

**AC 2010-926: SELECTION OF MATERIAL, SHAPE, AND MANUFACTURING
PROCESS FOR A CONNECTING ROD**

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Selection of Material, Shape and Manufacturing Process For a Connecting Rod

ABSTRACT

This activity centers on the courses of strength of materials and production design offered at a sophomore level Mechanical Engineering curriculum. A connecting rod is one of the most mechanically stressed components in internal combustion engines. The objective of the activity is to select the appropriate material for a connecting rod where the constraints are to make the product as light and cheap as possible and yet strong enough to carry the peak load without failure in high cycle fatigue. The fracture toughness also needs to be above a certain minimum value. A further requirement is that the connecting rod should not buckle during operation. These constraints are used to select an appropriate cross section and material for construction. The next phase involves the selection of manufacturing process for which the constraints are shape, mass, quality and economics. The selections of the material, the cross-sectional shape and the manufacturing processes involve the use of CES EduPack, which yields materials that meet the constraints. The current manufacturing processes for connecting rods by fracture split drop forging and fracture split powder forging are highlighted and compared based on current information.

INTRODUCTION

A connecting rod in a high performance engine is subjected to inertial forces and bearing loads. It should be able to withstand these forces for a large number of cycles. In order to reduce the forces exerted during operation, the connecting rod should weigh as little as possible and should have very high fatigue strength. The connecting rod undergoes cyclic tension, compression as well as bending. The connecting rod is subjected to a combination of axial and bending stresses. Furthermore the connecting rod is subjected to a large compressive load so that it is imperative that buckling does not occur. To mitigate this problem, 'I'-section is commonly used. A further consideration involves the shape of the cross-section. When a structural member is subjected to an axial tension the area of the cross-section is important but the shape is not. All sections with the same area will carry the same load. For bending, an 'I'-section is better than a solid section of the same cross-sectional area. To characterize this, we need a metric – a way of measuring the structural efficiency of a section shape, independent of the material which the connecting rod is made of. We define the shape factor of a section as the ratio of stiffness or strength of the shaped section to that of a 'neutral' reference shape typically a solid square cross-section with the same cross-sectional area. The material selection as influenced by the shape is outlined in this work. The selection is also based on the application of an additional standard constraint that the fracture toughness should exceed $15 \text{ MPa}\sqrt{\text{m}}$.

In order to select the proper manufacturing process, the economic, technical and quality constraints are employed. The economic constraints involve raw material cost and batch size used in production. The technical constraints consist of estimated connecting rod mass and a minimum section of the connecting rod. The quality constraints involve manufacturing tolerance

and surface roughness. The competitive processes of powder methods and forging are carefully investigated tracking the latest developments in alloy development.

Ashby (2005) has indicated a procedure for selection of material for a connecting rod based on the constraints of high cycle fatigue and elastic buckling and has concluded the alloys of magnesium, titanium, beryllium and aluminum as potential choices for connecting rod materials. Ashby, Shercliff and Cebon (2008) have identified high strength magnesium, aluminum and ultra high strength steels as attractive candidates for connecting rod materials based on the constraints of high cycle fatigue and fracture toughness. They have also refined the search on connecting rod materials and identified aluminum reinforced with silicon carbide, boron or alumina fibers, beryllium alloys and a number of high performance carbon reinforced composites. Farag (2002) has listed some of the general (not specific to connecting rod) material performance requirements and has related possible modes of failure with the material properties. He states that the catastrophic fracture due to impact loading is resisted by the high fracture toughness, which is a rigid material requirement and should be used for initial screening of materials. He also states that the local and the global buckling are resisted by high elastic modulus, and is a soft material requirement.

Ashby, Shercliff and Cebon (2008) have looked at the shaping of a steel connecting rod and have arrived at the short list of processes as (a) die casting, (b) forging and machining, and (c) powder methods and machining. They have concluded that for a production batch size of 10,000, forging comes out the cheapest followed closely by die-casting. They point out that powder methods are more expensive because of slower production rate and high capital cost.

