The Engineered Nail

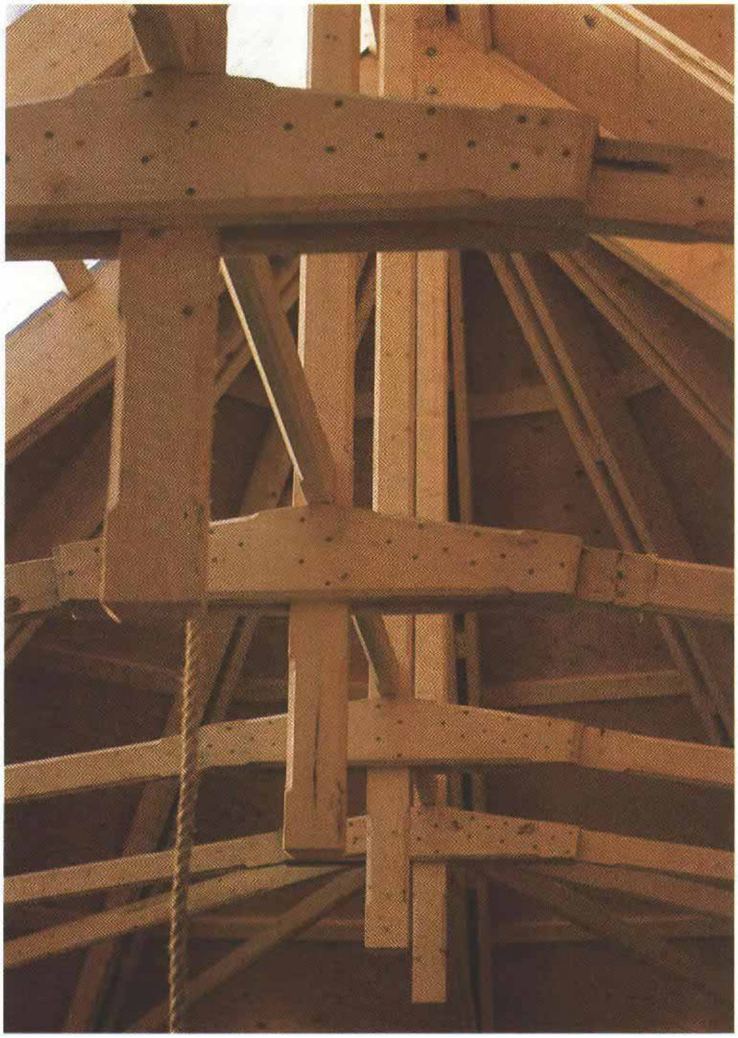
Ten steps to secure connections

by Edward Allen

The nailed connections in an ordinary house frame conform to a chart found in most building codes. Most designers and builders seldom give them a second thought. But many building designs contain connections that aren't of the ordinary sort—columns to major beams, connections in trusses, splices in roof ties and unusual intersections in floor framing. And many times a nailed connection must be designed for some nonstandard project such as a footbridge, a large wind-buffeted sign, a piece of playground equipment or a temporary exhibit structure.

Too, a builder often designs scaffolding, concrete formwork and other one-of-a-kind temporary structures in which nailed connections must be counted on to carry substantial loads without failing. In any of these special situations, it's reassuring to know that nailed connections can be engineered with the same degree of precision as connections made with bolts, lag screws and split rings.

All things considered, nails are the most versatile fastening devices available for wood construction. They are inexpensive and lightning fast to install; they are always available in the sizes that we use most; and they are less obtrusive than bolts and lag screws. As a bonus, nailed connections are a lot less complex to engineer than bolted or screwed connections.



Structural connections in wood, like those shown for these roof trusses, can be engineered with precision and confidence. By knowing how much force the connection must transmit and being able to determine what the holding power of each nail is, you can design nailed connections for everything from carrying beams to cupolas. The simplified look-up tables in this article were compiled from data published in the *National Design Specification for Wood Construction.*

General considerations—The design of nailed connections is governed under all of the major building codes by the *National Design Specification for Wood Construction,* which I will refer to in this article as the NDS. It's the bible of engineering practice for wood construction, and is published by the National Forest Products Association (1250 Connecticut Ave. N. W., Washington, D. C. 20036). You may find it worthwhile to become familiar with this book if you design wood buildings, because it covers calculations for beams, joists, columns, tension members, glue-laminated wood, and connections using bolts, wood screws, lag screws and split rings, as well as nails.

But to use the NDS effectively you need to have had a course or two in structural engineering. For this article, I have summarized its provisions on designing connections using common nails, and have tried to put its guidelines into a form that's easy to use.

