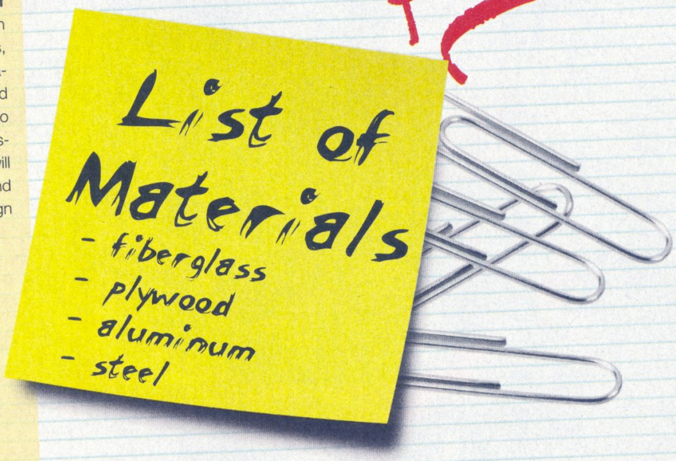
The Car Audio System Nobody Would Build part 5

BY JON R. WHITLEDGE

Last month's article dealt with the selection of the principal audio system components such as amplifiers, interconnects, loudspeaker cables, and power cables. In this article, Part 5, the fabrication process will begin, starting first with the overhead electronics console. Since there are plenty of how-to articles available regarding the fabrication of fiberglass-reinforced composites, the emphasis of this article will be on materials' properties, mechanical design, and how they correlate to improved audio system design and implementation.



Materials Science 101

Before delving into the fabrication process, it's necessary to discuss the fundamental properties of materials common to the car audio industry. Knowing the basic mechanical properties of these materials will aid in their selection and optimize their implementation. "Stiffness" and "strength" are two of the most fundamental and important properties of materials. Stiffness is a term used to describe a material's resistance to deformation when subjected to a load. The simplest characterization of a material's stiffness is known as the "modulus of elasticity" or "tensile modulus of elasticity," or "Young's modulus." The modulus of elasticity is usually derived from the slope of a stress-strain curve. Since strain is defined as the change in length divided by the original length, the units for strain are dimensionless. By definition, a stiffer material has a higher modulus of elasticity. The International System of Units (SI) for modulus of elasticity is the Pascal, abbreviated Pa, and is defined as N/m^2 (Newton per square meter). The traditional non-SI units used in the U.S. are psi (pounds per square inch).

Strength describes a material's ability to withstand loads. Stress is defined as the load per unit area. The term strength usually encompasses such properties as "ultimate tensile stress," or "tensile strength," or "shear strength." Sometimes, however, it's experimentally advantageous to create tensile stresses in beams by subjecting them to bending. The problem in doing so, however, is that this method of testing doesn't impose pure tensile stresses on the test specimen, but rather imposes a complex mixture of tensile, compressive, and shear stresses. The stiffness and strength of MDF and plywood are determined and reported from bending mode tests. Data reported in this manner, especially with regard to strength, can be somewhat misleading. For example, the estimated tensile strength, sometimes called the "modulus of rupture," of MDF derived from a standard bending test is estimated to be 23 MPa (3.48 kpsi). However, another kind of test called "Internal Bond Strength EN 310" subjects an MDF test specimen to an almost purely tensile load and reveals that MDF can only withstand about 0.75 MPa (109 psi). The impact of this material property is widely known and understood by professional installers. First, this property limits MDF's screw-holding capability. Using T-nuts sandwiches the MDF, thus subjecting it to reasonable compressive stresses, a state of stress that MDF can better handle. Second, professional installers know MDF works well for loudspeaker enclosure construction, since the panels of the enclosure are subjected to primarily bending stresses.

Density is defined as the weight of material per unit volume. The SI unit for density is N/m^3 (Newton per cubic meter). The traditional non-SI units used in the U.S. are lb/in^3 (pounds per cubic inch). It's commonplace in the U.S. to express weight in kilograms, which is technically incorrect. The kilogram is the SI unit for mass, not weight. A balance or force transducer that determines weight in kilograms is actually determining the mass in kilograms of force. Kilograms of force multiplied by the acceleration of gravity, 9.80665 m/s^2, will yield the weight in N.