According to Ilia et al (2005) there are at the present time two processing technologies available to manufacture connecting rods: fracture-split drop forging and fracture-split powder forging. There are some contradictory results reported in the literature regarding the strength of connecting rods manufactured through powder forging and drop forging. Afzal and Fatemi (2004) claim that the fatigue strength of drop forged connecting rod is higher than that of a powder forged connecting rod. However, Ilia et al (2005) maintain that the reverse is true and that higher performance, superior raw material utilization and lower total cost of the finished machine and assembled product are the main reasons why the use of powder forged connecting rods has significantly increased in the last two decades, taking away the market share of drop forged connecting rods.

The students in the courses of strength of materials as well as production design use CES EduPack (2009) software as a design-led procedure for selecting materials and processes.

MATERIAL SELECTION

If ' A ' denotes the area of cross-section of the connecting rod and ' L ' its length and ' ρ ' the density of the material of which it is made then the mass ' m ' is:

$$m = AL\rho \quad (1)$$

If the applied force on the connecting rod is 'F' and the endurance limit of the material as ' σ_e ', the fatigue constraint requires that,

$$F / A \leq \sigma_e \quad (2)$$

The mass from equation (1) by eliminating 'A' is then given by,

$$m \geq FL\left(\frac{\rho}{\sigma_e}\right) \quad (3)$$

In order that the mass is minimized we need to maximize the material index, 'M':

$$M_1 = \frac{\sigma_e}{\rho} \quad (4)$$

Creating a chart with ' σ_e ' and ' ρ ' as axes and applying an additional constraint that the fracture toughness exceeds 15 MPa \sqrt{m} identify materials with high values of this index. This is the selection process for direct tension or compression load on the connecting rod. The selection is shown in Figure 1 and uses the Level 2 Materials Universe of CES EduPack software.

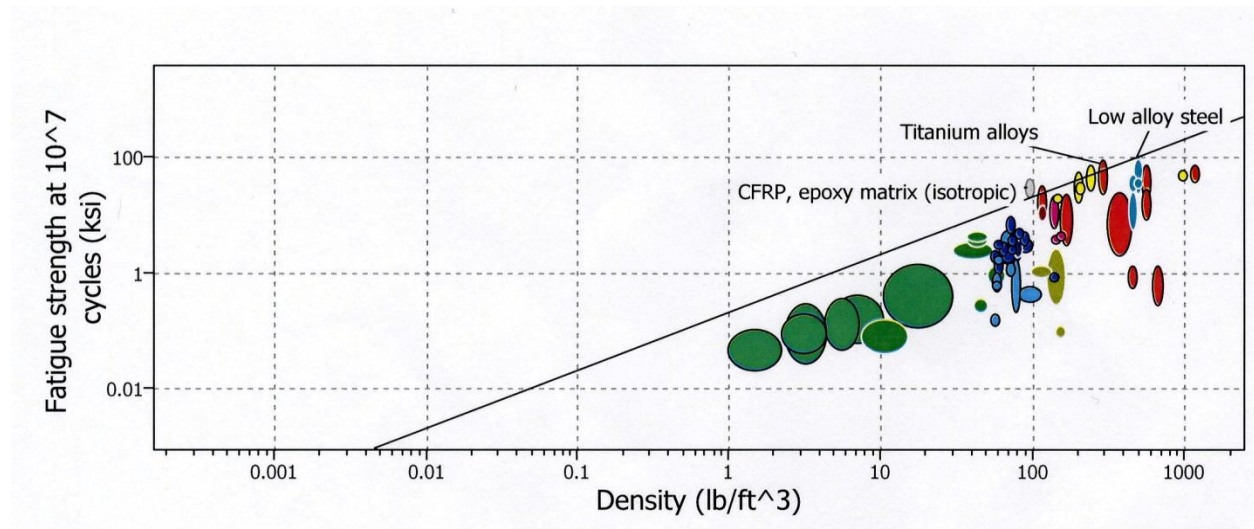


Figure 1: Fatigue Strength vs. Density

From Figure 1 a number of candidate materials emerge. The prominent one is low alloy steel which is extensively used as the connecting rod material for engines running at high rotational speeds.

