The Dowel Joint

Why round tenons fall out of round holes, and the elastomer compromise

by R. Bruce Hoadley

Dowel joints must surely be among the oldest methods of joining wood. What could be more basic than a cylindrical tenon fitting a drilled-round mortise, locked forever with good glue? The image of perfection.

But not quite. For our experience suggests that if anything is as old as dowel joints, it is loose dowel joints. We have become resigned to loose and wobbly chairs, and to our mothers warning us not to tilt back at table. Accepting this has always seemed unreasonable to me, so some years ago I set out to study the traditional dowel joint, to find out why they fail and especially to discover the recipe for a joint that would not fail. After many experiments I arrived at the troubling conclusion that no matter how well the joint is made, the conflicting dimensional behavior of the mortise and the tenon in response to humidity variations in our everyday environment can cause self-induced loosening. The very nature of wood ensures that it eventually can come loose. However, some recent research encourages me to believe that soon we will have a dowel joint that is successful, virtually indestructible. In this article I will explore the self-destructive effect of moisture variation on the traditional dowel joint, and I will suggest some remedies and some lines for further exploration.

A plain round tenon in its simplest form, such as an unshouldered rung inserted into a chair leg, responds to external loading differently from a shouldered tenon, a dowel in a rail/stile frame joint, or a grooved, serrated or precompressed tenon. This article makes no attempt to address such special cases, but focuses on the individual dowel or tenon insertion.

Obviously, the species of wood and the dimensions of a successful joint will accommodate the loads it must sustain. In a typical chair (figure 1), analysis can determine the dimensions and proportions of the joint so that axial stresses along the mating surfaces are safely within the strength properties of the wood. Adding glue provides shear resistance to whatever minor withdrawal load might be imposed. And the commonly used dimensions, which have evolved by experience and tradition, are more than adequate to resist loads imposed by use—or even moderate abuse. Chair rungs are rarely so small in diameter that they fail simply because of excess bending stress and break off at the joint. When they do break here, it is usually because the other end has fallen out of its socket, and someone then steps on the rung. Likewise, as long as the joint remains tight, its bearing areas are usually large enough to distribute the racking loads.

But two common shortcomings lead to problems. First, the mortise may be too shallow in proportion to its diameter. In a Windsor chair, for example, the thickness of the seat limits the mortise to a shallow hole compared with the rather large tenon diameter at the top of the leg. Second, the mating surfaces may be of poor quality. Poor turning or shaping of tenons is not nearly as common as badly bored holes. If the spurs of the auger aren't in top condition, the surface of the hole is liable to be lined with damaged cells, which can neither support the bearing loads nor develop a successful glue bond. Proper fit is also critical. With water-based emulsion glues (white or yellow), highest withdrawal resistance develops when the dowel diameter is several thousandths of an inch less than the mortise diameter. If the tenon is oversized, the joint will be scraped dry upon assembly; if undersized, the glue line will be excessively thick.

Moisture variation is to blame — If a joint is properly designed and well made, it will carry any reasonable load at the time of assembly. The mystery is why an apparently successful joint loosens due to nothing more than humidity change. The humidity variation in typical indoor situations is wide. In Northern states, humidity in the 80% to 90% range may prevail through August and September, only to plummet to 15% to 20% relative humidity in the subzero days of January and February. This may cause the average equilibrium moisture content of wood to cycle from as low as 4% in winter to as high as 15% in the summer. Even greater extremes occur in such areas as basement rooms, with condensation dampness in summer and a nearby furnace causing excess dryness in winter. Furniture assembled in Scottsdale, Arizona, later moved to New Orleans, and ultimately back to Scottsdale, would go through a similarly drastic moisture cycle. An unfinished wooden ladder, stored flat on the ground and covered with a tarp in summer, then returned to a heated shop for winter storage, would suffer likewise. As a result of moisture cycling, the dimension of wood perpendicular to its

