

THE RESISTANCE OF CASEIN GLUE JOINTS

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THE RESISTANCE OF CASEIN GLUE JOINTS

IN WOOD TO FATIGUE STRESSING

By

Ali Ashraf Moslemi

A THESIS

Submitted to the School of Graduate Studies of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Department of Forest Products

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ABSTRACT

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> In this investigation, the strength of casein glue joints in wood to fatigue stressing was studied. A specimen which suited test conditions to an appreciable extent, was designed. This specimen, according to its design, was subjected to a stress pattern consisting of torsional and simple shear components in which the previous was dominant in the resultant stress. In order to determine the strength of the glue joint to fatigue stressing, its strength to statical shear stresses created by the employed stress pattern had to be found. The results of the investigation are summarized in the following list:

- Casein glue joints in wood withstand higher statical torsional shear stresses than the standard maple block conventionally used for determination of shear stress in the glue line.
- 2. Failure by fatigue could be induced in the casein glue joints in wood.
- 3. Casein glue joints resist to a considerably high number of cycles in fatigue stressing in shear when the stress approaches about 30 per cent of average ultimate static shear stress of the joint.
- 4. The endurance limit of casein glue joints in fatigue stressing is expected to be approached if the magnitude of applied stress falls in a range between 20-25 per cent of average ultimate static shear stress of the joint.

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1 - INTRODUCTION

1.1 - Definition of Fatigue

Fatigue is the phenomenon of fracture under repeated stresses. The number of cycles to which the specimen resisted before failure has been termed the "life" of the specimen.

The term "fatigue" is not admittedly a proper descriptive term (7), but it has become so widely established in the literature that it will be wise to adhere to it throughout this paper.

1.2 - Historical Background

Fatigue testing was first undertaken on a large scale by August Wöhler in Germany in 1852 (7). Prior to Wöhler, however, similar experiments had been carried out in 1829 on mine-hoist chains (11).

Today, workers are still engaged in studying this unsolved problem all over the world in order to enable engineers and designers to predict the life of a material under repeated stresses, which is an important factor in the design of certain structures as well as machine parts.

1.3 - Fatigue Testing and its Importance

The fatigue strength of materials is one of the most challenging fields for engineering progress (8). This subject is of considerable concern since materials rupture at a unit stress not only less than the ultimate static strength of the material, but even less than the elastic limit, provided the stress is repeated a sufficient number of cycles.

Fatigue causes difficulties in a tremendous number of applications such as earth-moving equipment, railroad rolling stock, farm machinery, automobiles, as well as structures which are exposed to vibrating stresses.

Fatigue testing, primarily involves the application of cyclic loads on the material under investigation. The method of load application, depending on the investigator's purpose of analysis, is different. Fatigue tests can be made under conditions such as (a) complete reversal of tension and compression loads of equal magnitude, (b) complete reversal of tension and compression loads of unequal magnitudes, (c) fatigue tests in tension only and (d) fatigue tests in compression only. A material may or may not have the same behavior when subjected to these different forms of repeated stresses.

In fatigue research, usually the investigator finds out the life of the material in question, in terms of number of cycles to failure, at different stress levels and plots the calculated stress, S, as ordinate against the number of cycles, N, as abcissa. These diagrams are known as S-N curves (5) (6) (8).

In collecting fatigue data, a wide scatter is encountered in both homogenuous and heterogenuous materials (3). Although attempts have been made to investigate the character and range of such scatter in order to improve procedures of presentation and interpretation of test results, fatigue tests are in general planned and interpreted as if the fatigue life of a material were a fairly well controlled physical characteristic that can be determined, with

reasonable accuracy, by a small number of individual tests performed at various stress levels (3). The ASTM Manual on Fatigue Testing (9), for instance, recommends, as a normal procedure of S-N curve determination, testing at least ten specimens selecting stress values so as to yield a more or less uniform distribution of test points throughout the slected intervals of cycles-tofailure.

1.4 - Statement of the Problem

The purpose of this study was to find characteristics of adheaive bond to fatigue stressing. Data were to be represented by using statistical methods and interpreted. Conclusions were to be drawn.

1.5 - Design of Specimen

Frequently the shear strength of the glue line exceeds that of the wood, consequently resulting in appreciable wood failure on the glue bond. Getting a significant amount of wood failure on the bond would not obviously determine the true shear strength of the adhesive used. In addition, in many specimens used for shear strength determination of the glue line, such as standard maple block, the calculation of shear stress is not precisely performed.

To eliminate as much wood failure as possible throughout this investigation, a wood species which had high strength values had to be used. Hard maple seemed satisfactorily suitable for this purpose, since it possesses relatively high strength values (15).

To choose the adhesive for this study, one point had to be thoroughly considered. This was the strength properties of glue relative to those of the wood species employed. In a considerable number of adhesives, for many practical uses the glue bond yields higher strength values than the wood used. This phenomenon would consequently result in failure in the wood adjacent to the adhesive bond. In order to induce the failure on the glue bond and not in the wood, a kind of adhesive had to be used which had lower strength values than the wood species. Among commercially produced adhesives, casein seemed appropriate for the purpose since this type of adhesive yields lower strength values than those of other adhesives such as phenol formaldehyde, urea formaldehyde, resorcinol, etc.

