EFFECT OF EPOXY IMPREGNATION ON THE MOE AND MOR OF INTACT AND FAILED YELLOW-POPLAR (*LIRIODENDRON TULIPIFERA* L.) SAPWOOD BEAMS[1]

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(Received March 1983)

ABSTRACT

The effects of epoxy impregnation on the MOR and MOE of intact and failed yellow-poplar (*Liriodendron tulipifera* L.) clear sapwood beams were investigated. Both impregnated and unimpregnated specimens were partially failed in bending, impregnated to stabilize the cracks, and retested. The presence of induced cracks had a significant effect on the MOR of the material after impregnation or reimpregnation, but not on the MOE. Both the MOR and MOE of the failed, then impregnated material exceeded the values for unimpregnated yellow-poplar.

Keywords: Epoxy, impregnation, wood-polymer composites.

INTRODUCTION

Epoxy resins are becoming more widespread in their use as a repair compound for wood as well as for other materials. Presumably, this increase in usage is due in part to the epoxy's ability to bond to the materials in question, to stabilize the

[1] This research was supported by funds from McIntire-Stennis Project 2311. This is Paper No. 6602 in the Journal Series of the Pennsylvania Agricultural Experiment Station and was authorized for publication on February 9, 1983.

Wood and Fiber Science, 16(4), 1984, pp. 508–517

surrounding area, to resist chemical attack, and to fill gaps, voids, and cracks. Although a number of field trials have been run on a variety of damaged structures (Avent et al. 1978, 1979; Murray and Schulthers 1977), relatively little has been reported on basic research in this area, particularly with regard to wood.

Blankenhorn and Kline (1977) have reported that failed concrete specimens, impregnated with high viscosity monomers, and subsequently polymerized in situ, not only recover their original compressive strength and modulus, but attain values for these two properties comparable to sound impregnated concrete. Hence, impregnation completely erased the effects of the cracks, particularly as far as compressive strength and modulus were concerned. The impregnating systems used in their study were relatively high viscosity (approximately 150 to 160 cps) liquids: MMA prepolymer (70 parts by weight methyl methacrylate; 30 parts by weight polymethyl methacrylate; 0.5 parts by weight azobisisobutyronitrile), and an epoxy system (100 parts by weight Epon 828*; 35 parts by weight styrene oxide; 13.4 parts by weight diethylaminopropylamine). The epoxy's performance was found to be slightly superior to that of the MMA prepolymer, presumably due in part to the lower shrinkage characteristics of the epoxy after polymerization in the large cracks. However, it was not clear that the same advantages can be obtained in other testing modes and with other materials, such as wood.

In the present study, the effects of epoxy impregnation on the static bending properties of intact and failed yellow-poplar (*Liriodendron tulipifera* L.) clear sapwood beams were examined. Static bending properties were obtained and analyzed for unimpregnated wood specimens, failed wood specimens impregnated after failure, impregnated wood specimens and impregnated wood specimens reimpregnated after failure.

EXPERIMENTAL

Specimen preparation

Specimens were obtained from a yellow-poplar (*Liriodendron tulipifera* L.) log cut in central Pennsylvania during the winter of 1979. The log was live sawn into 5/4 boards which were kiln-dried as part of a mixed load using a schedule for the most refractory species in the load (*Robinia pseudoacacia* L.). Twenty specimens $\frac{1}{4}$ in. × $\frac{7}{16}$ in. × 6 in. were machined from the sapwood portion of one of these boards. The oven-dry densities ranged from 24 to 29 lb/ft^3. These specimens were divided into two groups (Fig. 1): one for testing to failure; and the other for impregnation, followed by testing to failure. After testing, each of these two groups was split into two additional groups: one for retesting (to obtain an estimate of the residual strength and stiffness), and one for impregnation followed by retesting.

Impregnation procedure

All specimens designated for initial impregnation were oven-dried to constant weight at 221 F. They were then placed in a vacuum-pressure chamber and impregnated, using a vacuum-pressure technique described in Moore (1981). The impregnant was a stoichiometric mixture of a diglycidyl ether of bisphenol

* Epon 828 is a Shell Chemical Co. product.