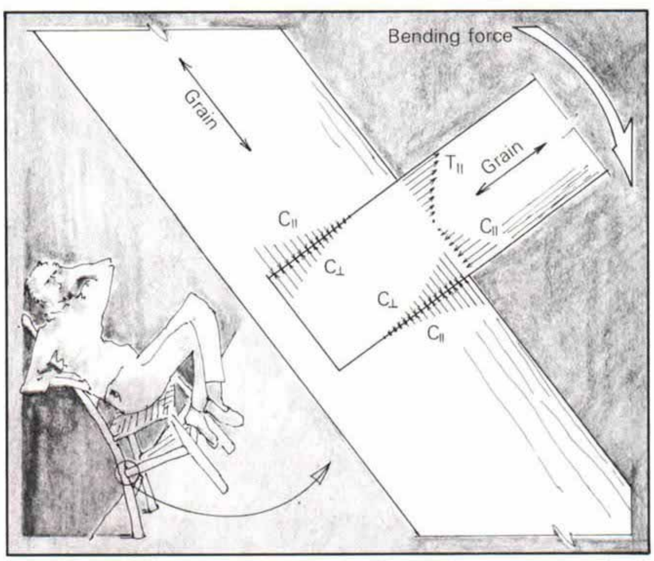


Fig. 1: Tilting back in a chair racks the joints. The rung tends to bend, causing axial stresses (tension, $T_{\|}$ and compression, $C_{\|}$). In turn the rung tenon bears against the mortise walls, compressing the rung perpendicular to the grain ($C_{\perp}$) and the mortise parallel to the grain ($C_{\|}$).

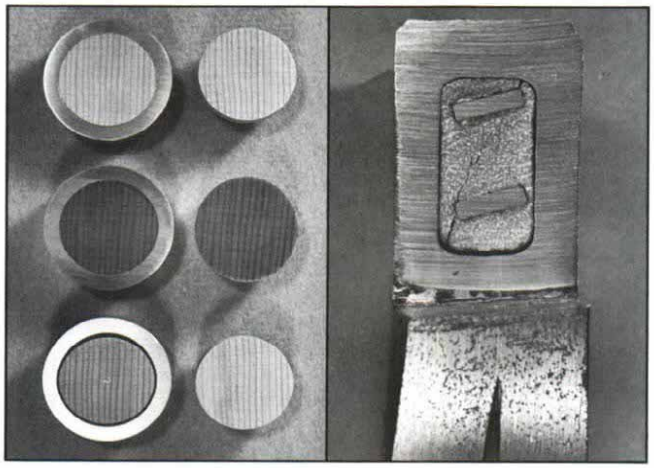


Fig. 2: Paired discs of American beech, left, dramatize the effect of cyclic moisture variation. The top two are as originally turned at 7% moisture content—the wood tightly fits its steel sleeve. The central pair has been moistened to the fiber saturation point (about 30% MC). The lower two were moistened to fiber saturation, then dried to their initial 7% MC. Compression set makes the restrained disc smaller than it started out, whereas the unrestrained disc has returned to about its original size. Right, the handle was tight when this hammer head was sectioned by hacksaw. Then it was stored in a damp place and later redried—the hickory shows severe compression shrinkage, and moisture variation, not the pounding of use, is to blame. This is why soaking a tool in water to tighten a loose handle is a temporary solution at best.