The shape of the specimen was to be such that errors caused by bending moments would be entirely, or at least to a great extent eliminated. This elimination of bending moments would determine the true shear stress of the glue bond.

First, it was decided to make specimens composed of two members which, after gluing, would form a small beam with rectangular cross section. The glue line in this case would be located at the neutral axis of the beam. In this type of beam, the shear stress has a parabolic variation and it approaches its maximum magnitude at the neutral axis according to the following formulas

$$T_{xy} = \frac{3}{2} \frac{V}{b h} (1 - 4 \frac{V^2}{h^2})$$

in which V is the shearing force, b and h are the width and depth of the beam and y could be any point on the y axis, provided the origin is at the neutral axis. In the design of such a specimen two difficulties were encountered.

- 1. If the specimen was designed so that the failure would be likely to occur on the glue bond, a great amount of load had to be applied and in this study, the amount of load was limited to only 200 pounds in the fatigue machine.
- In the case of staying within the fatigue machine capacity, the specimen would fail by bending before the glue line fails in shear.

Because of the following reasons, it was decided to design a specimen in which the failure would be induced by torsional stresses in the glue line:

- 1. Failure could be induced by loads within the capacity of the fatigue machine.
- 2. The shear stress exerted on the glue line is well defined.
- 3. The influence of bending moments which would yield erroneous data, would be greatly eliminated.

The glue area had to be as small as feasible due to the following reasons:

1. Wood by nature is variable in its physical structure and behavior. In glue joint of the test specimens, the effects of variation in anatomy, specific gravity, moisture content of the different points on the glue line, and alignment of annual rings are of great significance. The degree of effectiveness of each of these variables is a moot question. Many of the abovementioned variables could not easily be entirely eliminated whereas their effectiveness could be decreased by reducing the glue area as much as practicable.

- 2. A small glue area will serve to reduce the development of internal stresses to an appreciable extent (14).
- 3. The shear stresses developed on the joint by the application of stress pattern subsequently described will be fairly uniform (1) (5).

The axis of rotation was chosen to be perpendicular to the glue line for simplicity and practical reasons.

A circular glue area had to be used because in a plane perpendicular to the axis of rotation, shear stresses act in a direction at right angles to the radial lines and therefore would tend to distort the shear plane if it was not circular. In the case of a square or rectangular glued area, the mathematical expressions for variation of stresses along x-and y-axes are:

 $T_{x} = f_{1} \left(1 - \frac{x^{2}}{a^{2}}\right) \frac{y}{b}$ and $T_{y} = f_{2} \left(1 - \frac{y^{2}}{b^{2}}\right) \frac{x}{a}$

in which ζ_{j} is the shear stress component along the y-axis and ζ_{x} the second component along the x-axis. After a mathematical process based on the definition of twisting moment and by using double integration, the maximum magnitude of the two shear stress components which are f_{1} and f_{2} turn out to be $f_{1} = \frac{kT}{ab^{2}}$ and $f_{2} = \frac{kT}{b^{2}a}$ in which f_{2} will tend to distort the glue area. In the case of an elliptical glue line there will again be $f_{1} = \frac{2Ty}{\pi ab^{2}}$ and $f_{2} = \frac{2}{Tx}$ may be in which the same discussion as in the case of the rectangular bar holds. In other words, in only one special case in which the tangent at every point on the boundary is at right angles to a line passing



The specimen employed in this investigation. Note that the point of load application is 15 inches away from the center of the joint. Figure 1.



Figure 2. Detailed dimensions of the three wooden members of each specimen. Note the circular glue line.

through the center of the glue line, the glue line will not tend to warp and this must consequently be a complete circle (see Figures 1 and 2).

As previously noted, a stress pattern was applied to the joint designed for this study. This pattern was a combination of torsional and simple shear stresses in which the first one was dominant. The torsional component of the stress pattern is computed as follows:

the torque

but

$$f = \frac{G \sigma_r}{L}$$

therefore

$$\mathbf{T} = \frac{\mathbf{G} \mathcal{O}}{\mathbf{L}} \int \mathbf{r}^2 \mathbf{d} \mathbf{r}$$

the last integral is

$$\int r^2 dA = 2\pi \int r^3 dr = \frac{\pi d^4}{32}$$

d.

because

dA = 27(rdr (see Figure 2a)

In the specimen used in this study, the glue area was confined to an area located between two concentric circles with the diameters $d = 0.8^{\circ}$ and $D = 1^{\circ}$. For this case:



Figure 2a.