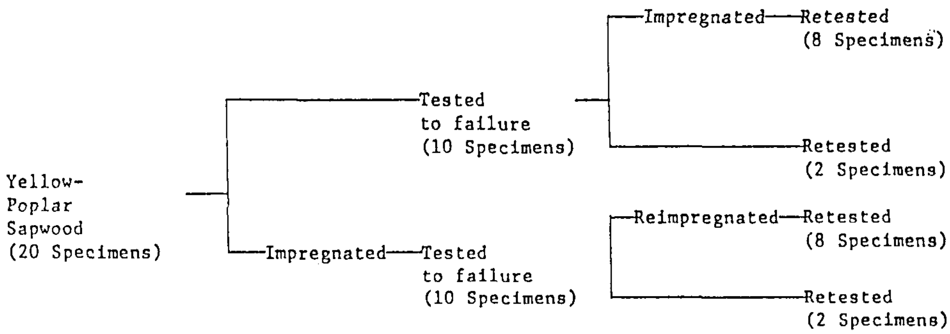

FIG. 1. Experimental design.

A-based epoxy resin (Epon 828) and metaphenylenediamine. The properties of this impregnation system have been described in detail in Moore (1981). After impregnation, the surfaces of the specimens were wiped free of excess resin, and the specimens were allowed to cure at room temperature (70 F) for 24 h, followed by 24 h at 126 F and 24 h at 221 F.

Static bending tests

The bending tests were run on a Tinius Olsen universal testing machine. All wood specimens were tested in three point loading using a 4-inch span, with the load applied to the radial faces. The crosshead speed for all testing was 0.1 inches/minute. Modulus of rupture (MOR) and modulus of elasticity (MOE) values were calculated using standard methods (Gurfinkel 1973). All specimens were tested in the oven-dry condition.

In obtaining failed specimens, the tests were run only to the point where the first sharp cracking sounds were heard. This ensured that the specimens remained in one piece and could be straightened to approximately their original shapes prior to impregnation. All retests were conducted in the original configuration; that is, the loads were reapplied at the same locations on the specimens.

Analysis of variance was used to determine significant differences in the data sets. Significant differences were established at the 0.05 level.

RESULTS AND DISCUSSION

The amount of impregnant retained by the yellow-poplar specimens during the various impregnation procedures is given in Table 1. Retention is expressed in

TABLE 1. *Volume fraction of impregnant.*

Specimen*	No. of specimens	Average impregnant volume fraction	Coef. of variation
Impregnated before testing to failure	10	0.619	0.053
Impregnated after testing to failure	8	0.623	0.045
Impregnated before testing to failure and reimpregnated after testing to failure	7	0.651	0.062

* All specimens were impregnated and tested in the oven-dry state.

