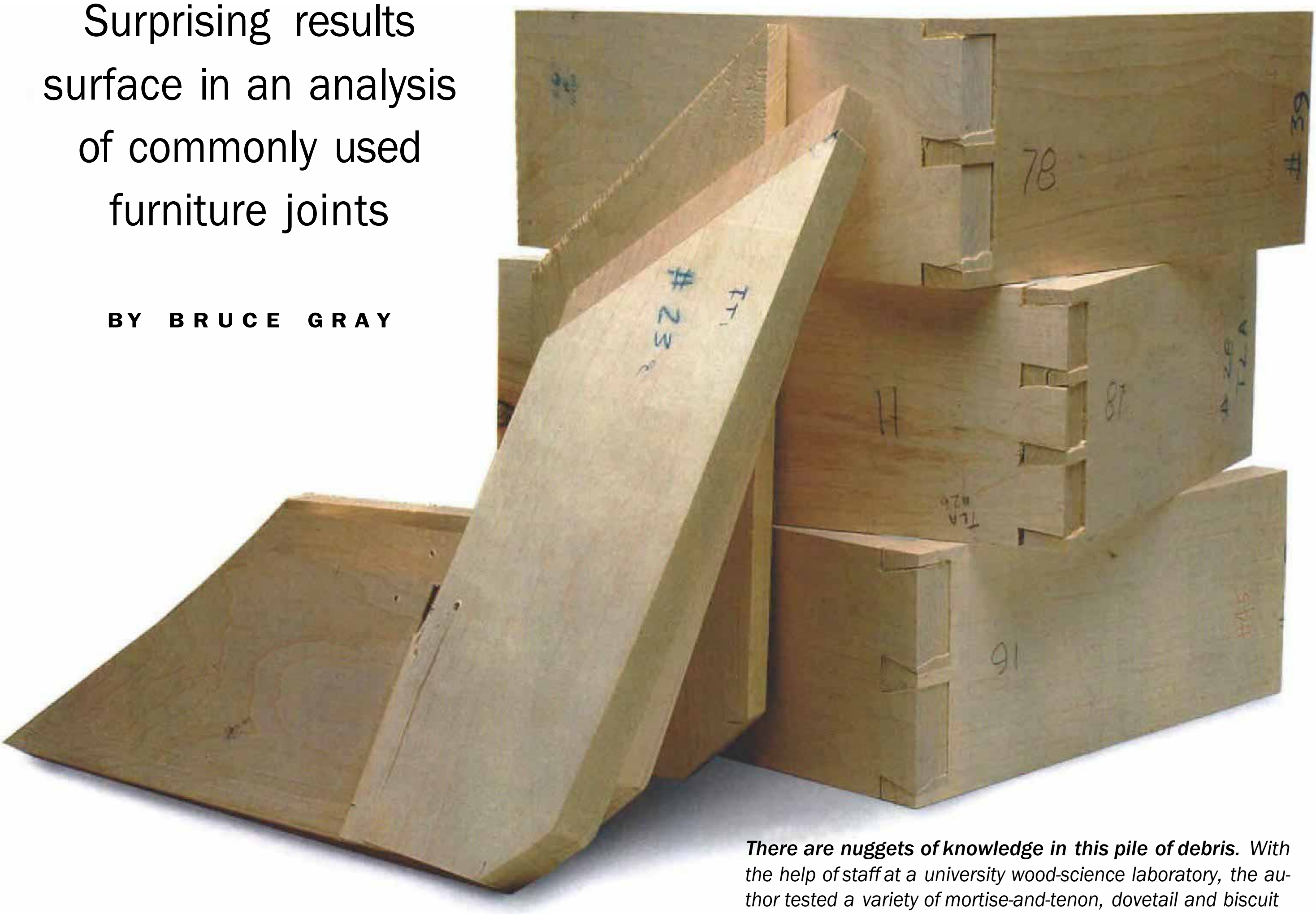
Testing Joints to the Breaking Point

Surprising results surface in an analysis of commonly used furniture joints

BY BRUCE GRAY



There are nuggets of knowledge in this pile of debris. *With the help of staff at a university wood-science laboratory, the author tested a variety of mortise-and-tenon, dovetail and biscuit joints. Some results were predictable; some were unexpected.*

Most furniture makers have an entrenched point of view regarding the strength of different types of wood joints, based as much on speculation as on observation. As a puzzled furniture designer who wondered about the relative strength of various joints, I wanted some reliable answers. To find them, I sought expert technical advice and access to the laboratory testing facilities of the Wood Science and Technology Center of the University of New Brunswick. What we discovered may surprise you and should help you design and build stronger furniture.