There are some things to keep in mind when you set out to design a nailed connection. Common nails, box nails, spikes and threaded, hardened-steel masonry spikes and nails can all be used in structural connections under the NDS. But finish nails can't be used as structural fasteners.

Box nails are weaker than common nails, so if you want to design a connection using box nails you will have to refer to the NDS, as you will for common spikes, which have somewhat higher values than those given here for common nails. Vinyl-coated sinker nails don't yet appear in the NDS, so we have no firm basis for designing with them. For this article, threaded hardened-steel spikes and nails have the same load-carrying capacities as common nails.

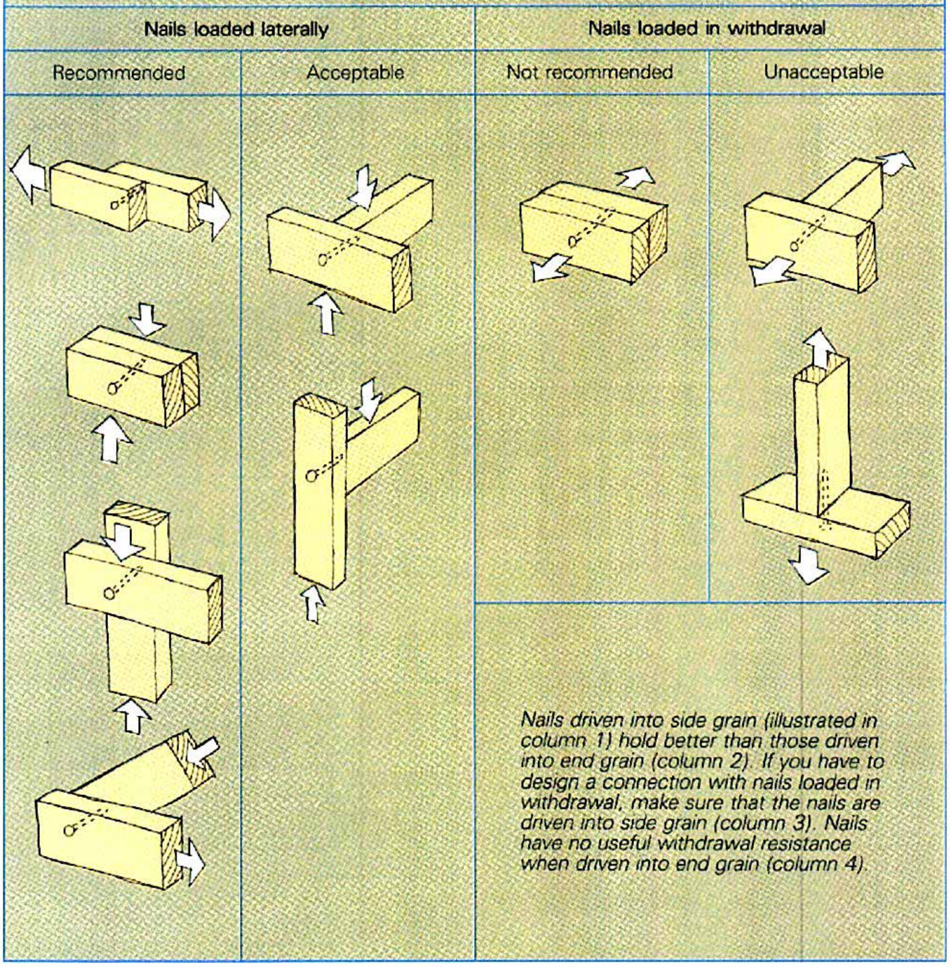
A word of caution here. Never use drywall screws as structural fasteners. Drywall screws are good for hanging gypsum board and for non-load-bearing connections in cabinetwork. But they are much weaker than nails or common screws, and they are very brittle. Even a properly installed drywall screw will fail without warning at a distressingly low loading.

It is best to design nailed connections so the nails are loaded laterally rather than in withdrawal, as shown in figure 1 on the facing page. A nail that is loaded in withdrawal from end grain is prohibited by the NDS, and a nail loaded in withdrawal from side grain, while acceptable, is discouraged. Withdrawal loadings can almost always be avoided by using overlapping connections, scabs or gussets of plywood or metal.