"Specific stiffness" is defined as a material's stiffness divided by its density. A material with a high specific stiffness is, in simple terms, both stiff (possesses a high modulus) and light in weight. If the modulus of elasticity is expressed in GPa (Giga Pascals, or 10^9 Pa) and the density in kN/m^3, the units for specific stiffness will be meters x 10^6. If the modulus of elasticity is expressed in Mpsi (Mega pounds per square inch, or 10^6 psi) and the density in lb/in^3, the units for specific stiffness will be inches x 10^6.

"Specific strength" is defined as a material's strength divided by its density. A material with a high specific strength is, in simple terms, both strong (possesses a high tensile strength) and light in weight (low in density). If the strength is expressed in MPa (Mega Pascals, or 10^6 Pa) and the density in kN/m^3, the units for specific stiffness will be meters x 10^3. If the strength is expressed in kpsi (kilo pounds per square inch, or 10^3 psi) and the density in lb/in^3, the units for specific stiffness will be inches x 10^3.

As an audio system designer and builder it's essential to know the aforementioned materials' properties so you can exploit their properties in your design. You'll most likely need to consider many more physical (viscoelastic behavior, thermal stability, machinability, bondability, and formability, for example) and chemical properties (e.g., resistance to solvents and ultraviolet light, conductivity, magnetic properties, and compatibility with finishing materials) to be certain these materials will perform as intended in your design. You'll likely design parts such as mounting structures for audio components, loudspeaker enclosures, and cosmetic panels. For structures on which audio components are mounted, designing for strength will most likely to be your primary goal, due to the weight of the components and the shock to which they'll be subjected in the automobile environment. For loudspeaker enclosures and cosmetic panels, designing for stiffness will most likely be your primary goal, because most materials are adequately strong for these applications. Loudspeaker enclosures must be designed for maximum rigidity, otherwise they'll vibrate excessively and color the sound of the music they're producing.

Table 1 (page 66) summarizes the aforementioned materials' properties for materials commonly used in the mobile audio industry. The properties listed represent conservative estimates. For example, the properties listed for fiberglass composites were obtained from composites with the lowest reported fiber contents of 25 and 37.7 weight percentage for those comprised of chopped strand mat and woven roving, respectively. Given the practical limitations of hand lay-up techniques, the use of the conservative values was deemed most appropriate. In a likewise manner, the properties listed for Baltic Birch plywood were obtained from Species Group 5, which had the lowest reported modulus and bending strength.

Table 1 also shows the moduli of elasticity of materials commonly used in mobile audio applications span almost two orders of magnitude, with MDF at the low end of the spectrum and low-carbon, cold-rolled steel at the high end. In addition, the data in Table 1 clearly illustrates that steel is three times stiffer than aluminum, and that a fiberglass composite comprised of woven roving is essentially twice as stiff as a fiberglass composite comprised of chopped strand mat. This demonstrates the significant advantage of using woven roving wherever possible to create the stiffest possible structures. Baltic Birch plywood is 63 percent stiffer than a fiberglass composite comprised of chopped strand mat, and 216 percent stiffer than MDF.

The strengths of materials commonly used in mobile audio applications span about one order of magnitude, as seen in Table 1, with MDF at the low end of the spectrum and low-carbon, cold-rolled steel at the high end. A reasonably sophisticated but widely available alloy, 6061-T6 aluminum, possesses about the same strength as low-carbon, cold-rolled steel. In addition, the data in Table 1 clearly illustrates that a fiberglass composite comprised of woven roving is essentially twice as strong as a fiberglass composite comprised of chopped strand mat. Again, this demonstrates the significant advantage of using woven roving wherever possible, to create the strongest possible structures. Baltic Birch plywood is 25 percent stronger than MDF, and a fiberglass composite comprised of woven roving is about six times stronger than MDF.

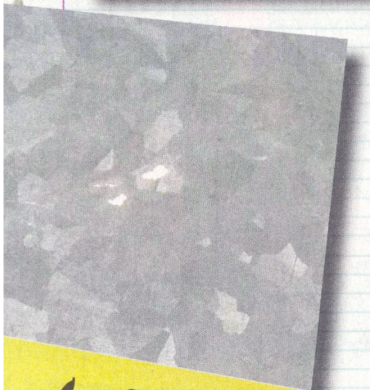
The densities of materials commonly used in mobile audio applications also span about one order of magnitude, with Baltic Birch plywood at the low end of the spectrum and low-carbon, cold-rolled steel at the high end in Table 1. Interestingly, fiberglass composite materials are about twice as dense as those materials derived from wood.