The types of joints tested

We chose to examine what I believe are the joints most commonly found in tables and chairs, carcases and face frames, doors and drawers—all products of amateur and professional woodshops. We tested traditional rectangular mortise-and-tenon joints; floating (or what some people call *loose)* tenons, both rounded and straight-edged; double #20 biscuit joints; narrow and wide dovetails and low- and high-angle dovetails. Let's look at which joint proved to be the strongest and where and why the joints failed.

Traditional mortise-and-tenon joints—The traditional rectangular mortise and tenon served as a base of comparison for the other similar joints. I figured that this joint (which is more time-consuming to make) wouldn't provide a significantly stronger result when compared with floating tenons of the same size. I was wrong. In the tests, the traditional mortise and tenon beat all other

Photos, except where noted: Author; this page: Michael Pekovich

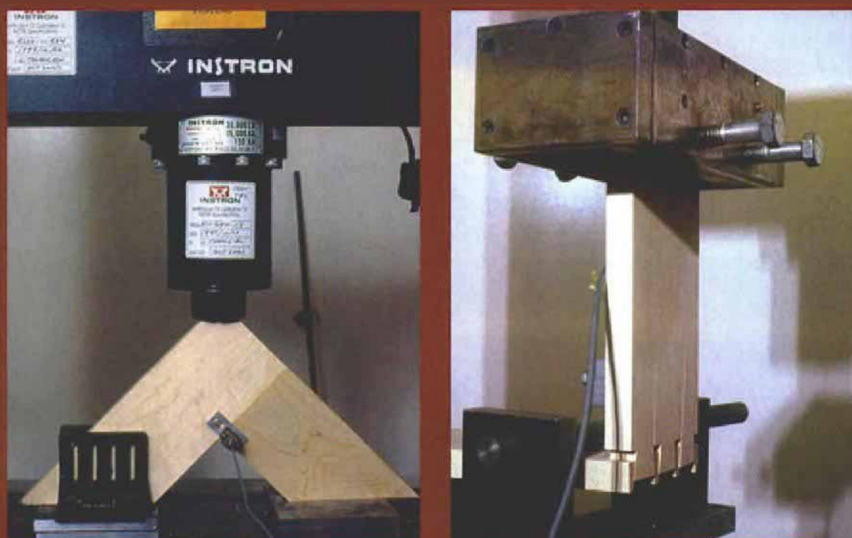
How the samples were prepared and tested

Our aim was to construct and test all of the joints in a scientifically objective manner and to use samples that correspond to joints used in real-world applications. The American Society for Testing and Materials (ASTM) doesn't spell out a specific test procedure for joints of this type but does lay out some guidelines and suggest a number of variables to monitor in controlled experiments. We paid attention to the choice of wood, its moisture content, growth rate and grain orientation; the type and age of adhesive, thickness of film applied and the duration of the open joint; clamp pressure, curing time, room temperature and humidity; how the wood was dressed and cut and how the sample groups were assigned for testing. We prepared eight types of sample joints and six samples of each type for a total of 48 test samples. In addition, we also made several extra samples to sacrifice for the set-up procedure of each joint.

All of the stock was clear, flatsawn hard maple from a single source, dressed to ¾ in. thick. I cut the mortises with a new high-speed-steel bit in a horizontal-mortising machine and the tenons with a carbide blade on a tablesaw. I cut all of the biscuit joints with a fairly new biscuit joiner using a carbide blade. I cut all pins and tails on the dovetail samples using a tablesaw, bandsaw and chisel. Final fitting was done with a chisel. To negate biasing any one sample type due to the human factor of possibly improving my technique as I went along, I cut and fitted them in a sequenced order.

We conducted the tests using an Instron machine, a computer-driven press that controls the rate at which a load is applied and the rate at which readings are taken. A clip gauge measured how much the joints moved as they deflected and opened up (called displacement). The Instron machine was fitted with a 6,720-lb. load cell, which determines the amount of force used. The load was applied at a rate of 1mm to 1.5mm, or about 3⁄16 in. per minute. Five readings were taken every second. A unique feature of the test was that we could see graphically how each sample was reacting internally as the force was applied.