IMPACT OF SECTION SHAPE

The shape of the cross section plays a very important role in carrying loads, especially bending and torsion. The shape can be optimized to maximize performance for a given loading condition. Simple cross-sectional geometries are not always optimal. For example, I-beams can carry bending loads more efficiently when compared to a solid cross-section, like a solid square. By efficiency we mean for a given loading condition the section uses as little material as possible.

We define the shape factor in bending, ' Φ_B^e ' due to stiffness effects as:

$$\Phi_B^e = \frac{S}{S_o} \quad (5)$$

Here ' S ' is the stiffness of cross section under consideration, and ' S_o ' is the stiffness of reference solid square cross-section. It should be noted here that the bending stiffness ' S ' is proportional to ' EI ', where ' E ' is the elastic modulus and ' I ' is the area moment of inertia. Noting that for a square of side ' b ' we have, comparing sections of same area, A ,

$$I_o = \frac{b^4}{12} = \frac{A^2}{12} \quad (6)$$

$$\Phi_B^e = \frac{S}{S_o} = \frac{EI}{EI_o} = \frac{12I}{A^2} \quad (7)$$

The shape efficiency as determined by the shape factor ' Φ_B^e ', is dependent on the material, with the constraints appearing from the considerations of manufacturing, material properties and local buckling. The maximum value for structural steels can be as high as 65.

The other shape factor relates the strength-efficiency of the shaped beam, and is measured by the ratio of the section moduli as

$$\Phi_B^f = \frac{Z}{Z_o} \quad (8)$$

Where Z_o is the section modulus of a reference beam of square cross section with the same cross-sectional area, A

$$Z_o = \frac{b^3}{6} = \frac{A^{3/2}}{6} \quad (9)$$

Thus:

$$\Phi_B^f = \frac{Z}{Z_o} = \frac{6Z}{A^{3/2}} \quad (10)$$

The failure of the connecting rod (stress exceeding the endurance limit, σ_e) if the limiting moment M_e is reached, that is when,

$$M_e = Z\sigma_e \quad (11)$$

Replacing Z by expressions in equations (8) and (9) we have,

$$M_e = \frac{\Phi_B^f}{6} \sigma_e A^{3/2} \quad (12)$$

Substituting A into the equation (1) for mass of the connecting rod, we have,

$$m = (6M_e)^{2/3} L \left[\frac{\rho^{3/2}}{\Phi_B^f \sigma_e} \right]^{2/3} \quad (13)$$

The best material and shape combination (using maximum bending strength as a criterion) is that with the greatest value of the new index M_2 , where

$$M_2 = \frac{(\Phi_B^f \sigma_e)^{2/3}}{\rho} \quad (14)$$

Similarly, the best material and shape combination (using maximum stiffness as a criterion) is that with the greatest value of the new index M_3 , where

$$M_3 = \frac{(\Phi_B^e E)^{1/2}}{\rho} \quad (15)$$

CALCULATION OF SHAPE FACTORS

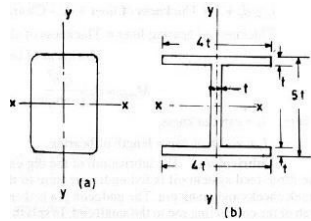


Figure 2: Connecting Rod Rectangular and I-Beam Cross-Sections

With the assumed shape of the cross section for the connecting rod as shown in Figure 2(b), the cross sectional area of the I-beam section is $11 t^2$.

Ilija et al (2005) provide the minimum I-beam area for the connecting rod for the 1.9 L and 2.2 L engines as 132 mm^2 and 141 mm^2 respectively. This gives the minimum thickness of the order of 3.5 mm. Using 3.5 mm as the thickness dimension,

The baseline area, A

$$A = 11 (3.5)^2 = 134.75 \text{ mm}^2 \quad (16)$$

The moment of area about the x-x axis, I

$$I = \frac{t(3t)^3}{12} + 2\left(\frac{4t.t^3}{12} + (t.4t)(2t)^2\right) = 34.917t^4 = 5240\text{mm}^4 \quad (17)$$