$$\int r^2 dA = \frac{\pi}{32} (D^4 - d^4)$$

therefore

$$T = \frac{G\Theta\Pi}{32L} (D^4 - d^4)$$

The maximum torsional stress will be:

$$\overline{\zeta}_{max} = \frac{G \Theta}{L} \mathbf{r}_{max} = \frac{G \Theta D}{2L}$$

or finally

$$\overline{\zeta} = \frac{16TD}{(D^4 - d^4)}$$

The second part of the stress concerned, as previously mentioned, is simple shear which is equal to the applied load divided by the area subjected to stress, that is $\leq = \frac{P}{A}$. The algebraic addition of the two above-mentioned stresses would determine the final stress pattern as:

$$S_f = \tilde{c}_{max} + S_s = \frac{P}{A} + \frac{16 TD}{T(D^4 - d^4)}$$

in which the torque T would be the product of the load and the torque arm chosen as 15 inches in this paper. The length of the horizontal member for convenience of handling was 18 inches. The vertical members which serve as supports for the joint were 5½ inches long each. Both vertical and horizontal members were 2 inches wide and 3/8-inch thick. The thickness of 3/8-inch was chosen to reduce the inertia effect of the horizontal member on the joint due to lower weight, which may particularly influence the accuracy of the fatigue data and also to minimize the magnitudes of moments not considered in calculations. The magnitudes of these moments were very small compared to the magnitude of total shear stress applied, and they were negligible.

2 - EXPERIMENTAL PROCEDURE

2.1 - Selection and Preparation of Specimens

The lumber used for the specimens was air-dried and most of it defect-free. This air-dried lumber was put through cutting and planing process and the final dimensions of the members were precisely obtained within the different machine accuracies employed.

Careful scrutinization was exercised to discard all abnormal specimens before, as well as after they were assembled and glued together. However, the only area of the members possessing great importance in influencing the strength was the first four squared

inches at the top of the L-shaped specimen where the circular glue area was being cut out (see Figure 3). At this stage, the members were marked and conditioned at a temperature of 70° F. and 65 percent relative humidity.

The second step in preparing test samples, which obviously had appreciable influence on the strength of the joint, was to establish the circular glue area as precise as practicable. The joint areas of the horizontal member (4 squared inches each) were covered with a 2-inch wide cellophane tape. The thickness of the cellophane tape was in the order of magnitude of a normal glue line (.002-inch). After the tape was applied the circular glue line was established (see Figure 3).

Care was taken to get the circular cut-outs located exactly opposite each other. Otherwise, different torque arms would result which consequently would produce erroneous data.

The glue under question was an "Aircraft Casein" manufactured by National Casein Company. The glue was carefully prepared according to manufacturer's instructions (13). Although the recommended pot life of this brand was five hours, the glue used for this study was applied from 20 minutes to almost $1\frac{1}{2}$ hours after mixing.

When specimens were to be assembled, some of them contained some defects that were missed in the first rejection period, or some imperfections were observed in the tape covering the joint such as tiny torn out spots visible with the naked eye. Numbers missing in the data, therefore, are discarded non-defect-free specimens.

Specimens were glued together and assembled in a jig (Figure 4). The necessary pressure was applied on the joint by tightening a bolt

Figure 3. The members of the specimen. A part of the long member has been cut off. The area of the joint except the circular area was covered by cellophane tape.



Figure 4. Jig used to assemble the specimens.



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which fitted through a hole at the center of the joint area with a torque wrench. The diameter of this hole was limited to 5/16-inch in order to eliminate any interference with the glue area. To improve the pressure distribution over the joint area, a 2-inch diameter washer was used on each side of the assembly. The pressure applied on the glue line was 200 pounds per square inch according to the following formula (2):

$$FL = \frac{WD(\pi fD + K)}{2(\pi D - fK)}$$
where F = force applied, in pounds
L = lever arm, in inches
W = total load, in pounds
D = mean diameter of the screw,
in inches
K = pitch of thread, in inches
f = coefficient of friction

2.2 - Static Testing

To accomplish the purpose of determining the fatigue characteristic of the adhesive bond, the static strength of the joint subjected to the stress pattern previously described had to be found.

All static testings carried out in this investigation were performed on a Baldwin Emery, SR-4 Testing Machine (See Appendix No. 11), at a speed of .018 inches per minute (see Figure 5). Since the platen of the machine was not large enough, a piece of hard maple lumber 1-3/4inch thick was properly bolted to the lower platen of the testing machine extending almost five inches out. To one side of the maple lumber, a clamp was bolted which would hold up the specimen. The clamp was carefully inspected prior to use. Since the pressure applied to vertical members of the specimen would crush the wood, two pieces of rubber were provided and used on both sides of the member subjected to crushing.

To record the ultimate load applied to the specimens to the nearest half pound, a load cell (see Appendix No. 12) was employed in which the hundred pound range was used. On this load cell which was overhanging from the top, a bolt which was sharpened at the

Figure 5. Baldwin Emery SR-4 Testing Machine. Strain Amplifier measures the strain on the top edge of the horizontal member of the specimen at 13.5 inches from the point of load application.



Figure 6. Specimen mounted on the testing machine. Note load cell and clamp fixture.

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lower end to a knife edge was used, which would apply the load at the determined spot of the horizontal member (see Figure 6). As the lower platen started to move upward, at the specified speed, the load would apply through the load cell and the bolt.