Putting on the pressure



At top left, student Ellen Dalton monitors a load vs. displacement graph in real time. All of the mortise-and-tenon and biscuit joints were tested by pushing down on a flat cut at the outside corner (left). This setup is the equivalent of kicking out the inside of a table leg or racking a cabinet carcase. The dovetail setup (right) replicated the force on a drawer as the front was pulled out, with the pin board (or drawer face) held down while the tail board (drawer side) was pulled straight up.

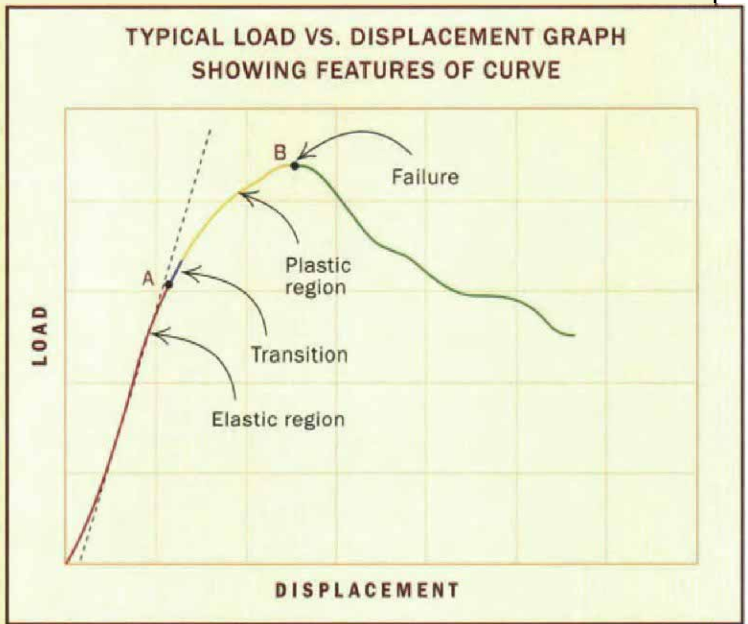
joints hands down. The joint proved to be significantly stronger than either variation of floating tenons and twice as strong as the double #20 biscuit joint.

For the ¾-in.-thick by 4-in.-wide samples we tested, the average maximum working load (how much stress the joint can take without failing) was nearly 5,000 lbs., and the average failure load was right around 6,000 lbs. One of the traditional mortise-and-tenon samples accepted a load of 6,605 lbs. before it failed. That's like piling up three cars on top of that test sample.

If you look at the graph on p. 77 (for more on how to read the graphs, see the story on p. 76), the line in the elastic region (in which the joint is stressed but not damaged) is sharply vertical, meaning the joint is very stiff and resists deflection. This may or may not be a desirable characteristic, depending on the application. The top of the curve is broadly rounded and the tail long and high. This means that failure was gradual, and the joint was able to support a heavy load long after it was damaged.

Floating-tenon joints—I like floating tenons for two reasons: They are useful in many different applications, and I have a horizontal mortising machine that simplifies cutting mortises. When milling floating-tenon stock, I have always rounded over the edges so that they mate tightly to their corresponding rounded mortises. Then it occurred to me that straight-edged tenons would be simpler to make and provide a reservoir at the sides to accept excess glue, thus helping prevent hydraulic dams. I guessed correctly that

How to interpret the charts



Due to our high sampling rate, we ended up with thousands of data points from each sample. The beauty of these was that rather than giving us only the maximum value of a sustained load before the joint failed, we had a more revealing continuous graph. The graph gave us insight into what was happening as the Joints were stressed, long before they failed. Let's examine a typical load graph and a few of the terms that will help you interpret what it all means.

As furniture makers, we are primarily interested in what is called the *elastic* region. This is the range of loads that a wood joint can be subjected to and still return to its original shape. In other words, no damage is done. The load at point *A* is a key value. This is the maximum working load. As the load increases beyond this point, the joint enters a short *transition* zone, then a *plastic* region. Once a joint reaches the plastic region, it is damaged and cannot return to its original form. However, it is still capable of sustaining high loads. The peak of the curve is the maximum sustained load and represents joint *failure* (seen on the graph as point B). This is easy to see on the graph, but it is not as valuable to furniture makers as the maximum working load.

You may wonder how many times a joint could be stressed up to the maximum working load (point A) and not fail. Up until then, none of the glue bonds or wood fibers has been damaged. So theoretically, repeated stressing to this point should have no lasting effects. In practice, engineers usually recommend loading a joint to no more than a percentage of the maximum, say 50% or 75%. The more critical the joint, the larger you want your safety margin to be.