The specific strengths and specific stiffnesses of materials commonly used in mobile audio applications are also in Table 1. Steel has the highest specific stiffness, while a fiberglass composite

comprised of chopped strand mat has the lowest. Aluminum and steel have similar specific stiffnesses, but aluminum has the highest specific strength, more than 2.63 times that of steel. Interestingly, the specific stiffness of Baltic Birch vastly exceeds that of a fiberglass composite; however, a fiberglass composite comprised of woven roving has the second highest specific strength. From this data, a few important conclusions can be made. First, if the best combination of strength, stiffness, and lightness is your goal, choose aluminum for your application. If stiffness and strength is your goal, without regard for weight, choose steel for your application. If your application requires the creation of "free-form" 3-D shapes, choose fiberglass composites comprised of woven roving. Finally, for your loudspeaker boxes, choose Baltic Birch over MDF whenever possible.

Material	Modulus of elasticity E GPa (Mpsi)	"Strength" σ MPa (kpsi)	Density ρ kN/m^3 (lb/in^3)	Specific Stiffness E/ρ m x 10^6 (in x 10^6)	Specific Strength σ/ρ m x 10^3 (in x 10^3)
MDF	2.40 (0.348)[1]	24 (3.48)[1]	7.306[2] (0.027)	0.328 (12.89)	3.28 (129)
Fiberglass composite, chopped strand mat	4.64[3] (0.673)	69[3] (10)	14.572[4] (0.054)	0.318 (12.5)	4.74 (185)
Fiberglass composite, woven roving	9.05[5] (1.31)	141[5] (20.5)	15.710[6] (0.058)	0.576 (22.6)	8.98 (353)
Plywood, Baltic Birch	7.58 (1.10)[7]	30 (4.35)[7]	7.058 (0.026)[8]	1.07 (42.3)	4.25 (167)
Aluminum, 6061-T6[9]	71.0 (10.3)	276 (40)	26.6 (0.098)	2.67 (105)	10.4 (408)
Steel, 1010 cold-drawn[9]	207 (30)	303 (44)	76.5 (0.282)	2.71 (106)	3.96 (156)

Table 1. Physical properties of materials common to mobile audio applications.



There are other practical ways to use the information in Table 1. For instance, let's assume a sealed box loudspeaker enclosure is to be designed using an alternative material to MDF. For the sake of simplicity, let's assume the loudspeaker enclosure consists of six flat panels bonded together. The loudspeaker transducer produces an internal pressure, *q*, which acts uniformly on the walls of the enclosure, thereby producing deflections in the walls of the enclosure. The maximum deflection, y_{max}, in any given wall of the enclosure can be estimated using the equation for the deflection of a plate, simply supported at its edges, and subjected to uniform pressure over its entire area[10]:

$$y_{\max} = -\frac{C_1 q b^4}{E t^3}$$

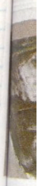
C_1 is a constant based on the ratio of plate width-to-length, *q* is the uniform load per unit area, *b* is the plate width, *E* is the modulus of elasticity, and t is the thickness of the plate. Equation 1 indicates that the deflection of a plate is inversely proportional to the product of the modulus of elasticity and the thickness cubed. For a given deflection, the required thickness of an alternative material, t_2, may be calculated:

$$t_2 = \sqrt[3]{\frac{E_1 t_1^{\,3}}{E_2}}$$

List of
Terms
- stiffness
- strength
- stress

where E_1 and t_1 are the modulus of elasticity and thickness of the reference material, respectively, and E_2 is the modulus of elasticity of the alternative material.

Let's assume the reference material in this case is MDF, nominally ¾-inch thick (actual thickness is 19.12mm). The values for modulus of elasticity, E_2, for the various materials were substituted into Equation 2, along with 2.4 for E_1, and 19.12 for t_1, and solved for t_2. Table 2 summarizes the results of the calculations. It's interesting to note that a fiberglass composite comprised of chopped stand mat would need to be 15.35mm (0.604 inch) thick to have the equivalent rigidity of the MDF reference. A fiberglass composite comprised of woven roving would need to be 12.28mm (0.483 inch) thick. It's common practice for mobile audio installation professionals to fabricate fiberglass composite loudspeaker enclosures approximately ¼-inch (6.35mm) thick using chopped strand mat. Of course, these enclosures are plenty strong, but are they adequately stiff? Possibly not. Although this analysis applies only to flat plates, and the complex curvature of most fiberglass composite structures enhances its rigidity, it establishes important guidelines for the fabrication of enclosures and emphasizes that enclosures may need to be thicker than previously believed, if a system designer's loudspeaker enclosure rigidity goals are to be met.