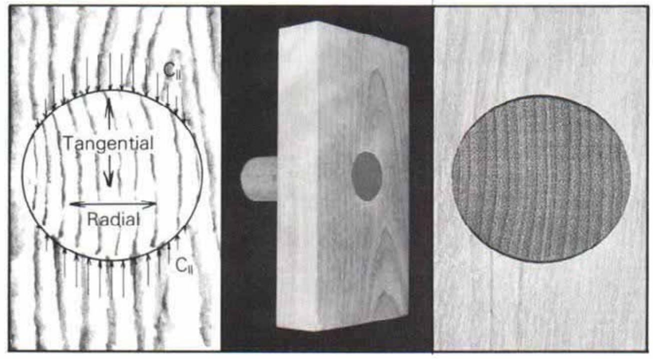


Fig. 3: Increased moisture swells the mortise across the grain by about the same amount as the tenon swells radially. But the mortise doesn't change in height (parallel to the grain). Thus, like the steel sleeve, the end-grain surfaces of the mortise restrain the tangential swelling of the tenon (diagram, left). When the unglued birch joint shown in the photographs was cycled from dry to wet to dry, compression set made the redried tenon smaller tangentially than it originally was, yet still a snug fit radially. Since most woods move more tangentially (in the plane of the annual rings) than radially (perpendicular to the rings), the orientation shown here is not optimum. Turning the tenon 90° in the mortise would be better.

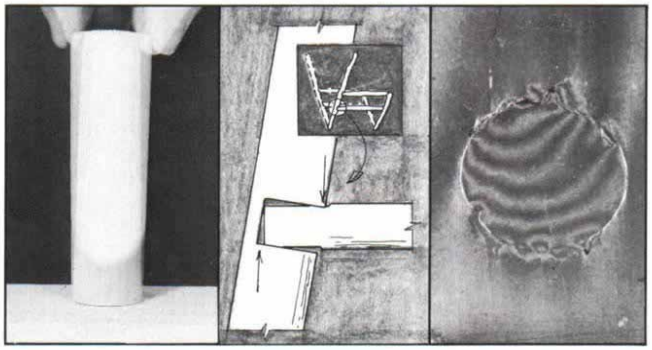


Fig. 4: This white ash ladder rung, left, was driven tightly into a western hemlock rail, then put through a severe moisture cycle. The double exposure shows how loose the joint has become. The diagram shows that once looseness develops in a joint, racking results in concentrated load that may further crush the wood: The worse it is, the worse it gets. Right, a birch dowel in ponderosa pine was coated with moire strain-analysis material and photographed through a grill of undistorted lines. The light-dark patterns show that compression damage extends well into the end grain of the mortise.

grain direction can change by up to 4% of its original dimension. This amounts to a change of 1/32 in. across a 1-in. diameter tenon.

First, consider a wooden dowel confined in a metal socket, such as a hammer handle tightly fitting into its steel head. For our experiments, we simplified this to a dowel of wood fit snugly into a stainless-steel sleeve, then cycled from low to high and back to low moisture content. An unconfined dowel would simply swell and reshrink to approximately its original diameter. However, the restrained dowel crushes itself, and upon redrying to its original moisture content, assumes a smaller-than-original size. Confining a piece of wood to prevent it from swelling by 4% is essentially the same as allowing the piece of wood to swell and then squeezing it back to its original dimension. The trouble is that in confining wood perpendicular to the grain, the limit of elastic behavior (that is, its ability to spring back) is less than 1%. Any additional squeeze will cause permanent deformation, or "set," as in figure 2. In addition, the wood surfaces, already somewhat damaged by machining, do not behave elastically, and seem simply to crush. The result is a concentrated surface layer of crushed and mangled cells.

The wood-to-wood mortise-and-tenon joint is a special situation in that the restraint is unidirectional. The diameter of the mortise does not change parallel to the grain, but its diameter perpendicular to the grain varies right along with the diameter of the tenon. It becomes ovoid during moisture cycling (figure 3). After a dry-wet-dry cycle, compression set is greatest against the end-grain surface of the mortise, while the tenon remains snug at the side-grain surfaces of the mortise. The tenon will therefore be looser in a plane parallel to the grain direction of the mortise.

Such looseness in the side rungs of a post-and-rung chair will allow the chair to rock forward and back. As soon as this looseness begins, the joint-surface load is no longer distributed evenly, but is concentrated at specific points. The concentrated loads may now exceed the strength of the wood at these points, further crushing the surfaces. So the joint gets looser—the worse it is, the worse it gets (figure 4). With woods of equal density, most of the damage will turn up as crushed tenon because of the lower strength of wood in compression perpendicular to the grain. However, where the mortise is in a lower-density wood than the tenon, such as a hard maple leg tenoned into a white-pine seat, the crushing may be worse on the end-grain walls of the mortise. This bad situation is compounded if the end grain was damaged when the mortise was bored, especially in fragile woods like pine.