Beyond the peak of the curve (point B), as displacement increases, failure in the glue joints and the wood fibers continues to occur. Ultimately, the joint physically breaks apart, and its load-carrying ability quickly drops to a low value.

they might also allow for some adjustment of the joint during assembly and would be virtually as strong as the round-edged version. But we also found some interesting differences.

The two floating tenon types showed little difference in maximum working load—both about 3,500 lbs. (see the graph on the facing page). The elastic portion of each of these two curves is about the same; both types of joints are very stiff. However, they behave a bit differently as they are stressed further. The round-edged floating tenon's peak on the graph is more gently rounded and higher than that of the straight-edged floating tenon. This means that the round-edged joint fails more gradually and sustains a slightly higher load—both desirable characteristics.

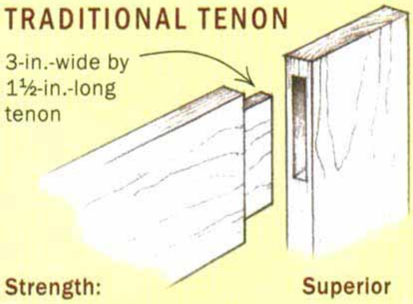
Biscuit joints—In the past 20 years, biscuit joints have become popular with some furniture makers. I suspect that the #20 biscuit is the most common; I use this size primarily for alignment of solid wood and when working with sheet goods. Previously published tests have suggested that biscuit-joint strength and stiffness were comparable to mortise and tenons, but that when biscuits fail, they fail suddenly, Before we tested them, I reasoned that they would be significantly weaker than either type of floating tenon or traditional mortise and tenon because the biscuits are thinner and don't offer as much glue area. I was only partly right.

The double #20 biscuit joint put in a respectable performance, but its average maximum working load was about half the strength of the mortise-and-tenon joints. The graph compares the maximum working and failure loads for the mortise-and-tenon and biscuit joints we tested. It is surprising to note that although the plastic region (in which irreversible damage occurs) is relatively small, the load curve is gently rounded, and the tail is long. This indicates that failure, as defined in this article, is not as sudden as others have suggested. Clearly, the joint is able to sustain a significant load over a wide range of joint movement, even after irreparable damage occurs. However, relatively long after technically defined failure—when parts physically fell apart—it was sudden and complete, with the joint showing no residual strength.

Dovetail joints—We compared dovetails with narrow and wide pins and dovetails with low- and high-angles (7° vs. 14°). Most woodworkers believe that dovetails with narrow pins are primarily decorative and not as strong as those with wide pins. I guessed that we would not find a big difference in strength between the two and that the increased glue area of narrow-pin dovetails may increase the strength of the joint. My hunches were right.

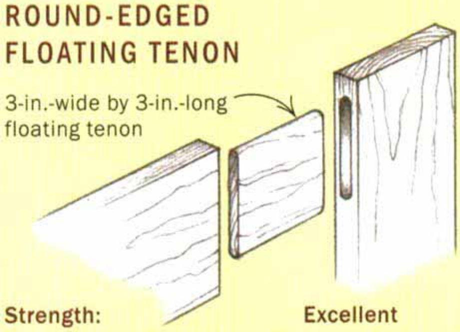
Dovetails with narrow pins were, on average, 30% stronger than the ones with wide pins. The maximum working load for the (¾-in.-thick by 4-in.-wide) sample pieces with narrow pins that we tested was about 1,800 lbs. To put this force in perspective, imagine a 4-in.-deep drawer locked in place, put both hands on the front and pull with a 50-lb. force on each side. The typical working load is more than 15 times as strong. The narrow pins also showed this remarkable strength over a broader range of displacement fol-

TRADITIONAL TENON



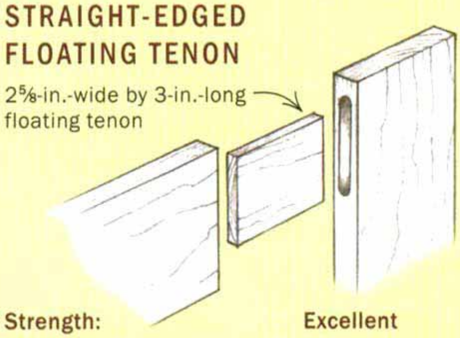
Strength:	Superior
Rate of failure:	Gradual
Strength after failure:	Superior
Rigidity:	Very stiff