Designing a connection—To design a nailed connection, proceed step-by-step as follows:

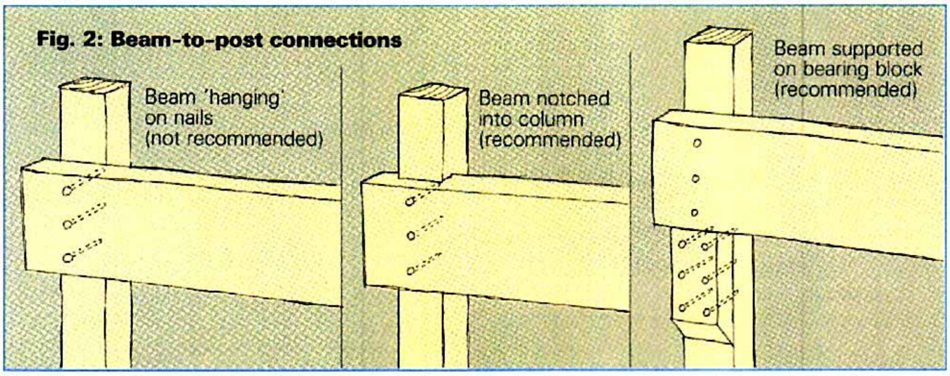
Step 1. Sketch the connection, and indicate with arrows the loads or forces the connection must transmit. Make the joint as simple as you can, and design it so that it does not use nails in withdrawal. As a general rule, avoid using nails to "hang" a beam or joist onto the side of a column without support from below. A beam held up by its own nails alone is liable to fail in

Fig. 1: Nailed connections



Nails driven into side grain (illustrated in column 1) hold better than those driven into end grain (column 2). If you have to design a connection with nails loaded in withdrawal, make sure that the nails are driven into side grain (column 3). Nails have no useful withdrawal resistance when driven into end grain (column 4).

Fig. 2: Beam-to-post connections



Species group

Commercial species are rated for hardness, ranging from group I (ash, maple, oak, etc.) to group IV (various softwoods).

Ash, commercial white: I
Aspen: IV
Balsam fir: IV
Beech: I
Birch, sweet and yellow: I
Black cottonwood: IV
California redwood: III
California redwood, open grain: IV
Coast Sitka spruce: IV
Coast species: IV
Cottonwood, eastern: IV
Douglas fir/larch: II
Douglas fir, south: III
Eastern hemlock: III
Eastern hemlock/tamarack: III
Eastern softwoods: III
Eastern spruce: IV
Eastern white pine: IV
Eastern woods: IV
Engelmann spruce /alpine fir: IV
Hem/fir: III
Hickory and pecan: I
Idaho white pine: IV
Lodgepole pine: III
Maple, black and sugar: I
Mountain hemlock: III
Mountain hemlock/hem-fir: III
Northern aspen: III
Northern pine: III
Northern species: IV
Northern white cedar: IV
Oak, red and white: I
Ponderosapine:III
Ponderosa pine/sugar pine: III
Red pine: III
Sitka spruce: III
Southern cypress: III
Southern pine: II
Spruce-pine-fir (SPF): III
Sweetgum and tupelo: II
Virginia pine/pond pine: II
West Coast woods (mixed species): IV
Western cedars: IV
Western hemlock: III
Western white pine: IV
White woods (western woods): IV
Yellow poplar: III

shear at the connection. (For an explanation of beam shear, see "Building Basics," *FHB* #32.)

There are a couple of ways to avoid hanging a beam, as shown in figure 2. One is to set the beam into a notch in the column so that it can transfer its load by direct bearing, and use the nails only to hold the beam in the notch. The other is to use nails to attach a bearing block to the side of the column, then to support the beam on this bearing block and keep it in place with nails. This kind of support minimizes the shear problem and allows you to use as many nails as necessary to carry the load.

Step 2. Determine how much load the connection must carry. If the connection is in a roof structure, add up all the loads that must pass through the joint you are designing, including the live loads required by your building code and the weight of the structure itself.

If you're designing a floor structure, the live load is usually figured as 40 lb. per sq. ft. under most building codes for a residential structure, but is generally more than this for commercial, industrial and agricultural buildings. For scaffolding, add up the largest total load of workers, materials, equipment and scaffolding planks. Then figure out what portion of this weight each connection must support.

Step 3. Determine the species group of the wood for which you are designing. For simplicity, the NDS uses density as a criterion to divide all species of wood into four groups. The denser the wood, the more load each nail can carry. All the species in Group I are hardwoods. Group II includes the strongest softwoods, and Group III consists of the majority of the softwood species used for framing lumber. Group IV includes still other species that are often used in construction for framing.

The chart above is an alphabetical list of common woods used in building structures, indexed by their species as shown on lumber-grade stamps, and assigned to a group (I, II, III, IV) according to density. Be sure you select the right species group for your design, because nail load-bearing capacities are heavily dependent on wood density. If you are in doubt about what wood species you are designing for, assume it belongs to Group IV, just to be safe.