Now consider glue. If a good glue bond develops between the tenon and the end grain of the mortise, the shrinking of the compression-set tenon during the drying cycle can be significantly retarded. This is apparent when we make matched samples with and without glue. The unglued joint will open with even the slightest cycle. Glued joints resist moderate moisture variation without failure. With exposure to more

Photos: R. Bruce Hoadley

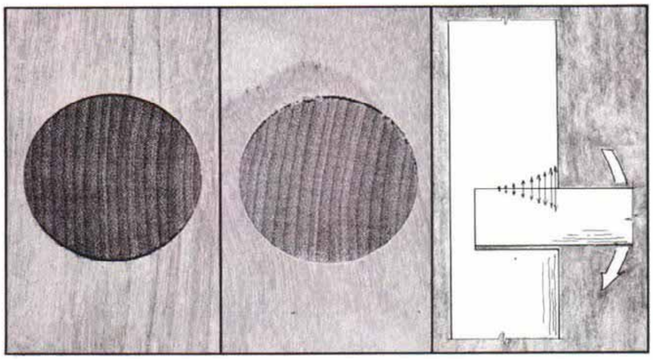


Fig. 5: Dowel Joints without glue (left) and with glue, after severe moisture cycling. Once one side of the joint has opened, the other glue line is no match for racking stresses and usually fails in tension. If the mortise was badly drilled, a layer of wood may pull away with the glue.

severe cycles, the joint eventually fails, at first along only one of the end-grain surfaces. The remaining glue bond is now no match for even moderate racking, for the critical stress has become the tensile loading of the glue line (figure 5). When a joint loosens, we assume that "the glue has let go." Close examination may show, however, that a layer of wood tissue has been pulled from the inside of the mortise. This is common where a high-density tenon is glued into a lower-density mortise—the maple leg in the pine seat.

One more point bears elaboration: the behavior of wood in tension perpendicular to the grain. As we have seen, if wood is compressed perpendicular to the grain to well beyond its elastic limit (that is, by several percent of its original dimension), the cell structure is permanently crushed but it remains intact. However, in tension perpendicular to the grain, the strain limit is 1% or 2% of the original dimension, whereupon the wood pulls apart. Therefore if the moisture cycle develops between 1% and 2% compression shrinkage, a glued tenon may be pulled apart during the drying cycle, no matter how perfectly the joint was machined and glued. The tenon actually splits near the glue line. So one way or another, the joint will fail if the moisture cycle is severe.

What to do? — I really didn't appreciate how destructive moisture cycling could be until I ran some experiments. I had arrived at a standard test assembly consisting of a 4-in. by 1-in. dowel inserted into a 1-in.-dia. hole, 1⅛ in. deep, in a 3-in. by 5-in. by 1¼-in. block. In one series, I made 20 similar maple-tenon-in-pine-block joints, using wood that had been conditioned to 6% moisture content. I used a PVA adhesive (white glue). Ten of the joints were stored in sealed plastic bags; the other ten were conditioned up to 18% moisture content and down to original weight, over a period of several months. The cycled joints weren't wobbly, although visible fracture of the squeezed-out glue along one side of the joints suggested that compression set had developed. Then, by racking the joints with hand pressure, there was an audible snap and the joints became wobbly. When pulled apart in a testing machine, the average withdrawal load of the uncycled specimens was 1,550 lb., while the cycled specimens averaged only 42 lb. This was a terrible predicament, for under commonly encountered moisture variations, even well-made joints were destroying themselves. I didn't want to believe it, but further experiments confirmed this cold, hard truth. To minimize the problem, I arrived at a list of five checkpoints for making joints with the best chance of survival:

1. Proportions. Avoid shallow mortises. I try to make the mortise 1½ times as deep as it is wide. However, if the mortise depth approaches twice its diameter, a new set of problems make the situation worse again.