Material	Thickness mm (inches)
MDF **3/4-inch nominal thickness**	19.12 (0.753)
Fiberglass composite, chopped strand mat	15.35 (0.604)
Fiberglass composite, woven roving	12.28 (0.483)
Plywood, Baltic Birch	13.03 (0.513)
Aluminum, 6061-T6[9]	6.18 (0.243)
Steel, 1010 cold-drawn[9]	4.32 (0.17)

Table 2. Equivalent thicknesses of materials for constant deflection.

I applied these principles and properties of materials in the design and fabrication of my audio system's structures, including the overhead electronics console, loudspeaker enclosures, headliners, and door panels. In fact, I took extraordinary measures to ensure my enclosures were as rigid as possible. For example, the loudspeaker enclosures on the dash, each of which houses a midrange and tweeter, were fabricated from 1-inch MDF, ¼-inch steel, ¼-inch aluminum, and fiberglass composite. The thickness of the fiberglass composite enclosure varied from 15mm to 32mm (0.591 to 1.26 inch), and weighed in excess of 106 N (24 pounds) each. The front baffle of these enclosures consisted of ¼-inch–thick steel, 1/8-inch–thick Sorbothane (functioning as a constrained-layer damping material), and 1-inch–thick MDF backed by another ¼-inch of fiberglass reinforcement.

The loudspeaker enclosures in the doors, each of which houses a powerful woofer, were fabricated using MDF and fiberglass composite, comprised solely of woven roving. The high specific strength and stiffness of this material was used to minimize weight and maximize rigidity. The thickness of the fiberglass composite was about 13mm (0.512 inch) in places subject to the greatest amount of deflection, which created enclosures that weighed 156 N (35 pounds) each. The mounting rings for each of the loudspeaker transducers, around which the fiberglass was securely molded, were fabricated from 52mm (2.2 inches) thick MDF.

The subwoofer enclosure, which houses six powerful woofers, was fabricated entirely from Baltic Birch plywood and aluminum. The wall thickness of the subwoofer enclosure was 75mm (2.953 inches) thick. The total weight of the enclosure was estimated to be 1,299 N (292 pounds). The rings that mounted the loudspeaker transducers face-to-face were 31mm-thick 6061-T6 aluminum, and the plates for the binding posts were machined from ¼-inch–thick 6061-T6 aluminum.

Fabrication of the Overhead Electronics Console

I chose to fabricate the overhead electronics console from fiberglass composite comprised of woven roving because of its high specific stiffness and strength. The use of fiberglass composite allowed the creation of a complex shape that flowed around the ribbed supporting structures in the roof of the vehicle. This shape created three, large recessed areas, and thus prevented the electronics from protruding excessively into the overhead space of the front cockpit. In areas of greatest stress, the thickness of the composite structure was increased, and in some places exceeded 3/4-inch (19.1mm) thick. The bare fiberglass composite console weighed 276 N (62 pounds), and with all of the electronics mounted, weighed about 454 N (102 pounds). The following figures show the various stages of fabrication.

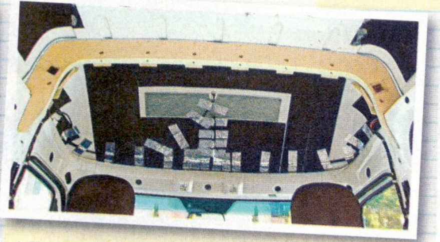
1. The OEM headliner was used as the basis for the mold. High-density fiberboard and duct tape were used to create the basic shape.

2. The overhead electronics console structure was removed from the mold after about six layers of 6-ounce woven roving were applied using polyester laminating resin.

3. To build up the composite structure thickness rapidly, layers of 48-ounce woven roving were used. Layers of Cascade Audio's VB-FD were incorporated into the composite to provide the structure with internal damping.