Step 4. Select the size of nail you would like to use in the connection. In most cases you will

Photo and drawings: Edward Allen

DESIGN VALUES IN POUNDS: Lateral resistance of common nails in side grain

Depth *	**Species group I**				**Species group II**				**Species group III**				**Species group IV**			
	Nail size				**Nail size**				**Nail size**				**Nail size**			
	8d	**10d, 12d**	**16d**	**20d**	**8d**	**10d, 12d**	**16d**	**20d**	**8d**	**10d, 12d**	**16d**	**20d**	**8d**	**10d, 12d**	**16d**	**20d**
½ in.	37	39	0	0	27	0	0	0	0	0	0	0	0	0	0	0
⅝ in.	46	49	51	0	34	36	38	0	23	0	0	0	17	0	0	0
¾ in.	56	59	62	67	41	43	45	49	28	30	31	0	21	22	0	0
⅞ in.	65	69	72	78	47	50	53	58	33	35	36	40	24	26	27	0
1 in.	74	78	82	90	54	58	61	66	37	40	42	46	28	29	31	34
1⅛ in.	83	88	92	101	61	65	68	74	42	45	47	51	31	33	35	38
1¼ in.	93	98	103	112	68	72	76	82	47	50	52	57	35	37	38	42
1⅜ in.	97	108	113	123	74	79	83	91	52	55	57	63	38	40	42	46
1½ in.	97	116	123	134	78	87	91	99	56	60	63	68	42	44	46	51
1⅝ in.	97	116	133	146	78	94	99	107	61	65	68	74	45	48	50	55
1¾ in.	97	116	133	157	78	94	106	115	64	70	73	80	49	52	54	59
1⅞ in.	97	116	133	168	78	94	108	124	64	75	78	86	51	54	58	63
2 in.	97	116	133	172	78	94	108	132	64	77	83	91	51	59	62	68
2⅛ in.	97	116	133	172	78	94	108	139	64	77	88	97	51	61	66	72
2¼ in.	97	116	133	172	78	94	108	139	64	77	88	103	51	61	69	76
2⅜ in.	97	116	133	172	78	94	108	139	64	77	88	108	51	61	70	80
2½ in.	97	116	133	172	78	94	108	139	64	77	88	114	51	61	70	85
2⅝ in.		116	133	172		94	108	139		77	88	114		61	70	89
Maximum drill size	7/64-in.	1/8-in.	9/64-in.	11/64-in.	3/32-in.	7/64-in.	1/8-in.	9/64-in.	3/32-in.	7/64-in.	1/8-in.	9/64-in.	3/32-in.	7/64-in.	1/8-in.	9/64-in.

* Depth of penetration of nail into member receiving the point.

want to use the largest size that is reasonable (the chart at right gives lengths and diameters for common nails).

For example, if you are face-nailing nominal 2-in. pieces of lumber to one another, 10d nails make the most sense because their length is just equal to the overall thickness of the connection. For end nailing, 16d or 20d nails are better because you get greater penetration.

Step 5. Determine the penetration of the nail into the second wood member. By using the sketch you have made, you can see exactly how much of the length of the nail you have selected is used up in going through the first piece of wood into which it is driven, and how much of the nail this leaves for holding power in the second piece.

Step 6. Look up the design value for the nail in the chart above. Start by finding the correct species group for the wood you are using at the top of the table. Next, within that species group, find the size of nail you are using. Then read down that column in the table until you come to the line that corresponds to the penetration depth you determined in Step 5.

The number at this location in the table is the design value in pounds for the lateral resistance of a common nail that has been driven into side grain. (These design values are based on laboratory tests of nailed connections, and include a factor of safety). Write down the value you find there and proceed to the next step.

Step 7. Now you'll need to modify the design value you have just found in accordance with NDS requirements. These requirements can be summarized as follows: If a nail is driven into end grain, its holding power is diminished, and so you'll have to multiply the design value by

Dimensions of common steel wire nails

Nail size	Length	Wire dia.
Eight penny (8d)	2½ in.	0.131 in.
Ten penny (10d)	3 in.	0.148 in.
Twelve penny (12d)	3¼ in.	0.148 in.
Sixteen penny (16d)	3½ in.	0.162 in.
Twenty penny (20d)	4 in.	0.192 in.

0.67. If it's a toenail, which is also weaker than a face nail, multiply the design value by 0.83.

The tabulated design values are for connections in which primary loading is typical of residential or commercial floor loads—the weight of people and furniture. If the major portion of the load on the nail comes from roof loads (snow or rain), multiply the design value by 1.15. For a connection made to resist wind or earthquake loadings, multiply the design value by 1.33. On the other hand, if the entire calculated load is permanently applied to the nail, multiply the design value by 0.9. These duration-of-load factors reflect the fact that wood can support short-term loads better than long-term loads. For floors, use a factor of 1.0, for roofs, 1.15, and for diagonal bracing, 1.33. An example of a permanent load, with a factor of 0.9, is support for a hot tub or water tank sitting on a deck.