2. Original moisture content. The wood (especially the tenon) should be slightly drier, not wetter, than its eventual average equilibrium moisture content. Better a little compression than tension at the joint interface.

3. Mortise surface quality. Carefully bore the mortise. Sharpen the bit, especially the spurs, with extreme care to produce the cleanest possible surfaces. Using a drill press or boring guide will improve the hole.

4. Grain/growth-ring orientation. If possible, bore the mortise radially into the female member; orient the tenon with its growth rings perpendicular to the grain direction in the mortise (figure 6). This minimizes the stress by putting radial, rather than tangential, dimensional change in opposition to long-grain structure.

5. Finish the product. Completed work should be given a coat of finish selected to provide maximum protection against short-term, but potentially disastrous, extremes of humidity. Lacquer, varnish or paint is best. And remember to finish all over, especially end-grain surfaces.

All of the above conditions cannot always be optimum, and there will be situations where severe moisture variation cannot be avoided. What other solutions might be possible? For unidirectional stress problems (the chair leg and rung in figure 3), I tried providing stress relief by making a saw-kerf slot in the tenon, thinking that compression would be relieved during the swelling cycle. This helped, but it had the disadvantage of shearing the glue line adjacent to the kerf as each half swelled. Finally I split the tenon—a plane of failure that would relieve stress during the drying phase of the cycle. As compression shrinkage took place, the split could open rather than the glue line failing. In our initial tests with circu-

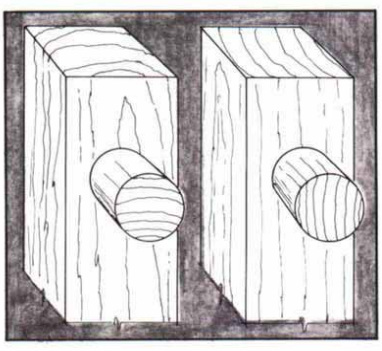


Fig. 6: The optimum condition (left): tangential movement coincides in both mortise and tenon, while the lesser radial dimensional change in the tenon opposes the stable long grain of the mortise. At right, tangential movement varies the depth of the mortise and may 'walk' the tenon out, while compression will cause the greater change in tenon height.

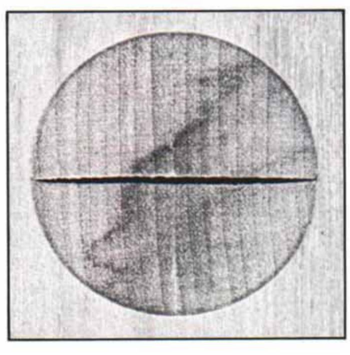


Fig. 7: Birch tenon was split both radially and tangentially before assembly. After moderate moisture cycling, compression shrinkage has developed entirely in one direction, opening the radial split, while the tangential split remains tight. The entire glue line remains intact. This may be what actually happens when tenons are wedged.

lar plugs in flat boards, the presplit tenon opened as predicted, and the glue line remained intact. In matched specimens without splits, the glue line failed. Analysis confirmed that in the compression-shrinkage phase the wood could actually distort itself by enough to relieve the strain. When I made regular, full-depth joints, splitting the tenon to the full depth of insertion, the joint stayed together under moderate moisture cycling (figure 7). I suspect that this mechanism is the real reason why wedged tenons work. Although the wedge is intended to supply lateral pressure to the glue surfaces and perhaps also to splay the tenon for a dovetail-style mechanical lock, it may actually do no more than provide a stress-release slot and thereby help the glue line survive.

Under moisture extremes, a new problem emerges: The mortise depth changes, and the glue line shears. After repeated cycling the tenon remains glued around the bottom of the hole, but shear and compression set develop near the outside junction, and racking eventually completes the break (figure 8). An especially tight fit, good gluing and finishing, and close control of moisture content at assembly can help prevent the mortise from changing depth relative to the tenon. The price is liable to be an unsightly bulge or a check on the back side of the chair leg. So the simple split has promise, but it is not the best solution.

