Optimization of Compliant Window Shutters

Steve Brewer | Brandon Hanna | Zachary Lindström

ME 575 - Optimization Techniques - Project 1
February 15, 2013

Problem Statement

The shutter and blind industry is mainly dominated by cheap mini-blinds for cost-sensitive users or expensive wood plantation shutters for those that consider aesthetics paramount. For a final project in a previous class, we developed an alternative that can provide the premium look and feel of plantation shutters, yet incorporates compliant torsion bars to hopefully reduce costs to that of mini-blinds (see Figure 1). Our compliant shutters have proven to be a sound concept and engineered solution to selectively shade windows. They lend themselves well to automated and simplified fabrication. They are less expensive, simpler, easier to produce, extremely durable, and can provide both premium and cost-effective options to meet customer needs.

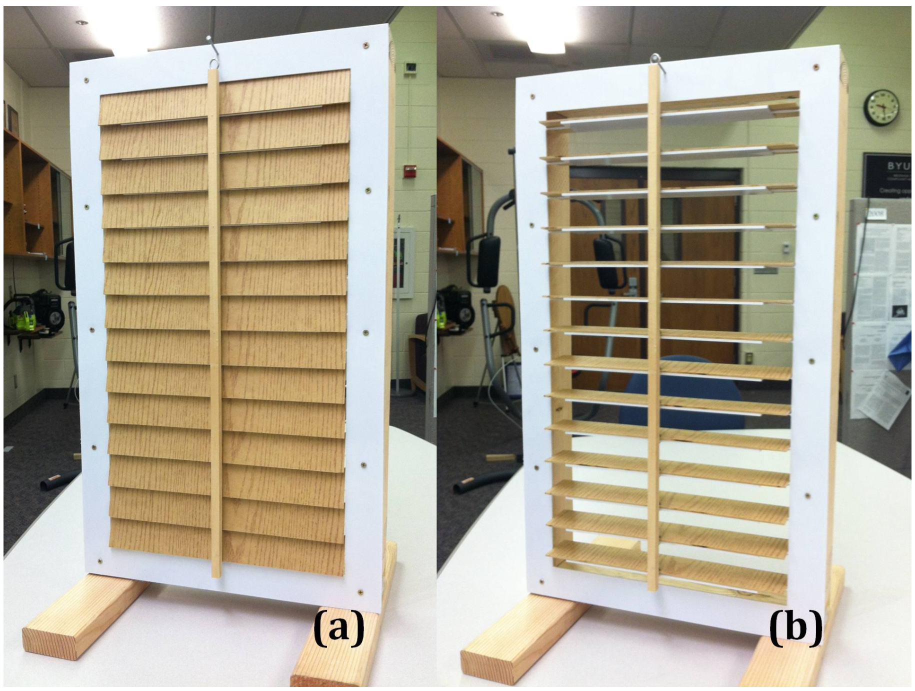

Figure 1: Prototype of shutters before optimization in the (a) closed and (b) open positions.

For our optimization project, we decided to optimize the compliant shutters to minimize the total weight of the shutters. Since the compliant members of the shutter slats are torsion bars at each end of the slat, we decided to make the geometry of the torsion bars our design variables.

The variables defining the design of the torsion bars of the shutters are bar width (w), bar thickness (t), number of slats (N), and bar length (l). A close up image of the model with labeled parameters can be seen in Figure 2.

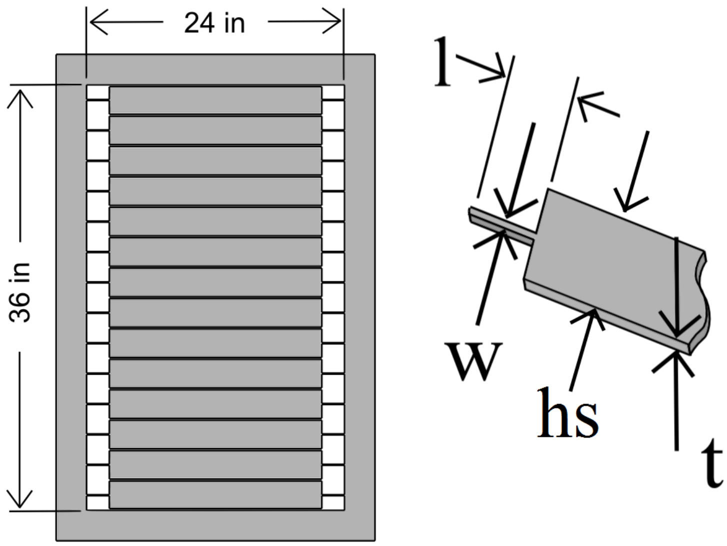

Figure 2. Diagram of the un-optimized full shutter design (left) and diagram of one torsion bar (right), with variables labeled.