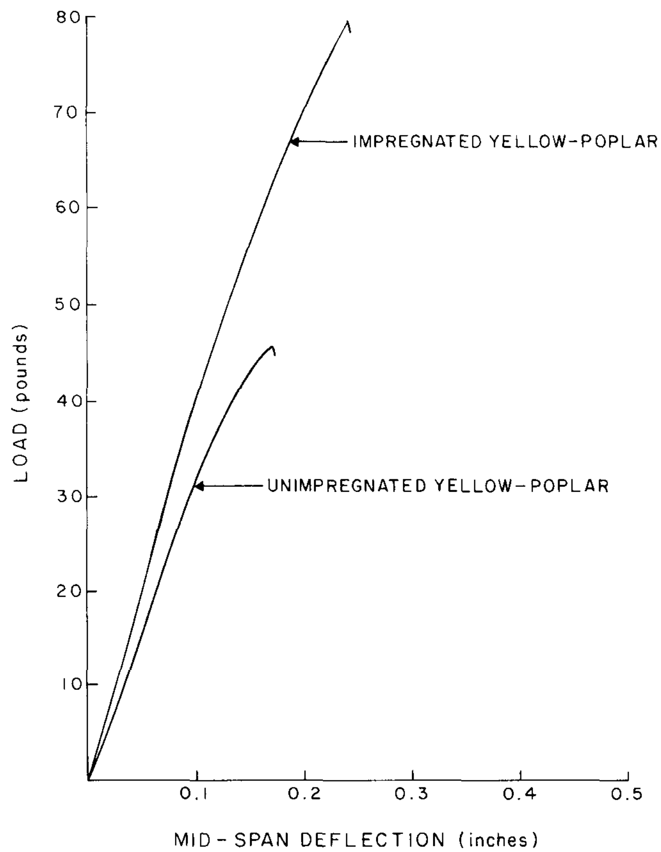

FIG. 2. Typical load-deflection curves for impregnated and unimpregnated yellow-poplar sapwood.

terms of volume fraction, or fraction of the total specimen volume occupied by the impregnant. In nonswelling systems (such as the impregnant used in the present study), this can be calculated from the following (Moore 1981):

$$v_m = \left(\frac{m_c}{m_w} - 1\right)\frac{\rho_w}{\rho_m} \tag{1}$$

where:

v = volume fraction
m = oven-dry mass
ρ = oven-dry density

TABLE 2. *Static bending results for unimpregnated and impregnated yellow-poplar being tested for the first time.*

Specimen	No. of specimens	MOE Average (psi)	MOE Coef. of var.	MOR Average (psi)	MOR Coef. of var.
Unimpregnated	10	982,000	0.102	11,736	0.120
Impregnated	10	1,287,000	0.072	19,871	0.064

TABLE 3. *Static bending results for retests of failed unimpregnated and impregnated yellow-poplar sapwood beams.*

Specimen	No. of specimens	MOE Average (psi)	MOE Coef. of var.	MOR Average (psi)	MOR Coef. of var.
Unimpregnated prior to testing to failure, and then retested without impregnation	2	418,000	0.025	1,007	0.010
Impregnation prior to testing to failure, and then retested without reimpregnation	2	828,000	0.050	10,032	0.317

and the subscripts m, c, and w refer to the impregnant, impregnated wood (composite), and oven-dry unimpregnated wood, respectively.

The impregnant volume fraction values obtained for the unfailed specimens were similar to previous data obtained for yellow-poplar sapwood and epoxy impregnants (Moore 1981; Moore et al. submitted). Analysis of variance tests indicated that there was no significant difference between the volume fractions of impregnant obtained for the unfailed specimens impregnated prior to testing to failure and the specimens impregnated after testing to failure. The relatively small coefficients of variation in these two groups suggested that the cracks formed in the failure process occupy a relatively small portion of the specimen volume. This was reasonable since all of the specimens were straightened after failure in order to close the crack as much as possible.

There was also no significant difference between the average impregnant volume fractions of the impregnated specimens and the specimens reimpregnated after impregnation and testing to failure. This was also reasonable since the first impregnation would be expected to drastically reduce permeability and fill all accessible voids, with the exception of the very small volume generated by the crack surfaces formed during the bending tests.

Table 2 summarizes the MOE and MOR results for the first set of bending tests and illustrates the effect of impregnation on yellow-poplar sapwood. As expected, impregnation substantially alters the static bending behavior of the yellow-poplar. The MOE increases by approximately 31% from 982,000 psi to an average of 1,287,000 psi; and the MOR increases by approximately 69% from an average of 11,736 psi to an average of 19,871 psi. For comparative purposes, the average flexural modulus of the impregnant utilized is approximately 400,000 psi, and the tensile strength is on the order of 12,400 psi. Figure 2 shows typical load-

TABLE 4. *Static bending results for retests of yellow-poplar specimens impregnated (reimpregnated) after the first set of bending tests.*

Specimen	No. of specimens	MOE Average (psi)	MOE Coef. of var.	MOR Average (psi)	MOR Coef. of var.
Unimpregnated prior to testing to failure, and then impregnated and retested	7	1,334,000	0.051	16,840	0.061
Impregnated prior to testing to failure, and then reimpregnated and retested	8	1,254,000	0.085	15,049	0.064