Silicone adhesives — It has always intrigued me to see a heavy motor set into a base with rubber-sleeve motor mounts. Why not set tenons into some kind of rubber sleeves inside the mortise? The rubber might yield enough during the swelling and shrinking phase of the cycle for the glue joint to survive. First, I bonded rubber tubing 1/16 in. thick around a 1-in.-diameter dowel and glued it into the mortise. A tedious procedure, but I was encouraged when the joint survived severe moisture cycles without failure. Next I experimented with General Electric's RTV (room temperature vulcanizing) silicone elastomers. A translucent formulation, RTV-108 (in hardware stores the product name is Clear Glue and Seal) worked well. To keep the tenon centered and parallel to the mortise while the silicone cured, I glued thin splines onto it at 90° positions (figure 9). Later we figured out how to machine a four-spline tenon with its base diameter undersized by the thickness of the glue line. Hand-carving a dowel to leave four or six thin ribs also works. If the modified portion of the tenon is slightly shorter than the depth of the mortise, the elastomer sleeve can be fully hidden in the joint. Before gluing, slide the tenon into the mortise to be sure the ribs fit snugly. Then wipe a dab of silicone adhesive into all mating surfaces. Next, quickly squeeze a dab into the bottom of the mortise and firmly push the tenon home, allowing the silicone adhesive to flow back up along it. Within an hour it will skin over firmly and you'll soon discover the point at which the squeeze-out solidifies enough to be neatly peeled off. The joint cures within 24 hours but does not reach full strength for a week or more.

I have experimented with various dowel sizes, adhesive layer thicknesses and wood species, and compared the results with conventional assembly glues. Predictably, with fairly thick elastomer layers (0.060-in. layer in 1-in.-diameter mortise) the joints are able to withstand severe moisture cycles (6%-24%-6% MC) without losing withdrawal strength. The same cycle destroys a standard PVA (white glue) joint. For example, in oak joints with white glue, it took an average of 1,100 lb. to pull apart uncycled joints. But after a 6%-24%-6% moisture cycle the average withdrawal resistance was only 41 lb. (most joints were loose enough to be wiggled apart by hand). With RTV-108 (silicone), the original joint strength averages 264 lb.; after cycling, 262 lb. Even though the white-glued joint was stronger in withdrawal to begin with, the silicone-glued joint is strongest after cycling. The silicone joints that withstand the severest moisture cycling are not nearly as rigid as conventional glues and unmodified tenons, and the silicone-glue approach cannot be considered a direct substitute for traditionally made joints. In defense, I point out that after severe cycling, the white-glued joints were often far worse than the silicone joints. However, the rigidity of silicone joints can be improved by increasing the relative depth of the mortise and by making the adhesive layer thinner. It is best to keep the depth of the mortise at

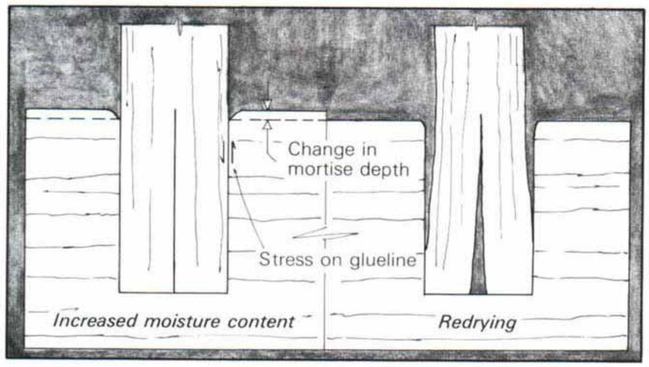


Fig. 8: In moisture extremes, typically high moisture content followed by redrying, the changing depth of the mortise and compression set near its mouth shear the glue line. The split tenon accommodates stress at the bottom of the hole, but racking will soon break it loose.