In static testing as well as fatigue testing, as illustrated in Table I, the torsional shear is considerably greater in magnitude than the simple shear. Figure 7 shows the comparative magnitude of component stresses as functions of applied load.

Load 1bs.	<u>Р</u> 2А р. в.і.	$\frac{\$ \text{TD}}{\pi (D^4 - d^4)}$ p.s.i.	Total Stress p.s.i.
5	8.93	324.4	413.33
10	17.86	648.8	6 66 .66
15	26.79	973.2	999.99
20	35.71	1297.6	1333.31
25	44.64	1622.0	1666.64
30	53.57	1946.4	1 999.97
35	62.50	2270 .8	2333.30
40	71.43	25 95.2	2666.63

Table I - Comparative stress magnitudes for the two component stresses in stress pattern employed





SONUOS NI GAOL

In testing a considerable number of specimens, adjustments were to be made. Not infrequently, the specimens' two vertical members were not exactly parallel and this would cause some deviations from the exact position of the specimen. It was decided to reject these specimens prior to testing.

After failure at ultimate load, the failed joint was inspected regarding the type of failure and the amount of wood torn out of the wooden members. Note should be made of the fact that the members of the failed specimens were still loosely attached together.

Strain measurements were performed on the tension side of the horizontal members at $13\frac{1}{2}$ inches from the point of lead application. These measurements were taken in order that they might be compared with corresponding measurements on the fatigue specimens for reasons to be explained later (see Figure 8).

2.3 - Fatigue Testing

Fatigue testing was carried out on a Sonntag Fatigue Testing machine (Appendix No. 14). This type of machine subjects the specimen to an oscillating force (constant amplitude).

Basically, the machine consists of a heavy stationary platen, a reciprocating assembly and a cabinet (see Figure 9). The stationary platen attached to the heavy frame of the machine is freely suspended by springs with no solid mechanical connection with the cabinet.



SONUOS NI GAOL

Figure 9. Sonntag Fatigue Testing Machine used in this study. The bridge-Amplifier and oscilloscope were used to check the vibration and measure the strain created at 13.5 inches from the point of load application.



The alternating force is produced by an unbalanced rotating mass in a cage-like frame. This rotating mass would apply the desired force, below or at the machine capacity, through the reciprocating frame at a constant speed of 1800 cycles per minute. The rotating mass in the machine is directly driven by an 1800 rpm synchronous electric motor which is connected to a 60 cycle power supply.

The specimen was subjected only to the vertical component of the centrifugal force since the horizontal component was absorbed by four flex-plates which would guide the reciprocating assembly in the vertical direction.

A compensator spring is positioned between the stationary frame and the vibrating assembly and absorbs all inertia forces. These forces, in absence of the compensator spring, would be transmitted to the specimen. The rigidity of this spring is not adjustable but the machine could be brought to exact proper resonance by adding weights to the reciprocating assembly. Weights to be added were specified by the manufacturer.

The machine is designed to be used with or without a pre-load.

In order to use the type of specimen described previously, a special fixture had to be made. The improper structure of the fixture could drastically influence the test results. Therefore, great care has been exercised in making the fixture used in this investigation.

The fixture consisted primarily of two parts. One part was fastened to the heavy stationary platen and the second part bolted

to the top of the reciprocating assembly (see Figure 10). The previous part of the fixture consisted of four steel plates assembled together by bolts so the vertical members of the specimen could be tightly fastened. The second part of the fixture which was bolted on the vibrating platen consisted of seven pieces, discarding the bolts used to fasten the fixture to the platen. The horizontal part of the specimen was inserted into the rectangular frame and fastened tightly by two semi-cylindrical pieces of steel and two bolts. Positioning two small pieces of rubber between each semi-cylindrical piece of steel and the specimen was considered an excellent practice. Preliminary testing revealed that after a few thousand number of cycles, the semi-cylindrical pieces of steel would press the wood fibers down, causing local crushings, which consequently would loosen the fixture and drop the load. The small pieces of rubber mentioned above greatly eliminated this loosening of the fixture. The upper part of the fixture which consisted of a frame-like piece of steel, would rotate around the base and this rotation point had to be regularly lubricated in order to facilitate its free motion with minimum friction.

The machine was capable of subjecting the specimen to different stresses such as complete tension, complete compression, etc., which has been described earlier.

To stay within the machine capacity, which was 200 pounds, considering 100 pounds static and 100 pounds created by eccentric rotating mass, the specimen was so designed that it was very likely to fail within a range of 40 - 50 pounds. The reason for this type of sample design was, first, to reduce glued area which would

Figure 10. Loading Fixture, consisting of two separate parts; one mounted on reciprocating platen and the other attached to heavy stationary platen.

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eliminate the variables described and second, to avoid using load multiplier.

The static preload was applied through a spring mentioned previously as compensator spring. This spring, under preload, would deflect and this deflection would be measured in inches to the nearest .0005 of an inch. Deflection measurement was performed by a dial (see Figure 9) which was attached to the stationary frame and as the reciprocating assembly moved due to compensator spring, the plunger of the dial would register the deflection. To convert inches into pounds, a conversion factor of .69 pounds was given, by the manufacturer, for every .001 inches.