ROUND-EDGED FLOATING TENON



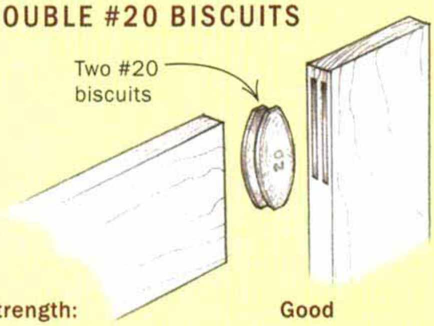
Strength:	Excellent
Rate of failure:	Gradual
Strength after failure:	Excellent
Rigidity:	Stiff

STRAIGHT-EDGED FLOATING TENON



Strength:	Excellent
Rate of failure:	Abrupt
Strength after failure:	Excellent
Rigidity:	Stiff

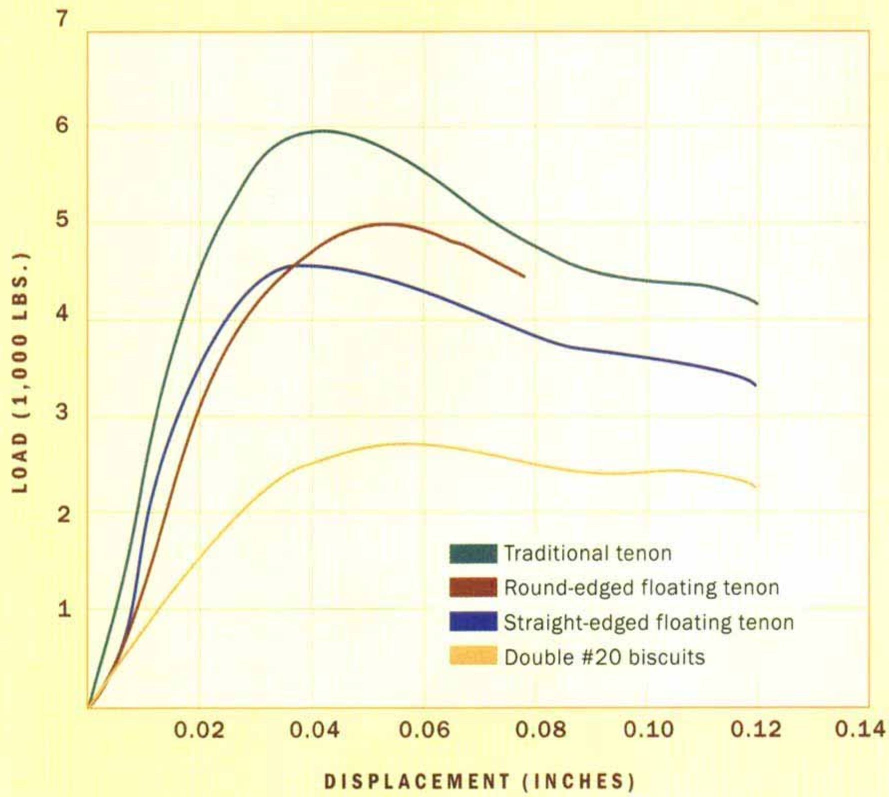
DOUBLE #20 BISCUITS

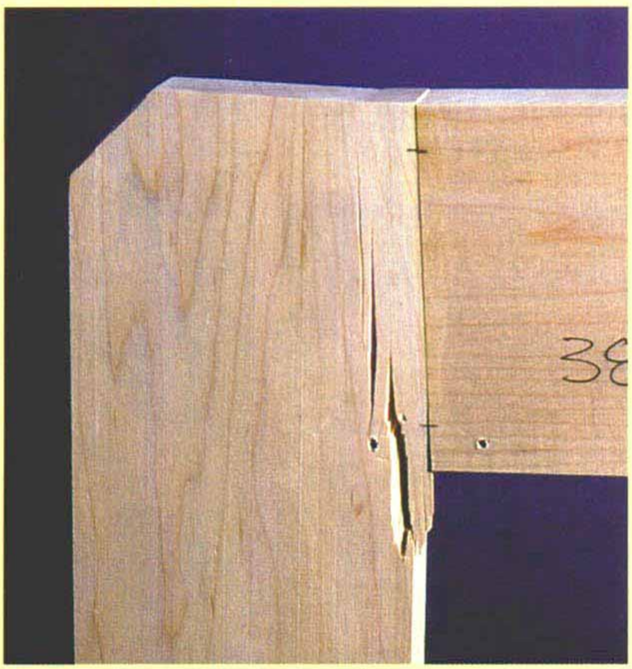


Strength:	Good
Rate of failure:	Gradual
Strength after failure:	Good
Rigidity:	Moderate

These varieties of joints are commonly used in cabinet carcases and face frames, chairs, frame-and-panel doors and where table aprons join to legs. As the graph below illustrates, with the lumber sizes and joinery layouts used in the samples, traditional mortise-and-tenon joints proved to be more than twice as strong as the double biscuit joints tested. All test boards were ¾-in.-thick by 4-in.-wide hard maple; ⅜-in. mortises were all cut 1½ in. deep.