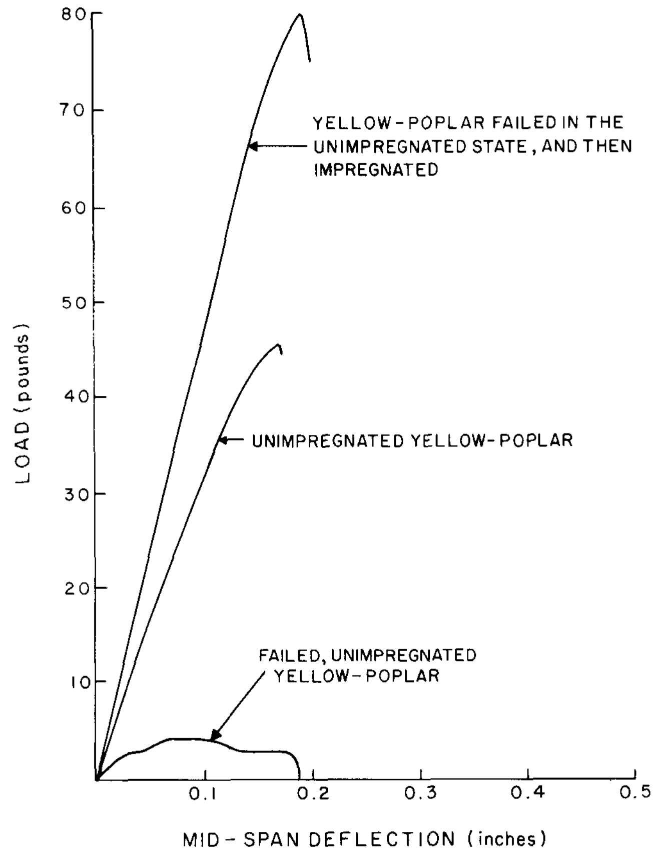

FIG. 3. Typical load-deflection curves for unimpregnated yellow-poplar before and after failure, and yellow-poplar impregnated after failure.

deflection curves for the unimpregnated and impregnated yellow-poplar specimens.

As previously noted, the wood specimens for this first set of tests were not completely broken, in order to have one-piece specimens for impregnation. However, visible separation of the fibers on the tensile side of the beam was evident in all of the failed specimens. To determine the residual strength and stiffness in these specimens, two specimens from each group of failed specimens (unimpregnated and impregnated) were straightened and retested (Table 3) without any attempt to stabilize the crack with impregnant.

A comparison of the results in Table 3 with those in Table 2 shows that the residual stiffness and strength values of the failed samples are relatively low compared to the original stiffness and strength values before failure. The average MOE and MOR values for unimpregnated yellow-poplar are 982,000 psi and 11,736 psi, respectively; while the residual MOE and MOR values for failed specimens are 410,000 psi and 1,007 psi, respectively. Similarly the MOE and MOR values for the impregnated yellow-poplar are 1,287,000 psi and 19,871 psi, respectively, and these values are reduced to an average MOE value of 828,000