To apply preload, the dial reading was recorded prior to inserting the specimen in the fixture. This reading would correspond to zero load. After inserting the specimen, the desired preload would be applied to the specimen through two wheels constructed in the machine for this purpose. Cut-off switches were provided in the machine. These switches would turn the machine off when deflection increased one-half inch. Preliminary testing showed that this amount of deflection corresponds to a broken specimen.

The maximum allowable movements of the reciprocating platen with and without full preload were $\frac{1}{2}$.375 and $\frac{1}{2}$ 0.225 inches, respectively, when the specimen was still rigid.

To accomplish a satisfactory fatigue test, it was decided to determine the effect of creep as well as any wood crushing influence under the semi-cylindrical parts of the fixture. This was performed

through observations in diminishing the static preload applied to the specimens, as well as the magnitude of strain recorded by oscilloscope. Eventually it was found out that some readjustments were necessary in order to maintain the stress at the assigned level. Figure 11 illustrates this effect on specimens subjected to different stress levels and Figure 12 shows the adjustments made in order for the stress to remain at the assigned level.

In fatigue testing, five distinct stress levels were predetermined which ranged from almost 83 to about 28 per cent of average static ultimate stress of the matched specimens. These five stress levels were 2000 p.s.i., 1666.64 p.s.i., 1333.31 p.s.i., 1000 p.s.i and 666.66 p.s.i. At each stress level 10 specimens were tested. One half of the load was static and applied through the compensator spring. The other half was generated by the rotating mass. The total load applied to the specimens would oscillate from sero to total load; Figure 13 shows that the load was oscillating in a simusoidal pattern ranging from sero to maximum assigned load. Each centimeter on the oscilloscope plate corresponded to 100 microinches per inch of strain. Any drop in load would be revealed by this curve because the amplitude of the curve would, of course, decrease. The strain gages were positioned at the same spot as static specimens, that is, 13.5 inches from the point of load application.

Adjustment curves are shown by Figure 12. As illustrated, the stress drop ranges from 140 to 70 pounds per square inch for the first thousand cycles. All stress levels approached the desired constant stress level after 15,000 cycles. The lowest



TOTAL STRESS IN PSI





Figure 13. Oscillation of strain as recorded by oscilloscope. Each side of a square corresponds to 100 microinches per inch of strain.



stress level employed, that is, 666.66 pounds per square inch, approached the constant magnitude equal to the amount mentioned, after 10,000 cycles.

Figure 11 shows the drop of stress without adjustment. As is readily concluded from this figure, if the adjustment was not performed, the stress would drop as much as almost 700 pounds per square inch. The curves were predetermined by using two specimens at each level and measuring the drop for five stress levels employed. Note that at all stress levels the stress drop readings for two specimens used at each level were very close. Average of stress drop readings was obtained and Figure 12 was established.

Strain measurements (Figure 8) for fatigue testing recorded the same readings as those taken through static testings. The coincident of the strain measurements for both fatigue and static testing implies that there was no load take-up in the fatigue machine.

3 - RESULTS

3.1 - Static Testing

Twenty-five specimens were subjected to static testing in order to determine the static strength of the joint. Results obtained are shown in Table II.

3.2 - Fatigue Testing

Table III shows the number of cycles, that is, the life of each individual specimen subjected to fatigue stressing at the predetermined stress levels. The five stress levels, as shown in this Table, range from 83.39 to 27.80 per cent of average ultimate static stress of specimens.

their corresponding	
Joints	
casein-glued	testing.
ata recorded for	stresses in static
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Table	

Specime	n Utimate	Utinate simple	Utimate torsional	Ultimate total	Nood	*
Number	load, lbs.	ghear stress p.s.i.	shear stress, p.s.1.	gnear suress p.s.1.	Side 1	Side 2
1-3	36.3	64.82	2355.14	2419.96	0	0
4-1	38.7	69.10	2510.86	2579.96	0	0
	39.0	69.64	2530.32	2599.96	<10	<10
1-7	33.0	58.92	2141-04	2199.96	0	<10
1	31.2	55.71	2024.26	2079.97	<10	6 0
1-9	36.0	64.28	2335.68	2399.96	<10	< 1 0
01-1	39.0	69.69	2530.32	2599.96	0	01)
11-1	36.5	65.17	2368.12	2433.29	<10	0 <u>1</u> 0
1-12	0.01	7.42	2595.20	2666.62	€10	01) 01)
1-13	30.0	53.57	1946.40	2000.00	0	01 2
1-14	33.8	60.35	2192.94	2253.29	<10	01 ∕
1-17	35.5	63.39	2303.24	2366.63	~ 1 0	0
1-18	34.5	61.60	2238,36	2299.96	<u>(10</u>	<10
1-19	34.5	61.60	2238.36	2299.96	0	< 10
1-20	38.0	67.85	2465.44	2533.29	10	0 0
1-21	37.3	66.60	2420.02	2486.62	(10	0 10
1-22	36.3	64.82	2355.14	2419.96	< 1 0	0
1-23	34.8	62.14	2257.82	2319.96	0	(10
1-24	34.3	61.25	2225.38	2286.63	0	0
1-25	35.2	62.85	2283.78	2364.63	~10	<10
1-26	38.0	67.85	2465.44	2533.29	610	<10
1-27	36.5	65.17	2368.12	2433.29	QD 0	01 0
1-28	38.2	68.21	2478.42	2546.63	0	410
1-29	36.8	65.71	2387.58	2453.29	0	0 1∕
1-30	36.0	64.28	2335.68	2399.96	0	0
			- and the second second	The energy and	4+1	

*food failure in most of the specimens was negligible. The specime no failure is mentioned as having Of wood failure (see Figure 14).