4. The finished structure was "bedded" into the structural ribs in the automobile's roof using Evercoat's Tiger Hair fiberglass-reinforced filler. Eight mounting locations were established, and the structure was held to the roof using eight M8 socket head cap screws (SHCSs). Eight rivet nuts, each with pullout strength of 15.7 kN (3,522 pounds), were installed in the roof structure to receive the screws. To prove this console possessed sufficient strength, two adult men, each 778 N (175 pounds), jumped up and down on the structure without any apparent damage.

5. View of the mounting surfaces of the composite structure prior to the application of fillers.



6. The factory wiring routed down the A-pillars was re-routed down to the foot wells and back up the B-pillars. This removed all 12-volt wiring in the vicinity of the A-pillars, down which the loudspeaker cables would be routed. Twelve- and 14-gauge GXL primary wires were purchased to match the OEM colors and, where appropriate, were striped to match the OEM colors. All connections were soldered with WBT's silver solder and protected with heat shrink tubing. The bundles of wires were wrapped with friction tape to match the OEM wire bundles and then secured with aluminum foil tape and/or nylon ties, whichever was appropriate.

7. The finished structure was cut into a more refined shape. Flat surfaces were created using Evercoat's Tiger Hair fiberglass-reinforced filler.

8. A piece of plate glass was used to press out Evercoat's Rage Gold body filler to create flat surfaces.

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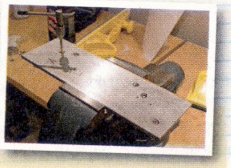
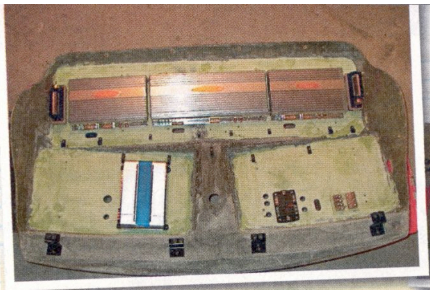
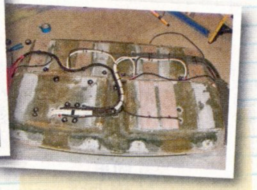
9. Aluminum plates were "bedded" onto the backside of the structure using Evercoat's Tiger Hair fiberglass reinforced filler.



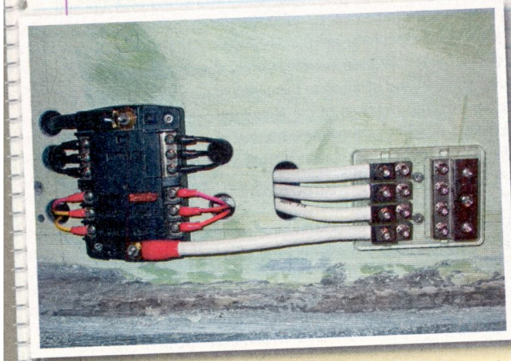
10. Each of the aluminum plates was drilled and tapped with M4 x 0.75 through-holes for mounting audio components and peripherals.



11. The audio components and the fused distribution blocks were carefully arranged to accomplish many objectives. First, the Alpine PXI-H990 Multimedia Manager (lower left) and the fused distribution blocks (lower right) were arranged to provide access to the fuses and computer port through openings behind the sunvisors in the headliner. An elliptical cutout in the headliner would provide access to the amplifiers' fuses. The arrangement of the amplifiers allowed for the shortest possible interconnects and loudspeaker cables.

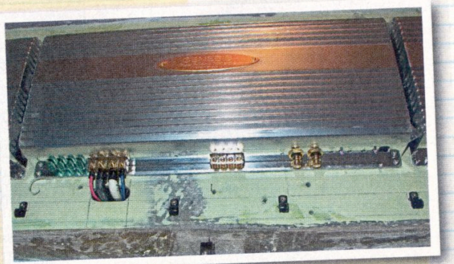


12. The 12-volt power wires were mounted on the backside of the console to keep the music-carrying cables on the front side free from interference.