The section modulus, Z is given by,

$$Z = \frac{I}{c} = \frac{I}{(2.5t)} = \frac{34.917t^4}{(2.5t)} = 139.67t^3 = 2096\text{mm}^3 \quad (18)$$

The stiffness related shape factor in bending is given from equation (7) by,

$$\Phi_B^e = \frac{12I}{A^2} = \frac{12(5240)}{(134.75)^2} = 3.46 \quad (19)$$

The strength related shape factor in bending from equation (10) is given by

$$\Phi_B^f = \frac{6Z}{A^{3/2}} = \frac{6(2096)}{(134.75)^{3/2}} = 8.04 \quad (20)$$

COSELECTION OF MATERIAL AND SHAPE

Material selection based on strength at a minimum weight is based on rewriting the material index for failure in bending from equation (14) as:

$$M_2 = \frac{(\Phi_B^f \sigma_e)^{2/3}}{\rho} = \frac{\left(\frac{\sigma_f}{(\Phi_B^f)^2}\right)^{2/3}}{\rho / (\Phi_B^f)^2} = \frac{\sigma_f^{*2/3}}{\rho^*} \quad (21)$$

The material with strength σ_f and density ρ when shaped behaves in bending like a new material of strength and density,

$$\sigma_f^* = \frac{\sigma_f}{(\Phi_B^f)^2} \quad \text{and} \quad \rho^* = \frac{\rho}{(\Phi_B^f)^2} \quad (22)$$

Material selection based on stiffness at a minimum weight is based on rewriting the material index for failure in bending from equation (15) as:

$$M_3 = \frac{(\Phi_B^c E)^{1/2}}{\rho} = \frac{\left(\frac{E}{\Phi_B^c} \right)}{\rho / \Phi_B^c} = \frac{E^{*1/2}}{\rho^*} \quad (21)$$

The material with modulus E and density ρ when shaped behaves in bending like a new material of modulus and density,

$$E^* = \frac{E}{\Phi_B^c} \quad \text{and} \quad \rho^* = \frac{\rho}{\Phi_B^c} \quad (22)$$

The co-selections based on minimizing mass for maximum strength and for maximum stiffness are shown in Figures 3 and 4 respectively. The Level 2 Materials Universe of the CES EduPack software is used for this purpose.