Figure 14. A specimen failed in static testing.

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	equal to half of	the total load	applied.*
Specimen	Total Shear Stre	85	Number of cycles
mumber	% of average ultimate		to failure
	static stress	p.s.i.	
2-2	83.39	2000	16,000
2 -4	M	#	6,000
2-5	N	11	3,000
2-6	Ħ	Ħ	6,000
2-7	11	tt	17,000
2-8	Ħ	n	5,000
2-9	10	n	7,000
2-10	11	Ħ	7,0 00
2-11	Ħ	Ħ	7,000
2-12	Ħ	11	7,000
2-13	69 .49	1666.64	23,000
2-14	Ŵ	N	34,000
2-15	11	Ħ	9,000
2 -16	11	ti	27,000
2-17	H	N	69,000
2 -1 8	n	N	36,000
2-19	n	1	12,000
2-20	n		67,000
2-21		1	89,000
2-22			21,000
2-24	55.92	1333.31	14,000
2-28	n		27,000
2-29		π	49,000
2-31	1		76,000
2-32	*		80,000
2-33	11		86,000
2-35	Ħ	W	102,000
2-36	11	n	146,000
2-37	99	Ħ	39,000
2-38	Ħ		64,000
2-39	41.69	1000	110,000
2-40	11	N	550,000
2-41		N	415,000
2-42	W .		1,228,000
2-43		1	236,000
2-44			1,051,000
2 -45	*	W	458,000
2-46		1	1,358,000
2-47	n		3,850,000
2-48			80,000
2-49	27.80	666.66	2,640,000
2-51	10	N	6,841,000
2-52	Ħ		4,861,000
2-55	n		4,911,000
2-56	H	T	6 ,226,000
2-57	T		0,037,000 0,28,000
2-58	-		2,450,000
2-29	T T	π	2.644.000
2-61	¥	Ħ	5.460.000

Table III. Number of cycles obtained for five different stress levels in fatigue testing. Preload was equal to half of the total load applied.*

*In almost all specimens subjected to fatigue testing, no wood failure could be observed (see Figure 15). Figure 15. A specimen failed in fatigue testing, showing pure glue failure.

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and a star and a second star and a second star a second

3.3 - Moisture Content

The specimens were conditioned at 70° F. and 65 per cent relative humidity. Moisture content measurements showed that the specimens after being in the conditioning room for one week to ten days, approached a moisture content of 6 - 7.8 per cent. At this stage, they were taken to the static testing room in polyethylene bags and tested within the next hour. But in the case of fatigue testing, sometimes the specimens would stay in the machine for as long a time as about eighty hours in the laboratory where the temperature. and humidity were not controlled. It was, therefore, decided to measure the moisture content change during the fatigue test. From the measurements it was determined that the moisture content would drop from 6 - 7.8 per cent at the beginning to 5.3 - 5.8 per cent after staying in the machine for 80 hours; from 6 - 7.8 per cent to 5.6 - 6 percent after 48 hours. Attention should be paid to the fact that all mentioned figures are averages. The moisture content determination samples were taken from the ends of horizontal and vertical members, which would add up to three moisture content determination samples for each specimen; the average of these three has been considered as the moisture content of the specific fatigue or static testing specimen. It would have been more desirable to determine the moisture content of the specimens closer to the glue line but no feasible way of performing such a task could be devised. All moisture content measurements were taken through oven drying method at 102 + 2 ° C.

4 - ANALYSIS OF RESULTS

One of the important results of this study is the fact that fatigue stressing induces failure in the glue line even at relatively low stress levels.

In fatigue testing, all specimens showed little or no wood failure after being failed in the machine. Among the specimens which showed wood failure, it had occurred at the point of maximum stress. There were, however, some specimens which had a few wood fibers torn out at other areas of the circular adhesive line.

In fatigue testing, two variables were considered. These two variables were stress level and the number of cycles to failure. The first variable was held constant and the second variable was dependent on the stress level. The functional dependence of two variables can be represented in the form of a so-called S-N curve (Figure 16).