The window size is fixed at 36 inches high (H_{win}) and 24 inches wide (W_{win}). To incorporate a flexible material into our design, polypropylene is chosen as the shutter material. Polypropylene has the material properties listed in Table 1. To keep the slat portion of the shutters rigid, the polypropylene sheet must be a uniform thickness of at least 0.125 inches. Also, to have enough surface area to apply veneers for aesthetic, torsion bar length must be less than 8 inches. The bounds on all design variables are given in Table 2, and were chosen for practicality.

Table 1. List of material properties for polypropylene.

Density (ρ)	56.12 lbm/ft^3
Young's Modulus (E)	183 $kpsi$
Poisson's Ratio (ν)	0.45
Yield Strength (S_y)	290 $kpsi$

Table 2. Upper and lower bounds for design variables.

Design Variable:	**LB:**	**UB:**
thickness (t)	0.125”	0.5”
bar width (w)	0.001”	0.5”
number of slats (N)	2	15
bar length (l)	0.125”	8.0”

In order to keep the slats from binding together when closed, there must be a distance between slats (gap) of at least 0.125 inches. The angle of rotation that the slats must travel through (ϕ) is 90 degrees in order to allow maximum sunlight in when the shutters are open.

To actuate the shutters, a bar is applied to each slat, and the user raises the bar up or down. The force required to actuate all slats (F) at once must be less than 10 lbs, but greater than 5 lbs. Calculating the torque (T) in each torsion bar is required to calculate overall actuation force. The equation for torque in a rectangular bar is

$$T = \frac{KG\phi}{l} \tag{1}$$

where K is the polar moment of inertia and G is the modulus of rigidity. Polar moment of inertia is given by

$$K = wt^3\left[\frac{1}{3} - 0.21\frac{t}{w}\left(1 - \frac{t^4}{12w^4}\right)\right] \tag{2}$$

where w and t are the dimensions of the bar cross section and $w \geq t$. The modulus of rigidity is given by

$$G = \frac{E}{2(1+\nu)} \tag{3}$$

where E and ν are material properties given in Table 1. Therefore the total actuation force required is given as

$$F = \frac{4NT}{h_s} \tag{4}$$

where h_s is the width of a slat and given by

$$h_s = \frac{H_{win} - gap(N+1)}{N}. \tag{5}$$

One thing to take into consideration is the sagging that may occur in each slat simply due to the weight of the slat. To make sure the deflection (y_{max}) from weight is minimal, we give the equation

$$y_{max} = \frac{W_S l^3}{48EI} \tag{6}$$

where W_S is the weight of each slat, and I is the area moment of inertia of the torsion bar cross section. The maximum deflection must be less than gap to make sure no binding occurs. The area moment of inertia is given by

$$I = \frac{wt^3}{12} \tag{7}$$

and slat weight is given by

$$W_S = h_s(W_{win} - 2l)t\rho gC \tag{8}$$

where g is the gravitational constant and C is a conversion factor that makes the units of W_S come out in pounds. Note that these equations rely on all length units to be in inches.

We must also calculate the maximum stress in each torsion bar at maximum rotation to make sure we don't exceed the yield strength (S_y) of the material. The maximum shear stress in a rectangular torsion bar is given by

$$\tau_{max} = \frac{3T}{wt^2}\left[1 + 0.6095\frac{t}{w} + 0.8865\left(\frac{t}{w}\right)^2 - 1.8023\left(\frac{t}{w}\right)^3 + 0.9100\left(\frac{t}{w}\right)^4\right] \tag{9}$$

where $w \geq t$.

To calculate total weight of the shutters, a volume (V) calculation is needed. The total volume of the shutters is given in terms of the variables by

$$V = t\left(H_{win}W_{win} - gap(N+1)W_{win} - 2lN(h_s - w)\right) \tag{10}$$

so a weight calculation is simply

$$Weight = VCg\rho. \tag{11}$$

Using the values and equations given above, we desire to minimize the weight of the entire shutter structure.