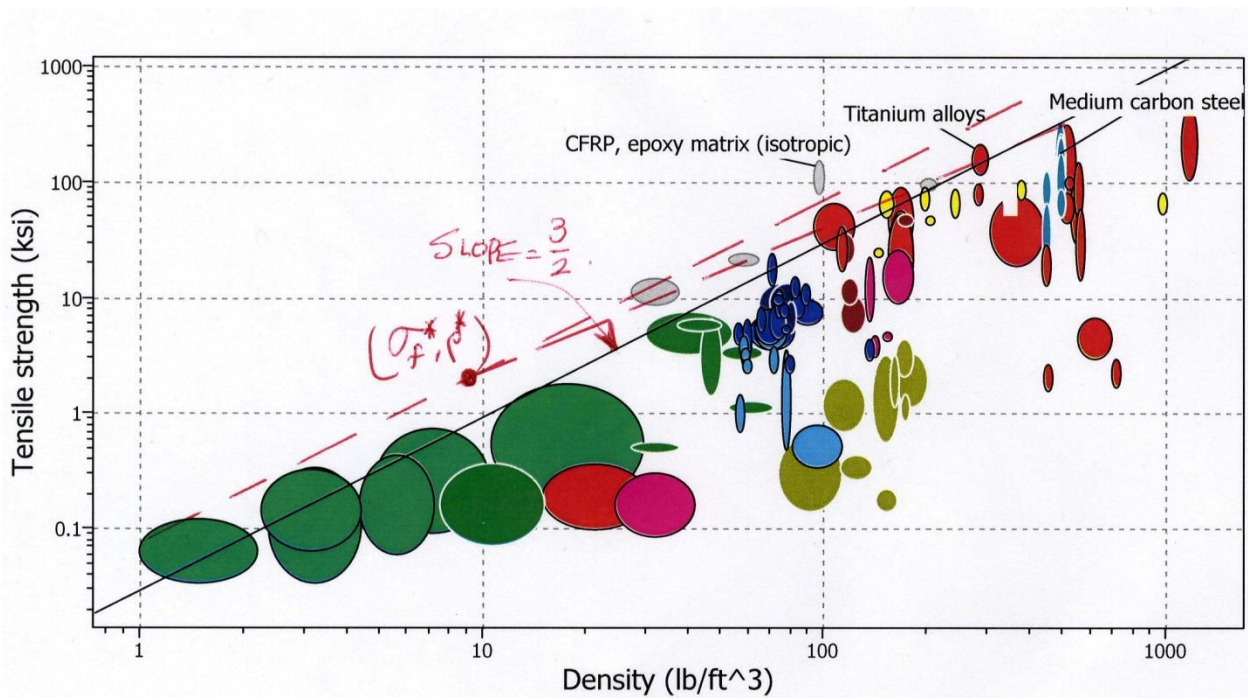


Figure 3 Tensile Strength vs. Density

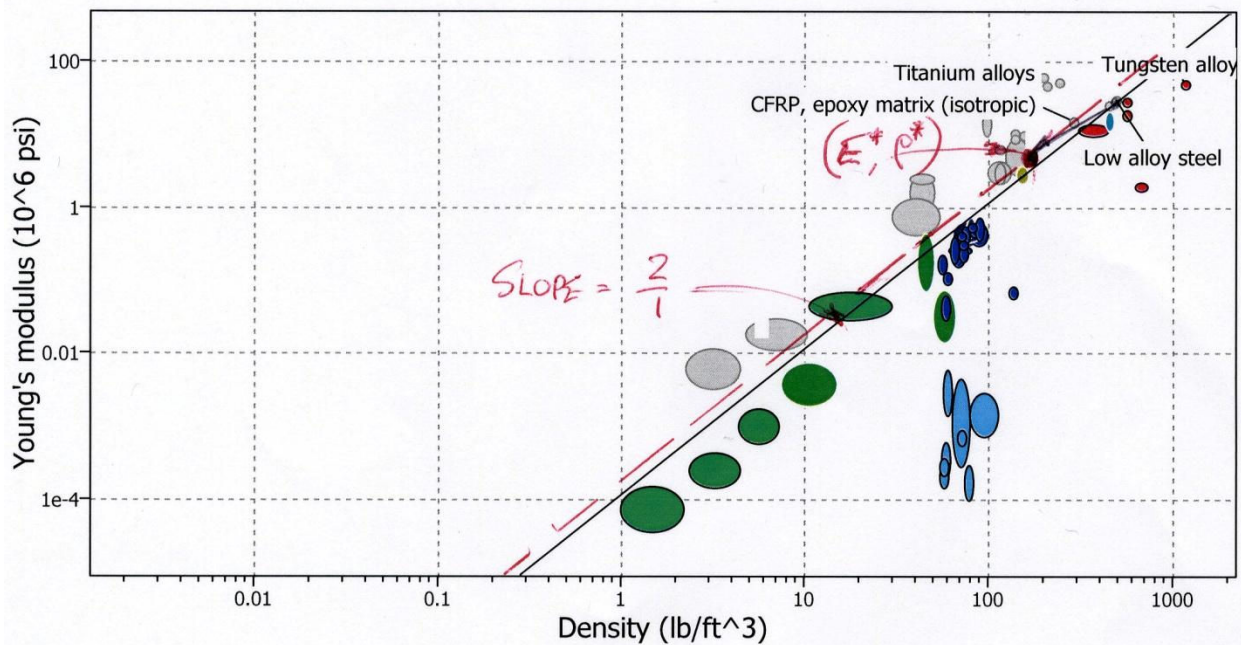


Figure 4 Young's Modulus vs. Density

Figures 3 and 4 clearly show the effect of the section shape on the overall performance in strength and stiffness respectively. The strength of the material based on the choice of medium carbon steel shows improved performance with a fictitious material whose tensile strength as well as density are (1/65) of that of the medium carbon steel, as shown in Figure 3. The stiffness of the material based on the choice of low alloy steel shows improved performance for a fictitious material whose elastic modulus as well as density are (1/3.46) of that of low alloy steel, as shown in Figure 4.