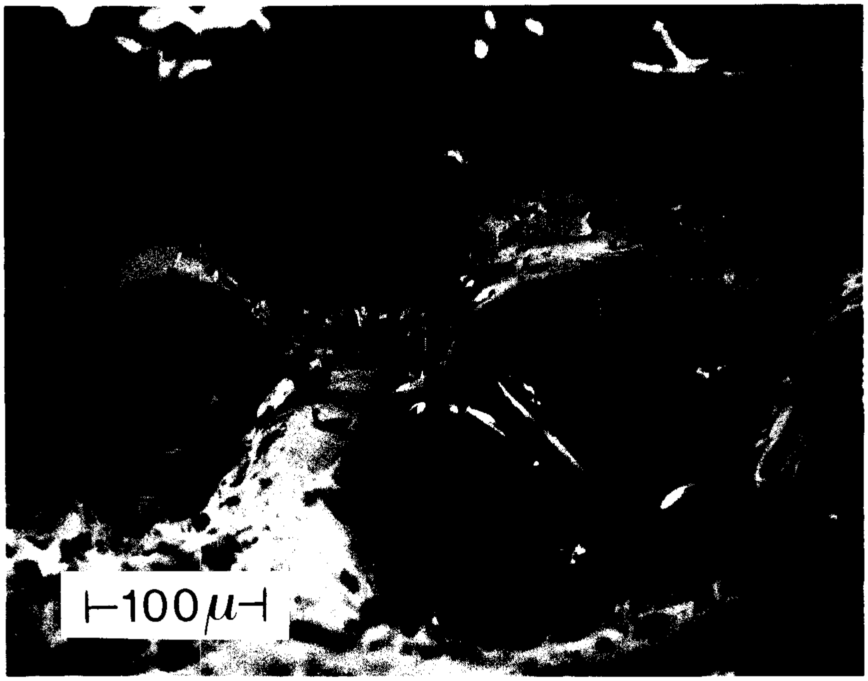

FIG. 4. Fracture surface from tensile side of beam (250×); view of radial-tangential plane.

psi and an MOR value of 10,032 psi after testing to failure. Thus, it is reasonable to assume that the cracks induced by the testing procedure employed represent severe structural limitations in these and the remaining sixteen specimens tested to failure.

The second set of bending tests conducted on the remaining specimens following impregnation and/or reimpregnation provided some interesting results (Table 4). Only seven specimens were retested from the group initially tested in the unimpregnated condition, because one of these samples broke completely in half during the impregnation procedure. It is interesting to note that all eight specimens from the group initially tested in the impregnated state survived the reimpregnation process.

For the group of specimens tested to failure in the unimpregnated condition, the average MOE and MOR values after impregnation are 1,334,000 psi and 16,840 psi, respectively. These values not only represent an improvement over the residual MOE and MOR values listed in Table 3 for the failed material prior to impregnation, but also exceed, to a highly significant level, MOE and MOR values for the original unimpregnated yellow-poplar (MOE = 982,000 psi; MOR = 11,736 psi). Figure 3 contrasts a typical load-deflection curve for the failed, then impregnated material, with those for the unimpregnated material before and after failure.

While impregnation apparently improves the failed yellow-poplar MOE and MOR values above those values for the unfailed, unimpregnated state, the effects of the cracks are not negligible. This can be seen by comparing the bending test

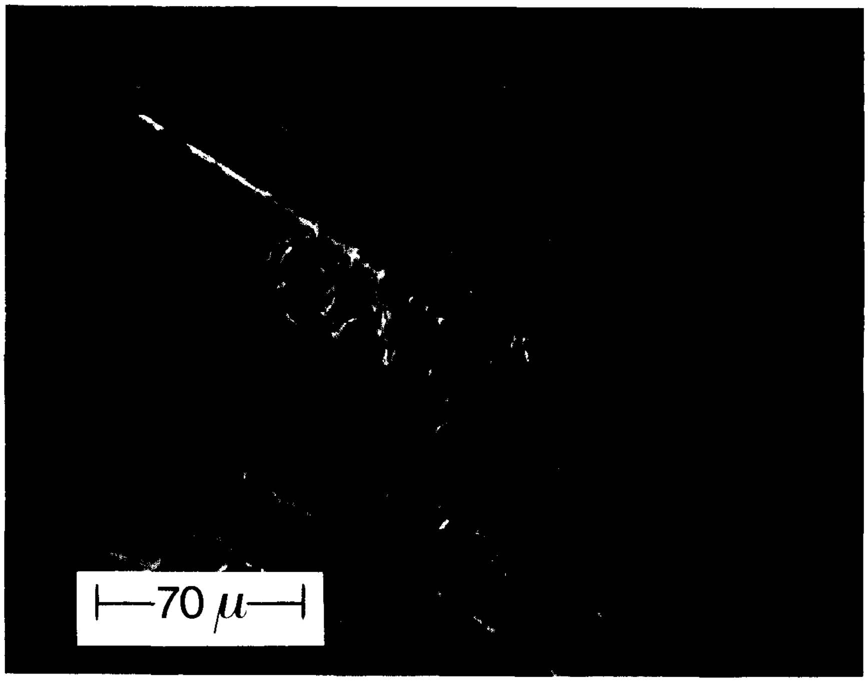

FIG. 5. Fracture surface from tensile side of beam (400×); view of tangential-longitudinal plane.