When using unseasoned or partially seasoned wood, or if the wood in the connection will be damp or wet in service, multiply the design value by 0.75. If you are using fire-retardant, treated wood, multiply the design value by 0.9 (a connection in preservative-treated wood is considered to be as strong as one in untreated wood).

If the joint is made with metal gusset plates through which the nails are driven, multiply the design value by 1.25. If the nail will be in double shear, through side pieces each at least 3/8 in. thick, is not over 12d in size, and is clinched at least three nail diameters, as shown in figure 3, at the top of the facing page, multiply the design value by 2. Notice that other than this provision of NDS, there is no increase in design value allowed for clinched nails.

These modifications are cumulative. This means that if, for example, you are designing a rafter connection between unseasoned wood members using toenails, you should multiply the tabulated design value for the nail by 1.15 for roof loading, then by 0.83 for toe nailing, then by 0.75 for unseasoned wood. The net effect of these computations in this example is that you will multiply the design value by 0.72.

Step 8. To get the required number of nails in the connection, divide the total load on the connection by the modified design value per nail and round upward to the nearest whole number. The strength of a nailed connection is equal to the sum of the strengths of all the nails in the connection. (This may seem patently obvious, but research has shown that it is often not true in bolted connections, for example.)

Step 9. Go back to your original sketch and lay out the locations of the nails in the connection. If only two or three nails are required, this is easy. Frequently, however, your calculations will show the need for a dozen nails or more in the same connection, and you'll need a scale drawing or full-size layout to figure out how to place them.

There is no hard-and-fast rule about nail spacings. The NDS specifies only that nails be spaced so as to avoid excessive splitting of the wood. As a rule of thumb, many architects and engineers try to space nails no closer together than the length of penetration at which they achieve their maximum design value. Consider using a 10d nail in a Group III species. The design-value chart shows that it reaches its maximum design value at a depth of 2 in., which can then be taken as the minimum spacing between nails. For the distance from the outermost nails to the sides of the piece, half this value is acceptable. The distance from the last nail to the end of the piece should be equal to the required spacing.

However, certain connections often call for more nails than this rule of thumb would allow. When this happens, prepare a sample connection with scraps of the same wood that will be used in the finished structure to see if splitting is a problem. If it is, try staggering the nails in such a way that they do not line up closely along the same grain line, as shown in figure 4. Drilling pilot holes for the nails further reduces the possibility of splitting.

Step 10. If you decide to drill lead holes, you'll have to select the right-size bit. The holes must have a diameter large enough to ease nailing and reduce wood displacement, but not so large that holding power is lessened. To find the correct size of bit to use (as recommended by the NDS) look at the bottom of the design-value chart. In sketching the connection, be sure to dimension the nail spacings you have arrived at, and indicate the diameter of drill bit that should be used for the lead holes. And remember that while the NDS allows soap or grease to be used on screws, this doesn't apply to nails in structural situations, because nails depend on friction for their holding power. Use no grease.

Example 1: A beam-to-post connection— Having gone through all the steps, let's design a connection to support the end of a double 2x12 floor beam that is sandwiched around a 6x6 post, and assume that both beam members and the post are KD Douglas fir. The first thing to do is *sketch the connection*. To avoid hanging the beams and the consequent shear problems, you can add nailed-on bearing blocks, as shown in the drawing at bottom right, which also prevents weakening the post by notching into it.

Next, you have to determine the load. Let's assume that calculations have already been done that show the total load on the beam to be 3,380 lb., uniformly distributed along its length. Half of this amount, or 1,690 lb., must be borne by the post at each end. Because the beam is double, each 2x12 brings half this amount, or 845 lb., to the post—so 845 lb. is the design load for each connection.

Third, look up the species group of the wood in the chart on p. 69, where you'll find that Douglas fir is a Group II wood. Now select the nail size. The post is thick enough to accept 20d nails readily, and if you drill pilot holes, there is little danger of splitting either the block or the post with such large nails.