As noted in Table III, when the stress level drops from about 56 per cent to about 42 per cent of the average ultimate static stress, the life of the specimen increases appreciably and when the stress is almost 28 per cent of the total ultimate static stress of the joint, the resistance of the joint to fatigue stressing approaches as high a magnitude as 9.4 million cycles. In many fatigue experiments, after ten million cycles, the specimen is taken away from the machine assuming the endurance limit of the material. On this basis, it is very likely to approach such a limit for casein if the stress level drops to about 20 per cent. This, however, is only an estimation and in this study such a limit has not been approached. The life of the specimen at higher stresses is relatively low.



Figure 16 illustrates the S-N curve derived. Acceptable statistical procedures (10) were employed in derivation of this curve. Note that the slope of this curve is decreasing as the stress level steps down and this slope may approach zero if the stress level drops down to 400 to 500 pounds per square inch.

It is deserving of mention that sometimes the fatigue data could be represented by a so-called response curve if the experiment is properly designed. In this type of representation, the probabilities of specimen survival (or failure) to a constant number of cycles, at pre-determined stress levels, are computed. Response curves are particularly useful in determination of endurance limit of the materials to fatigue stressing. In this study the time limitations did not permit such determination.

During fatigue testing, the machine oscillation was constantly measured by the sine surve previously described, which simultaneously would record the strain created at the point. Another way of checking the load was the dial mounted on the compensator spring which would well reveal any decrease in the preload applied to the specimen.

The standard deviation in static testing was ± 160.8 pounds per square inch. The average ultimate static stress was 2398.37 pounds per square inch. It could readily be concluded that this value is significantly higher than the value given by standard maple block test (see Table II). Furthermore, in the latter, very often there is a considerable percentage of wood failure whereas in specimens used in this investigation the percentage of wood failure is appreciably lower.

The grain direction on the joint was not parallel on the glue line and this has been concluded as having considerable influence

on the glue behavior and resistance (6) to load but without further interpretation of this effect, it is obvious from the data taken that this method of testing is very likely to give higher values of shear stress for adhesives.

The members of each failed specimen were loosely attached together and to see the joint, the members were to be pulled apart by hand. On this basis, each static-tested specimen member was taken apart and the amount of glue and wood failure was estimated. Table II, Columns 6 and 7, represent the per cent wood failure which occurred in the joint.

The wood failure was very often a few fibers torn off from both the vertical and horizontal members and most of the time from B to D on the circular glue line and, not infrequently, around point C (see Figure 2). This seems to be due to the fact that the two components of the stress pattern are added together at this point and this small area around C has very significant effect on the resistance of the joint to the load applied. The line across the glue line at A is subjected to least amount of shear, since the two components of the stress pattern, that is, torsional and simple, are subtracted at this point. At point A, there was very little evidence of the existence of wood failure.

5 - CONCLUSIONS

5.1 - Conclusion Derived

On the basis of tests discussed herein: a) using a specimen so designed that failure could be induced in the glue line both in static and fatigue loading b) employing a stress pattern composed of torsional and simple shear in which the latter had very low magnitude in comparison with the torsional shear component

c) using an Aircraft Casein glue

d) restricting the glue line to a very small area

e) testing specimens in fatigue stressing by means of a constant amplitude fatigue machine with special fixture made to suit the designed specimen and staying within the machine capacity

f) testing the specimens in static loading

it appears that the following conclusions are warranted:

- 1. That casein bonded wooden joints could withstand combined shear stresses.
- 2. That the casein bonded wooden joints as described in this paper gave a higher torsional shear stress than that of standard maple block shear specimen conventionally used.
- 3. That an exponential curve is resulted in fatigue testing as stress level is plotted versus the number of stress cycles applied to the specimen to failure.
- 4. That at high stresses the fatigue life of the specimen is relatively low.

- 5. That at low stresses the fatigue life is appreciably high.
- 6. That stepping down the stress levels from about 83 to 28 per cent of average ultimate static stress at five equal increments, endurance limit or fatigue strength of the material was not approached.
- 7. Load adjustments may have had a small influence on the fatigue life at the beginning of the test.

There did not seen to result a significant amount of wood failure in static and fatigue testings. The fact that there was little or no wood failure on the joints indicates that in this method of specimen design, the wood species could resist more cycles of fatigue stressing than the glue at all stress levels employed. It could therefore be concluded that the S-N curve for wood, if plotted, falls somewhat above that of glue (see Figure 17A).

If the joint was made of a strong adhesive such as phenol formaldehyde, the situation shown in Figure 178 would be likely to occur. The fatigue failure in this case would have occurred in the wood adjacent to the bond. Figures 17C and 17D illustrate other possibilities in which the wood, up to some extent, yields longer life in fatigue stressing, and from there on, glue produces longer life, or vice versa.

5.2 - Present Concept on Fatigue Failure

There are many schools of thought concerning fatigue failure in engineering materials, particularly metals, because this class of materials has been of great concern to this age of modern civilisation. There has, therefore, been a tremendous number of tests



carried out on metals since the last century. There is not, however, a very consistent concept on the cause of this phenomenon as yet and due to statistical nature of fatigue, there is not an entirely satisfactory limit at which the life of the structure or machine parts could be confidently guaranteed for a long time.

This part of the paper is devoted to some present theories on the cause of fatigue failure and their possible relation to the materials used throughout this investigation.