LOAD VS. DISPLACEMENT FOR MORTISE-AND-TENON PLUS BISCUIT JOINTS

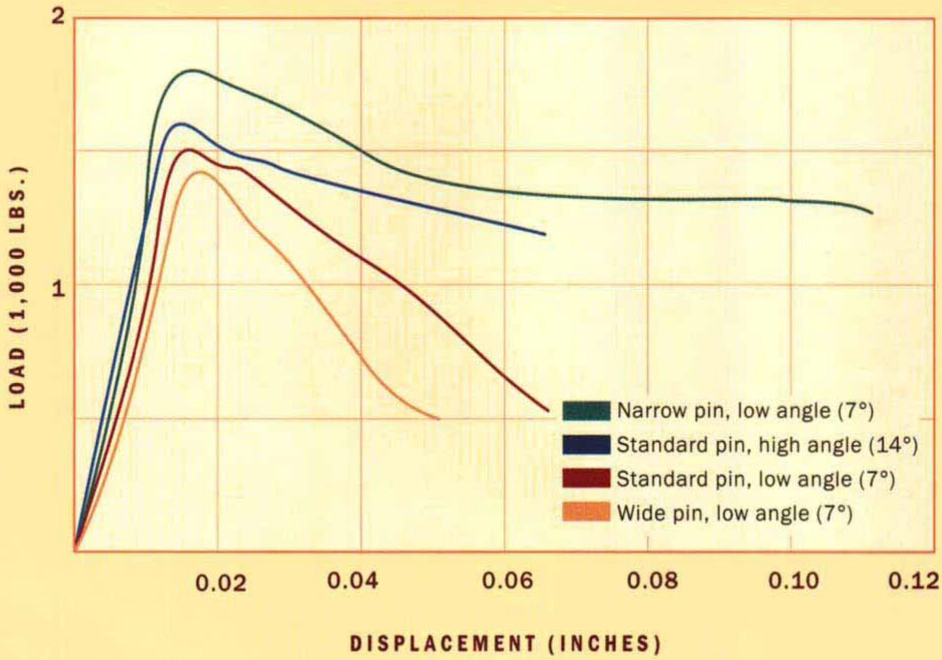




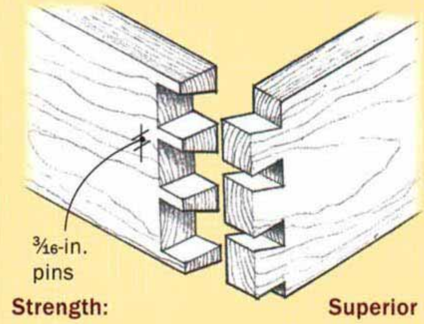
Biscuits break more easily than tenons. *In the sample at left, the glue joint within the mortise held firm. The failure happened near the joint but within the structure of the wood (of what could be a door stile or a table leg). Biscuits often broke in half under the stress, always on the diagonal line of the grain direction.*

By varying the width of the pins and the angles at which tails were let into the pins, we were able to obtain readings on a variety of dovetail joints. Surprisingly, dovetails cut with wide pins at a low angle—what is unquestionably the most common configuration used in the furniture industry—proved to be the weakest. All test boards were ¾-in.-thick by 4-in.-wide hard maple.

LOAD VS. DISPLACEMENT FOR DOVETAIL JOINTS

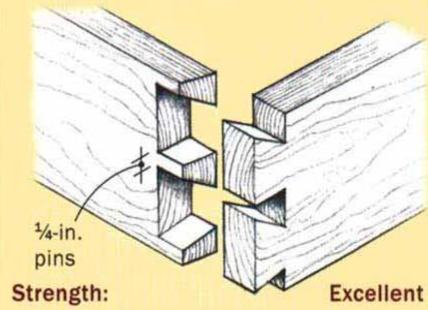


NARROW PIN, LOW ANGLE (7°)



Strength:	Superior
Rate of failure:	Sudden
Strength after failure:	Superior
Rigidity:	Very stiff

STANDARD PIN, HIGH ANGLE (14°)



Strength:	Excellent
Rate of failure:	Sudden
Strength after failure:	Excellent
Rigidity:	Very stiff

lowing failure. When we compared low- and high-angle dovetails (made with standard pins of the same width), we found no significant difference between them. The working load for both of these joints was about 20% lower than the narrow-pin joint.