Now you need to determine how deeply the nails will penetrate. A 20d nail is 4 in. long, and the bearing block is 1½ in. thick, leaving a penetration into the post of 2½ in. Next look up the design value for the nail in the design-value chart. Under Group II species, a 20d nail pene-

Fig. 3: Clinched nails in double shear

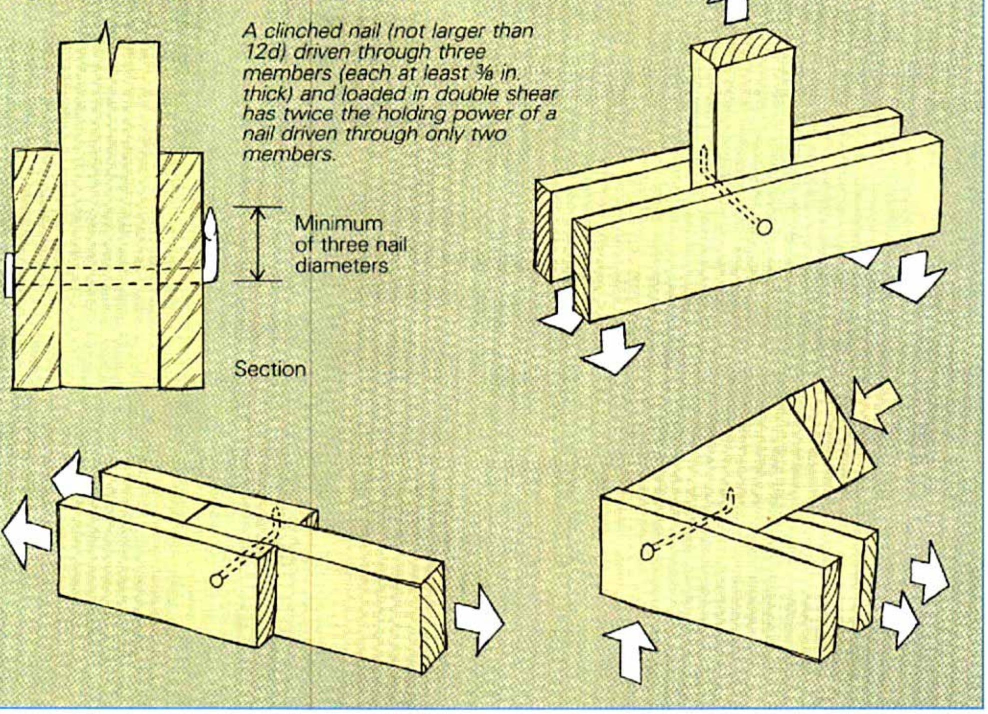
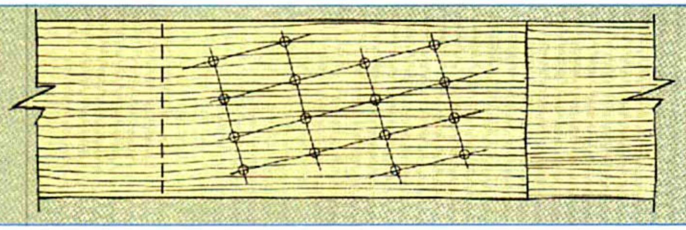
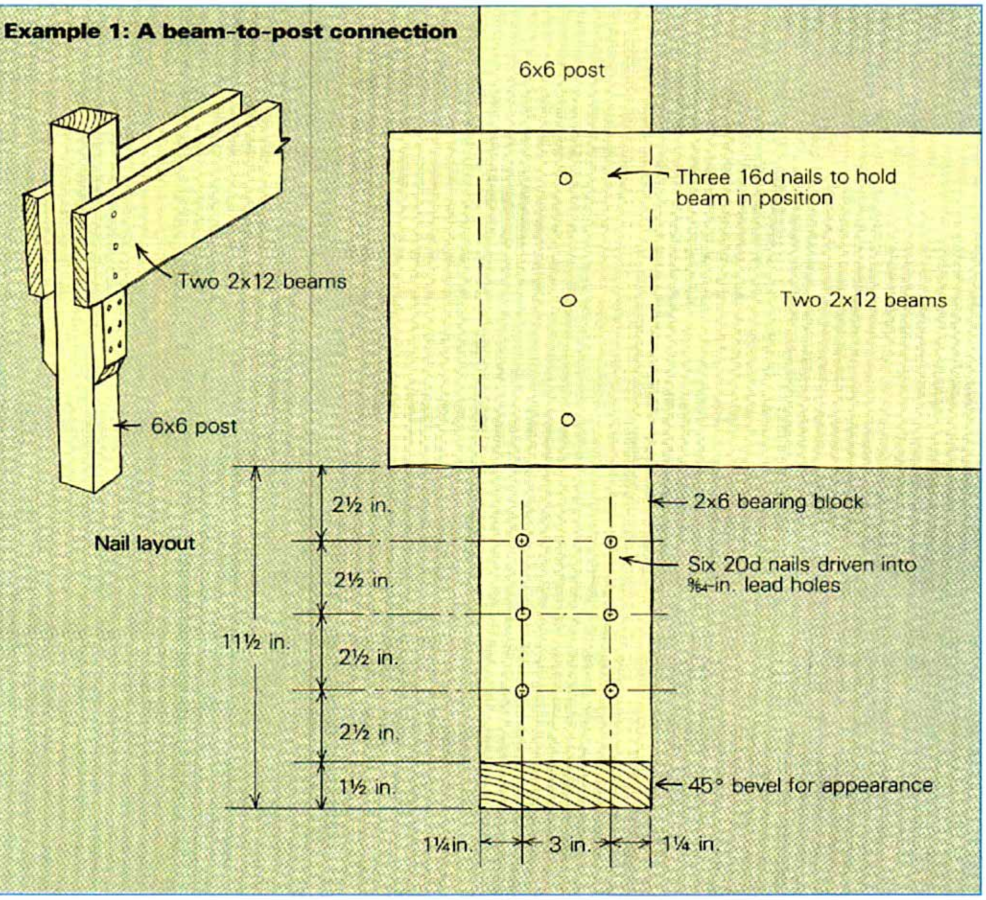