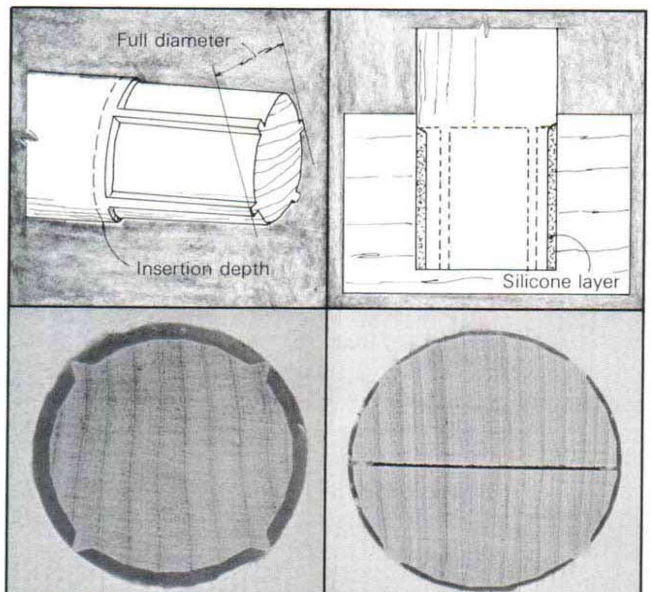


Fig. 9: The elastomer compromise. Four thin ribs are formed on the tenon, by machining, whittling or by gluing splines onto the tenon. The ribs should be 90° apart, and oriented at 45° to the grain of the mortise. The ribs keep the tenon centered and contribute to rigidity. Their depth determines the thickness of the silicone layer; their length can be short of full mortise depth, thereby concealing the modified portion of the tenon. A split in the tenon contributes to strain relief and allows the silicone layer to be quite thin. The silicone compounds with better adhesion to wood now being developed may solve the problem of wobbly chairs.

least 1½ times its diameter With 1-in. tenons, as the glue layer is reduced to about 0.020 in., the joint stays rigid, will have reasonable withdrawal strength and will withstand fairly drastic moisture variation. Effecting this can be a problem in leg-to-seat joints for Windsor chairs, where the seat thickness limits the mortise depth. If the glue layer is too thin, compression will develop. A good point of departure for experiments with 1-in. dowels would be a silicone layer of about 1⁄32 in. or slightly less. This should give a good compromise between durability under moisture variation, and rigidity.

I have also tried assembling several different types of woods with silicone adhesives. One style of captain's chair, having a pine seat and arms and maple turnings, was assembled using nominal 0.020 in. silicone layers. After six years, all joints are still secure. While seated in the chair, by intentionally racking the frame, you can feel slight springiness due to its non-rigid joints. But nobody who hadn't been told about the special system of joinery has ever commented on the slight wobble. In a set of twelve thumb-back chairs, half the joints were assembled with silicone, half with white glue. The chairs were left in a library lounge for six months of student use. The only failure was in one white-glued joint.

In other items silicone joints seem to be the perfect solution—attaching the smokestack to toy tugboats for the bathtub, where alternate hot-soak and drying of unpainted wood is a most severe exposure. Bathtub toys assembled with conventional glues compression-set and fall apart easily, but silicone joints can take it. Another application is attaching laminated beech sculptor's mallets to their maple handles. Silicone not only solves the loosening problems, but the layer of elastomer seems to contribute to shock absorbancy. I have also used it to reassemble a few pieces of furniture whose tenons were woefully undersized and loose because of compression shrinkage as well as fist-pounding reassembly many times. Success was predictable according to joint proportions: Shallow mortises didn't work out, but where the tenons were long and the mortises deep, the silicone did a perfect job of filling the gaps and solving the looseness problem, perhaps forever.

Note that all of these remarks apply to rectangular structures, which rely on joinery for rigidity. A triangulated structure, on the other hand, is inherently stable, and silicone glues might be exactly right. I hope some craftsmen may be encouraged to experiment along these lines.