SELECTION OF MANUFACTURING PROCESS

According to Ilia et al (2005), the weight of connecting rod for 1.9L engine is 545 gm, and that for a 2.2 L engine is 544 gm. The minimum section is about 3.5 mm. Dimensional precision is important so that the clearances at the crankshaft end and at the piston end are assured. A lower surface roughness is necessary so as to minimize surface crack initiation. The following parameters are inputted into the CES EduPack code using the Level 2 Process Universe. The details are shown in Table 1.

TABLE 1 Comparison of Manufacturing Processes

		Constraints
Function	Connecting Rod	
Objective	Minimize cost	
Constraints	Material: Medium Carbon Steel	Technical
	Shape: 3D Solid	Technical
	Mass: 0.545 kg	Technical
	Minimum section: 3.5 mm	Technical
	Tolerance: <0.25 mm (surface)	Quality
	Tolerance: <0.02 mm (bores)	Quality
	Roughness:<5 μm	Quality
	Batch size: 10 000	Economic

The processes that evolve are forging, die casting and pressing / sintering (powder methods).

For both fracture-split drop forging and fracture-split powder forging, one piece forging uses a cap that is broken off (fracture-split) the main part of the connecting rod. The drop forging process uses C-70 crackable forging steel. Alloying elements in this material enable hardening of the forged connecting rods when they undergo controlled cooling after forging. While the two competing forging processes are similar, there are subtle differences between two. The forged steel connecting rod is fabricated by starting with a wrought steel billet, heating and forging it in the material's plastic temperature range, fracture splitting and then machining portions of the product to realize the final dimensional characteristics. The powder forged rod is fabricated by consolidating metal powders into a perform that is sintered, reheated to forging temperature, fully densified by forging to final shape, fracture-splitting and machined (minimally) to final dimensions. Ilia et al (2005) conclude that powder forging makes a much better connecting rod that is stronger, more reliable, and cost effective. Powder forged connecting rods demonstrate improved tool life when compared with the drop-forged C-70 connecting rods, they require less machining, and has a much higher material utilization efficiency, leading to lower final cost of the finished product.

PEDAGOGICAL CONSIDERATIONS

The students were able to select material for high performance connecting rod by identifying the correct mechanism of failure, namely fatigue under cyclic tension and compression. The selection process was successfully accomplished using the Level 2 Materials Universe of the CES EduPack (2009) software. The students were able to see the improved performance of the

connecting rod in terms of stiffness and strength as the section changed from a square to a typical I-section from the discussion of shape factors. These activities were conducted as a module within the strength of materials course. The lab assignment is detailed in Appendix A.

The manufacturing process selection was carried out in a course on production design. The leading processes of forging and pressing/sintering emerged using the Level 2 Process Universe of the CES EduPack (2009) software. The students were initially not quite enthused with the process selection of the connecting rod, but this concept was carried out further by using a number of other examples of selection of processing in the book by Ashby, Shercliff and Cebon (2008).

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APPENDIX A

Selection of Material for Connecting Rod

A. Material selection for Fatigue

CES EduPack Level 2 Materials Universe: Fatigue Strength vs. Density.

Select material with maximizing material index: $M_1 = \frac{\sigma_e}{\rho}$

B. Material selection for Shape, Bending Strength and Bending Stiffness

Find shape factors for the I-section

$$\Phi_B^e = \frac{12I}{A^2}$$

$$\Phi_B^f = \frac{6Z}{A^{3/2}}$$

CES EduPack Level 2 Materials Universe: Yield Strength vs. Density.

Select material maximizing bending strength

$$M_2 = \frac{(\Phi_B^f \sigma_e)^{2/3}}{\rho}$$

CES EduPack Level 2 Materials Universe: Young's Modulus vs. Density.

Select material maximizing bending stiffness

$$M_3 = \frac{(\Phi_B^e E)^{1/2}}{\rho}$$