.98} = 0.958$.

Therefore $P_2 = S \ (h + c)b \frac{1}{0.958}$.

If $S = 70$ psi.,

then $P_2 = 70 \ (1.5 + 1) \times 3.75 \times \frac{1}{0.958} = 685$ lbs.