Fig. 4: Nail layout
When a connection calls for lots of nails, take care to stagger them so they do not lie close together across the grain. This helps avoid splitting the wood, as does drilling lead holes of the correct diameter.



Example 1: A beam-to-post connection



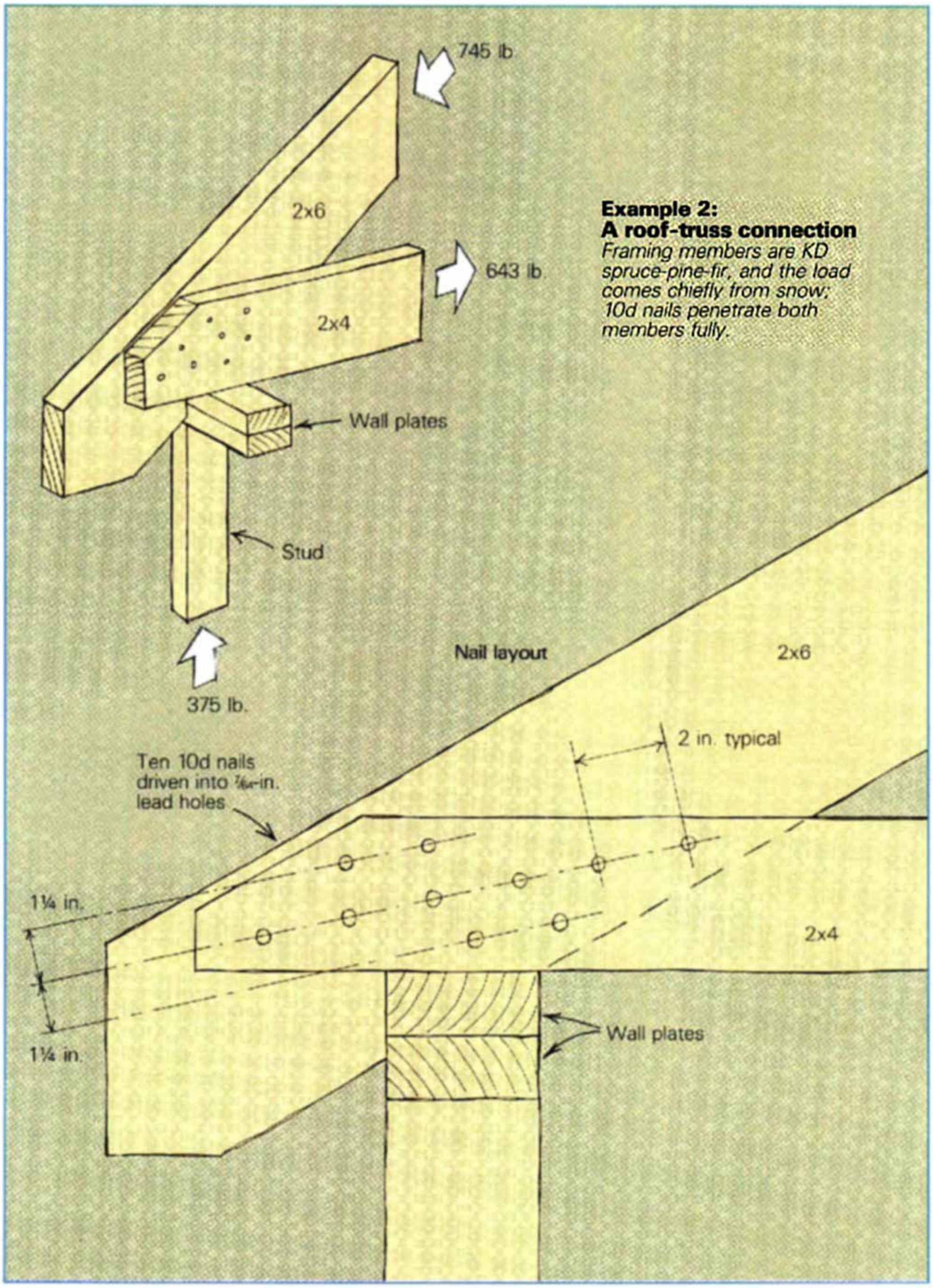
trating 2½ in. will support 139 lb. Design values usually have to be modified, as discussed above, but in this example, none of the modification factors apply; so we will proceed with a load-bearing capacity per nail of 139 lb.