In general, all of the dovetails were extremely stiff, as you can see on the graph above, in their steep, initial curves. The plastic region was nonexistent in these joints, and they took the load up to a maximum in the elastic region without damage before they failed abruptly. We found two surprising findings: The low-angle, wide-pin joint—what many consider the industry standard for hardwood—was the weakest of all. Also, joints that I cut somewhat sloppily—meaning they had considerable wobble when I dry-fit them before applying glue—seemed not to have lost any significant strength.

Why joints fail

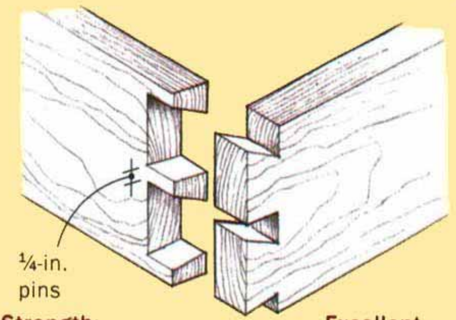
Now let's look at where and why the joints failed and consider some suggestions to strengthen your joinery. In the most basic sense, there are only two things that can go wrong: either the glue or the wood itself can fail. We found that, typically, a combination of these failures occurs at different stages as wood joints are subjected to extreme stresses.

With traditional tenons and both types of floating tenons, the failure was the same. In all cases, the bond at the glueline failed first, and then the mortise cheek failed. The tenons never failed or broke. The mortise cheek was in compression in the upper part of the joint and in tension in the lower half, which resulted in the cheek being crushed at the outside corner of the joint and ripped apart at the inside corner. If you have a choice in the design, this crushing effect could be reduced by moving the intersection of the joint away from the end of the mortised piece. The ripping apart occurred across the grain at the cheek of the mortise—the weakest spot. You could add strength by making the tenon thinner (on the edge) and wider (along the face) and the mortise deeper.

We found a different kind of failure with the biscuit joints. In almost all cases, the glueline began to fail, then the biscuits themselves failed. All of the slotted pieces of wood remained intact. In the tests, the direction of force applied to the samples was the same as on the mortise-and-tenon samples; however, because the grain orientation in the biscuits is diagonal, the failure always occurred along this line. Take a biscuit and break it apart in your hand; you'll see what I mean. The sample stock we used was ¾ in. thick, and you can't fit more than two biscuits in that size. To make a biscuit joint stronger (using standard-sized biscuits), you'd have to use thicker lumber to allow for a third biscuit or widen the workpiece to allow doubling up the double layer of biscuits.

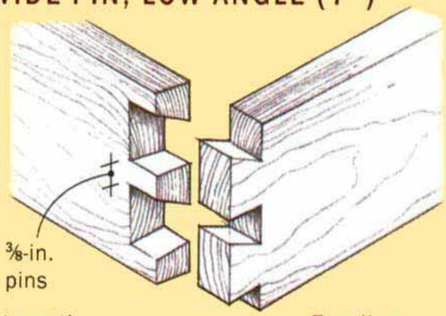
All of the dovetailed samples failed in a similar way. First the ends of the tails—not the pins—sheared, and then the glueline

STANDARD PIN, LOW ANGLE (7°)