results for the failed, then impregnated specimens in Table 4 with the test results in Table 2 for yellow-poplar not failed prior to impregnation. An analysis of variance shows that no significant difference exists between the MOE values of the two groups (1,334,000 psi for the specimens with induced cracks versus 1,287,000 psi for the specimens without cracks). On the other hand, there is a significant difference in the MOR values, with the cracks resulting in an average reduction of approximately 3,000 psi. The average MOR value for the specimens failed prior to impregnation is 16,840 psi (Table 4) compared to the average MOR value for specimens not failed prior to impregnation of 19,871 psi (Table 2). This difference in the response of MOE and MOR is reasonable, given the more defect-sensitive nature of MOR at high strain levels. The results also suggest that to obtain maximum efficiency in the strength properties of impregnated wood, the presence of cracks (and perhaps natural defects such as knots, decay, and insect damage) should not be ignored.

An interesting complement to these data is provided by the results for the specimens that were impregnated prior to being tested for the first time. One might expect that in this case there would be less opportunity in the reimpregnation process for the impregnant to penetrate and stabilize the cracks. However, this is apparently not the case. As indicated in Table 4, the average MOE value for the failed and reimpregnated specimens is 1,254,000 psi, compared to 1,287,000 psi for the original, unfailed impregnated specimens. An analysis of variance indicates no significant difference in these two means. There is a significant difference in the MOR means for the original, unfailed impregnated material (19,871 psi) versus the failed and reimpregnated material (15,049 psi). Nonetheless, these values represent a rather large increase over the residual strength of the failed material (10,032 psi). It is interesting to note that the increase in the residual strength results from the addition of a relatively small amount of impregnant. As noted previously, there is no significant difference between the average impregnant volume fraction after the first impregnation and that after the second impregnation (Table 1). This also emphasizes the efficiency that can be realized by a selective localized impregnation process.

One possible explanation for this improvement in the bending properties of the failed, impregnated specimens following reimpregnation becomes somewhat clear upon examination of fracture surfaces. Figures 4 and 5 are SEM micrographs of two fracture surfaces from the tensile side of the neutral axis of a failed impregnated yellow-poplar beam. It is apparent from these micrographs that a significant amount of cell wall (in addition to cells previously inaccessible to the impregnant) is exposed during the failure process. During reimpregnation, these exposed surfaces would be expected to provide a surface area of wood for bonding to the impregnant. Hence, improvement in the bending properties would not rely solely on an epoxy-epoxy bond.

SUMMARY

The effects of impregnation of small yellow-poplar clear sapwood beams with an epoxy resin were examined. Both impregnated and unimpregnated specimens were partially failed in bending, impregnated to stabilize the cracks, and retested in the same manner. It was found that the unimpregnated material apparently had no significant effect on the MOE values of the product that resulted after impregnation. On the other hand, the MOR values for the failed, then impregnated material were significantly lower than those for impregnated wood that was not failed prior to impregnation. However, both the MOE and the MOR values for the failed, then impregnated material exceeded the MOE and MOR values for the original defect-free unimpregnated material.

Reimpregnation of failed, impregnated material also produced significant improvements in MOR and MOE values, despite the low additional amounts of impregnant absorbed during the second impregnation procedure. The MOE values for the reimpregnated material were comparable to those for impregnated wood that was not failed prior to impregnation. However, the MOR values for the reimpregnated material were significantly lower than those for the defect-free impregnated wood.

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