Combining silicone with a stress-relief split in the tenon also looks promising. I found that the glue layer can be held to a minimum (0.010 in. to 0.015 in.), since part of the problem is handled by the opening of the split tenon. Some typical values for direct withdrawal of a maple tenon from a pine mortise, before and after moisture cycling, are: with white glue, 1,553 lb. and a mere 42 lb.; with a layer of silicone 0.010 in. thick, 830 lb. and 290 lb.; and with silicone plus a slit in the tenon, 753 lb. and a surprising 580 lb. The limiting feature of silicone adhesives has been adhesion to the wood surface. Average tensile strengths perpendicular to the surface are only about 200 PSI. Recently, however, we have tested some formulations (not yet on the retail market) which have more than double this strength. I am confident that we will hear a lot more about silicone elastomers, and see them specifically incorporated into joinery work. □

Bruce Hoadley teaches wood science at the University of Massachusetts, in Amherst. For more on repairing wobbly chairs, see FWW #20, *Jan. '80, p. 79.*

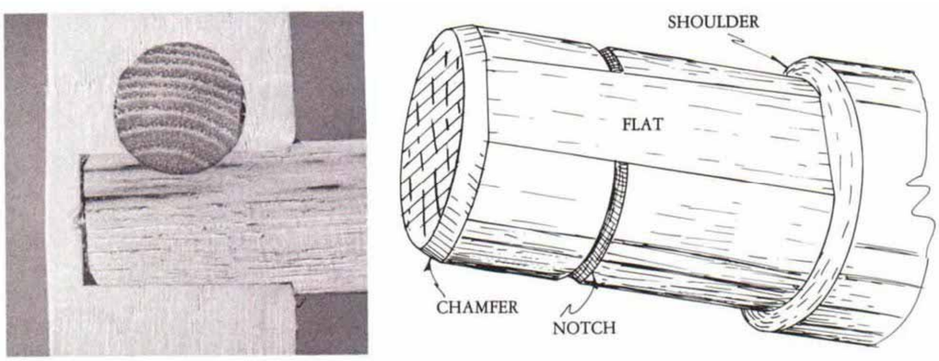
One Chairmaker's Answer

(EDITOR'S NOTE: The following is excerpted from *Make a Chair from a Tree: An Introduction to Working Green Wood,* by John D. Alexander, Jr., published by The Taunton Press, 1978.)

The goal is to employ the compressability of green wood without exceeding the elastic limit of the fibers in the tenon. When the moisture balance is tight, we can drive in an oversized tenon and create a tight bond between the surface of the mortise and its tenon.... At the time of mortising and assembly, the post should contain about 15% to 20% moisture (air-dried outdoors) and the rung about 5% (dried indoors near the stove).

... I flatten the sides of all the tenons in my chair—slightly more so on the tenons of the rungs near the top of the front posts. Flats not only prevent posts from splitting during drying, but after drying they act as a lock that prevents the tenon from rotating in the mortise. . . .Taper the flats a mite so they are broader and deeper toward the shoulders. This makes them slightly dovetailed when viewed from above. If all goes well, the shrinking post locks the dovetailed tenon into its mortise. Last, notch the tops and bottoms of the tenons so that when the compressed end grain of the mortise dries and straightens, a ridge of post wood will be forced into this notch.. . .

When the chair is assembled, the wood rays in the tenon should be oriented vertically, in the same direction as the long axis of the post. This orientation aligns the direction of maximum rung movement (the tangential plane) with the direction of maximum pressure from post shrinkage.. . . Looking from the top of the post, bore the mortises so that the plane of the wood rays bisects the angle between the front and side rungs. This allows each tenon to be compressed equally as the wet wood shrinks.. . . Bore the bottoms of the side mortises about 3⁄32 in. lower than the tangent lines laid out earlier from the tops of the front and rear rung mortises. This locks the rungs together inside the post. . .I use glue. I use every technique I can that might help the chair hold together. —*J.D.A.*



Interlocking tenons secure the joint; tapered flats and notches also help.