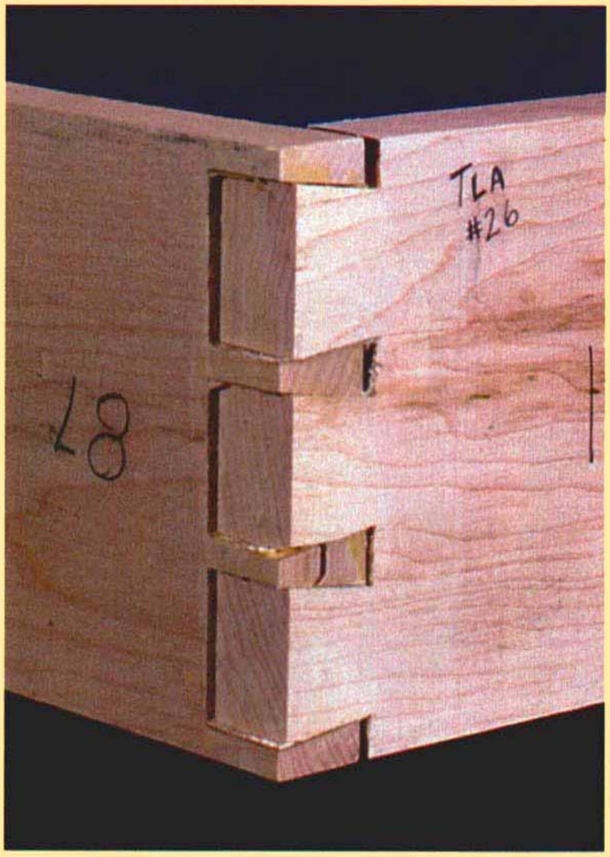


Strength:	Excellent
Rate of failure:	Sudden
Strength after failure:	Moderate
Rigidity:	Very stiff

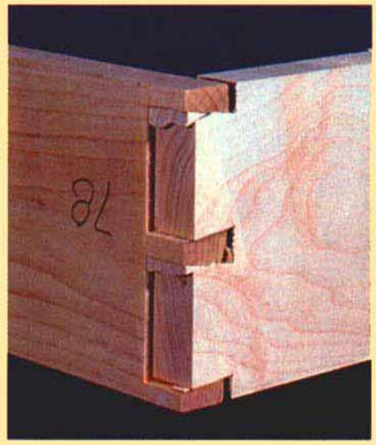
WIDE PIN, LOW ANGLE (7°)



Strength:	Excellent
Rate of failure:	Sudden
Strength after failure:	Moderate
Rigidity:	Very stiff



More tails made a difference. *By cutting dovetails with narrow pins set in at a low angle, you can fit more tails into the same amount of space along the width of a joint. These samples exceeded all of the others in overall strength.*



Failure doesn't necessarily mean it's all over. *Even though parts of pins and tails sheared and glue joints came apart, these test samples illustrate clearly why dovetail joints command the respect they get from woodworkers. After such catastrophic failure, the mechanical benefit of the joint design means that drawer or case parts can still hold together.*

failed. Only after the joints were severely displaced did the tails split and fracture some of the pins as they were pulled away.

Some conclusions about joint strength

So what does all of this mean? I think some woodworkers may need to rethink commonly held beliefs regarding mortise-and-tenon and dovetail joinery—both in terms of strength, as well as in how the joints fail.

It is noteworthy that all of the joints we tested were stronger than the most severe load that they would ever likely be subjected to in normal use or even abuse. Dovetails, especially, are a case in point. It's clear from our research that woodworkers should feel comfortable making choices based on artistic grounds rather than blindly adhering to accepted standard proportions, placements and spacing. To make the strongest possible dovetail joints, maximize the glue area by designing with lots of narrow pins.

I've always used narrow pins on dovetails in drawers, but now I'll also use them in carcases, especially if strength is an issue. Because there's no significant difference in strength between low- and high-angle pins, I can see no practical reason to select one over the other. As with pin thickness, the choice of dovetail angle should be based on aesthetics or convenience.

The results of our tests of mortise-and-tenon and biscuit joints won't change my approach to designing furniture much differently than the way I do it now. I'll continue to use floating tenons—rounding my edges whenever possible—and I'll still use biscuit joints for aligning solid stock and sheet goods. However, if faced with a need for a super-strong joint or one that must not deflect, I will now use a traditional mortise and tenon, even though it will mean spending more time in the setup.

Although I believe our test results are conclusive, there is lots of room for further research. The tests applied a load in one direction that furniture would likely experience in typical use. However, furniture can be subjected to other possible types of loads, as well as the effects of aging, freezing and significant fluctuations in humidity. I wanted to do fatigue tests, but money and time didn't allow it Other directions for interesting research might be to examine machined dovetails and the optimum proportions of mortise-and-tenon joints.

In closing, I'd like to acknowledge the help I received from Dr. Y.H. Chui and the staff of the Wood Science and Technology Center of the University of New Brunswick; Ellen Dalton, a graduate in forest engineering; Eaglewood Specialty Products Inc. of Fredericton, New Brunswick, for supplying the wood; and Franklin International, for technical advice about adhesives. □

Bruce Gray studied industrial engineering in college. He now designs and builds custom furniture in Douglas, New Brunswick, Canada.