Now you can figure out how many nails the connection needs by dividing the 845-lb. load by the 139 lb. that each nail will carry. You end up needing 6.08 nails. You could be conservative and use 7 nails, but 6 is close enough in this case (less than 2% overstress), especially when you consider that you'll also be attaching the beam to the post with three nails. These will give you a wide margin of safety.

Now you can lay out the detail of the connection, as shown in the drawing at the bottom of the previous page. Since 20d nails reach full bearing value at a penetration of 2⅛ in. in Group II woods, a spacing between nails of 2⅛ in. is about right, with an edge spacing of half this amount. The bearing block is 5½ in. wide and 11½ in. long. In laying out the detail of the connection to scale, you can of course increase the spacing if it improves the way the thing looks. The nails through the sides of the 2x12 beams are intended mainly to keep the beam in place, and not to transmit the load from the beam to the column.

The last thing you need to figure is the diameter of the bit you need to drill the lead holes. In the design-value chart we find that a 9/64-in. drill bit is suited for the lead holes. A larger bit would result in insufficient friction between the wood and the nail.

Example 2: A roof-truss connection—The problem this time is to design an end connection in a roof truss to be made of KD spruce-pine-fir (a common type of framing lumber cut from stands of trees of mixed species in the Pacific Northwest). The loads on the truss come primarily from snow. Assume that you've already consulted the building codes and done the math to figure the maximum design loads for the top and bottom chord and the weight the stud below must bear. The amounts and directions of the forces are indicated in the drawing below left. The wood belongs to Group III. We select a 10d nail because its length will just reach through the thickness of the joint. The penetration into the second member is 1½ in.



Example 2: A roof-truss connection
Framing members are KD spruce-pine-fir, and the load comes chiefly from snow; 10d nails penetrate both members fully.

From the design-value chart, you determine that the design value per nail is 60 lb. This is modified for snow loading by multiplying it by 1.15 to yield a value of 69 lb. per nail. Now you need to look at the sketch of the connection (drawing, below left) to figure out which of the three forces to design for. The 375-lb. force is carried by direct wood-to-wood bearing of the truss on the top of the wall, and needs no nails except to keep the truss in place. The 745-lb. diagonal force of the rafter is counteracted in part by the 375-lb. vertical bearing force, and in part by the 643-lb. horizontal force in the bottom chord of the truss. The only force not supported at least partly in direct wood-to-wood bearing is the 643-lb. horizontal force, so this is what we must design the nailed connection to resist.

Dividing 643 lb. by 69 lb. per nail gives a requirement of 9.33 nails, which we round up to 10. The rule-of-thumb nail spacing in this situation is 2 in., the penetration at which 10d nails reach full capacity in Group III woods. But trying to lay out ten nails in this connection with this spacing is fruitless. And going to a larger nail won't help much either, because at 1½ in. of penetration even a 20d nail holds only 8 lb. more than a 10d nail.

One thing you can try is to increase the size of the bottom chord to a 2x6 to increase the area that will receive the nails. Such an increase in member size is often necessary when designing wood connections. Alternatively, if Group II woods such as Douglas fir and Southern pine are available, you can try the design again in these species to see if the reduced number of nails and reduced rule-of-thumb spacings result in a workable design.

But let's go back to the original design and see if we can squeeze the nail spacings to make it work. One of the virtues of the lower-density woods of Groups III and IV is that many of them, like spruce-pine-fir, are very soft and don't split easily. In the proposed layout (drawing, left), the nail locations are staggered in such a way that they minimize splitting forces, and you'll reduce splitting further if you predrill the nail holes with a 7/64-in. bit as indicated by the design-value chart. Now mock up the assembly with scraps of your framing lumber and see if any splitting happens. If the sample shows signs of splitting, you will have to resort to an alternate design. If the layout works, make a template of the spacings so that you can locate the holes uniformly on the real connections. □

Edward Allen is an architect in South Natick, Mass. He is the author of Fundamentals of Building Construction *(John Wiley & Sons, 605 Third Ave., New York, N. Y. 10158).*