Hystersis is a term referring to the loop formed when a monperfect elastic member is subjected to load and its removal. In other words, the points of stress-strain curve in loading do not coincide with those of unloading the member; consequently they form a loop (7) (11) (8). This phenomenon caused by the loss of energy in the load-unloading cycle will form a permanent deformation. Barstow (7) expressed the opinion that when a material acts in a purely elastic manner, that is, forms no hystersis loop in the load-deformation cycle, fatigue would not occur. He did not, however, subject his specimens to a larger number of cycles. In materials in which hystersis loop results, in each cycle, the loss of energy would cause gradual deterioration effect of repeated stresses.

Molecular slip is another explanation of fatigue failure. When the elastic strength of individual crystals in metals exceeds by load application, localized deformations develop. These deformations within the crystal are referred to as slip bands (8). These bands, as the repetition of stress proceeds, cover the entire surface of the crystal (11). There is not a well-expressed opinion on the occurance

of such phenomenon in the case of adhesives. It is, however, believed that such slippage may take place between the molecules of the region under repeated stresses on the glue line.

The existence of secondary stresses is another fatigue failure interpretation expressed by experts.

According to this theory the actual strength of solid materials does not have the same magnitude as the strength they should possess by reason of molecular cohesive forces (11). Note should be made of the fact that materials are apt to contain very tiny defects when they are made, either naturally, as in trees, or artifically, as in metals or adhesives. These sub-microscopic defects form favorable spots for localizing fatigue failure. These defects could also present some irregularities in the material and eventually raise the stress at that point. Internal stresses definitely contribute to the failure of the material below the expected point.

This last theory could be applicable to a considerable extent on adhesives. It has been determined in experiments that the thinner glue line gives a higher strength value than a thick line. One of the reasons claimed for this phenomenon is that of increased possibility of getting internal defects on the glue bond. In other words, as a thicker glue line is applied, more defects develop, which would fail the bond at a lower strength value than the thin bond. Throughout this paper it has been assumed that the glue line possesses a thickness almost equal to that of the tape covering the entire joint except for the circular line, because as the pressure was applied, the members were practically brought tight together. This thickness was 0.002 inch. The thickness in this case is relatively small.

Consequently there exists less possibility of establishing defects in the glue line. But there are, undoubtedly, still sub-microscopic defects on the adhesive line. In addition, in the preparation of the adhesive which was to be applied to the specimens, foreign particles may have been introduced which would subsequently contaminate the prepared glue. These foreign rigid particles would function as stress raisers on the glue line.

The surface of wood is never smooth. This non-smoothness of the wood surface on the glue area would cause irregularity on the borders between the member and the glue, eventually establishing stress concentration at these areas.

The stress raisers mentioned above will actually cause the bond to fail when subjected to repeated stresses.

APPENDIX

LIST OF APPARATUS

- 1. Hard maple of stock from which specimens were prepared contained about 5 growth increments per inch.
- 2. Casein glue manufactured by National Casein Company, sold under the name "Aircraft Casein".
- 3. Cellophane tape, 0.002-inch thick; manufactured by Minnesota Mining and Manufacturing Company.
- 4. Compass. Included in drawing set, made by Eugene Dietzgen Co.

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- 5. Band Saw. Model B-18388, 36-inch bandsaw made by Yates-American Machine Company, Beloit, Wisconsin.
- 6. Circular Saw. Manufactured by the Tannewitz Works, Grand Rapids, Michigan.
- 7. Planer. Manufactured by Boice-Crane Company.
- 8. Jointer. Squared Industrial Control Division, Milwaukee, Wisconsin
- 9. Drying Oven. Temperature range up to 200° C, manufactured by Precision Scientific Company.
- 10. Strain Gages. SR-4 strain gages, type A-1, with a resistance of 119.6 ± 0.2 ohms and gage factor of 2.04 ± 1%. Gages made by the Baldwin-Lima-Hamilton Corporation, Waltham 54, Mass.
- 11. Static Testing Machine. Baldwin-Emery, SR-4 Testing Machine, Model FóT, made by the Baldwin-Lima-Hamilton Corporation, Philadelphia, Pennsylvania.
- 12. Load Cell. Baldwin SR-4 load cell, manufactured by Baldwin-Lima-Hamilton Corporation, Philadelphia.
- 13. Strain Amplifier. Baldwin SR-4, type M, Portable Strain Indicator manufactured by the Baldwin-Lima-Hamilton Corporation, Philadelphia.
- 14. Fatigue Testing Machine. Sonntag Universal Fatigue Testing Machine, Model SF-Ol-U, manufactured by the Sonntag Scientific Corporation, Greenwich, Connecticut.
- 15. Bridge-Amplifier. Model BA-1, manufactured by Ellis Associates, Pelham, New York.
- 16. Oscilloscope. Type 53/54 D, Plug-in Unit, manufactured by Tetronix Incorporated, Portland, Oregon.
- 17. Calculator. Marchant Calculator, manufactured by Marchant Division of Smith-Corona Marchant, Inc., Oakland, California

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