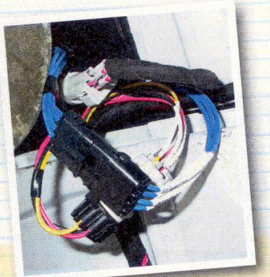
13. The high current carrying power cables were distributed and fused using Stinger's fused distribution block (right). The low current carrying power cables (head unit, processor, and other 12-volt accessories) were distributed and fused using Blue Sea System's fused distribution block. Because the fiberglass composite structure is electrically non-conductive, the generously radius-ed holes for the wires didn't need grommets or strain relief.

14. Genesis provides these protective ferrules for the power connections. These prevent the setscrew from damaging the fine strands of wire in the cable's conductor.

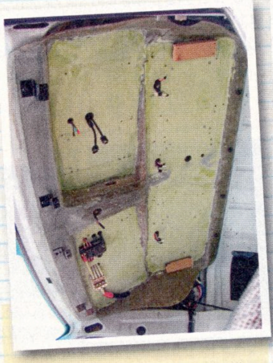


15. Each amplifier was mounted using four stainless steel M4 x 0.75 button head socket head cap screws with washers and lock washers. The Genesis Dual Mono Xtreme is shown with the fan wire (red), ground wire (black), positive wire (white), and the remote turn-on wire (blue) connections made. Note that it was later determined that the fans weren't needed.

16. Six Kimber Kable KCAG silver interconnects were terminated with WBT's WBT0108 Topline RCA connectors for the front soundstage. The wiring for the console is shown almost complete, except for the loudspeaker cables.

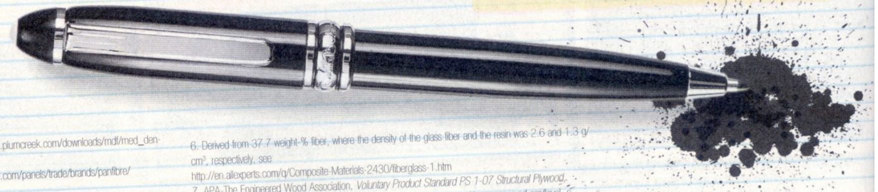


17. Remote turn-on and other power wires from the overhead electronics console were terminated with high-quality automotive plugs made by Weatherpack, which are available at most NAPA automotive stores. Each of the wires had labels that were heatshrunk into place. Note that these wires were pulled out of position for photographic purposes only.



18. The audio components and peripherals were dismounted and the overhead electronics console was mounted into the vehicle. The power connections were made (without fuses, of course) and the console is shown ready to accept the components.

19. The audio components, interconnects, and loudspeaker cables were installed. Note that wherever an interconnect is in the vicinity of a loudspeaker cable, it crosses at a right angle to the loudspeaker cable. Also note how the loudspeaker cables neatly flow from the amplifiers down the A-pillars, with no other wires in their vicinity.



Resources

1. ANSI A208.2-2002, Grade 140 specifications, see http://www.plumcreek.com/downloads/mdf/med_density_mdf_specs.pdf

2. Typical density of 745 kg/m^3 reported, see http://www.uniboard.com/panels/trade/brands/panfibre/technical_specs/

3. Typical property of E-glass chopped strand mat/unsaturated polyester resin, 25.0 weight-% fiber, see http://www.azom.com/Details.asp?ArticleID=1453#_Typical_Properties_of

4. Derived from 25.0 weight-% fiber, where the density of the glass fiber and the resin was 2.6 and 1.3 g/cm3, respectively, see http://en.allexperts.com/q/Composite-Materials-2430/fiberglass-1.htm

5. Typical property of E-glass woven roving/unsaturated polyester resin, 37.7 weight-% fiber, see http://www.azom.com/Details.asp?ArticleID=1453#_Typical_Properties_of

6. Derived from 37.7 weight-% fiber, where the density of the glass fiber and the resin was 2.6 and 1.3 g/cm^3, respectively, see http://en.allexperts.com/q/Composite-Materials-2430/fiberglass-1.htm

7. APA-The Engineered Wood Association, *Voluntary Product Standard PS 1-07 Structural Plywood*, Feb 26, 2007, p. 45, properties for Species Group 5 reported, see http://www.apawood.org/level_c.cfm?content=pub_ply_libmain

8. See http://www.atmlist.net/pipermail/atm/2004-December/005401.html

9. J. E. Shigley, Mechanical Engineering Design, 3rd Ed., McGraw-Hill, p. 636, 1977.

10. See http://www.me.umn.edu/education/courses/me5221/Lab/fea1plate.html