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Optimal design of an Indian carpet weaving loom structure

Himanshu Chaudhary* and Subir Kumar Saha
Department of Mechanical Engineering, IIT Delhi, New Delhi 110 016

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Present looms to weave the carpets in India are made of wood, which are susceptible to termite attacks and low service life. Besides, the high tension in the warps is generated manually through the pull of a rope by 2-3 persons. In order to avoid the above difficulties, an improved metallic loom was developed at IIT Delhi in 2001, which made weaving easy but the cost of loom is high. In this paper, optimisation of the metallic loom is carried out resulting in relatively lightweight and reduced cost. The design is verified using the Finite Element Analysis software, ANSIS.

Keywords: Carpet loom, Design, Optimization, Structure

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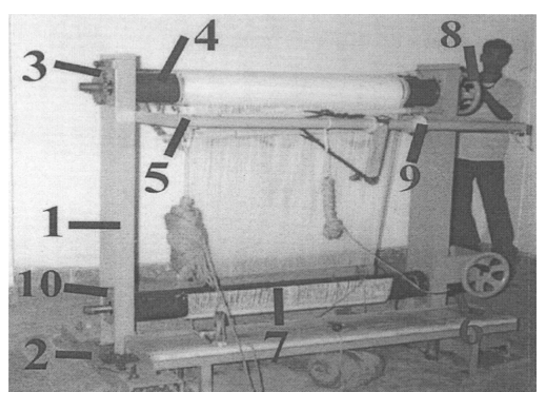
Introduction

Handloom weaving of carpets is different in many aspects from the handloom weaving of a fabric[1]. There is no better kind of the carpet than carpet made by hand; though this is far from implying that all hand-tufted carpets are superior to all machine-made ones[2]. Traditionally, Indian or oriental carpets are woven on wooden looms, which are becoming economically, environmentally, and functionally non-viable due to the following reasons[3,4]: i) Life is limited (5-8 years) due to susceptibility to termites and frequent investments are required; ii) Deforestation; iii) Laborious tensioning, as rope arrangement is used to generate high tension in the warps; and iv) Non-uniform tension in the warps over the time because the wooden beams gradually bends. The non-uniformity affects quality of the carpet.

A systematic approach to improve the existing tools and processes used by artisans engaged in carpet sectors and to enhance productivity and quality of the finished products in a cost effective manner has been initiated in 2000 by IIT Delhi[4,5]. Carpet loom (Fig. 1) has been developed and tested in many carpet-manufacturing belts in Northern India (Bhadohi, Mirzapur, Jaipur, Srinagar, etc.). The metallic loom has been designed considering all aspects of carpet weaving. The lower beam fitted with a worm and worm wheel for developing tension in the warp threads. A ratchet-pawl mechanism is used to lock the top (warp) beam. This paper attempts to optimize the carpet loom for its overall weight and price.

Optimization of carpet loom is a problem of structural optimization. It is the type of problem where the design variables are determined to minimize an objective function, such as weight while satisfying a set of geometrical and/or behavioural constraints[6]. Taking about optimization of structural elements like the beams and columns for single objective design criterion, Keller[7] determined the strongest simply supported column, which has maximum critical buckling load for given volume and length. Prager *et al*[8] presented a uniform methodology



1. Support channel; 2. Base channel; 3. Ratchet; 4. Upper (warp) beam; 5. Shedding pipe; 6. Tensioning device; 7. Lower (cloth) beam; 8. Handle; 9. Shedding roller; 10. Bush bearing

Fig. 1—Improved handloom[4, 5]

*Author for correspondence
Tel: 011-25591135; Fax: 011-26582053
E-mail: himanshubhl@rediffmail.com; saha@mech.iitd.ernet.in

using generalized stress-strain field for optimal design for maximum stiffness, maximum buckling load, and optimal plastic design for maximum safety of structural elements. Weaver & Ashby[9] integrated the selection of material and section-shape of load bearing structures in the optimization process. On minimum weight of hollow and sandwich compression structures, Budiansky[10] showed the weight comparison on the basis of appropriate structural indices and compressive strength as only failure criterion.

Materials and Methods

Warp and Cloth Beams

In textile terminology, the part used to wind the warp threads and carpet, are called beams, namely, the upper (warp) and lower (cloth) beams, 4 and 7, respectively. Their function is, however, very complex[11]. The function and constraints of these beams (Table 1) allow formulating the optimization problem correctly.

Table 1—Functions and constraints of warp and cloth beam

Function	Constraints
Resist bending and torque	*Kinematic*: Let off all warp threads equally, and lock for forward motion during weaving
	Geometric: Length of the beam specified by the width of a carpet
	Strength: Support the tension in warp threads, and lock torsion without failing
	Stiffness: Less deflection to maintain uniform tension in all warp ends

Load Modelling

Warp threads made of cotton yarn tested for breaking load on Textechono Statimat Me (a textile tester) under standard textile testing conditions[12]. Like a brittle metal (cast iron), the yield point (Fig. 2) for cotton is obtained by drawing a tangent line parallel to the line joined by origin to breaking point[12]. The yield point of the thread occurs slightly below force 9.81 N (~1000 g) at 5 percent elongation. Quality of threads used as warp in carpet depends on quality of fibre and tex (linear density of yarn). Considering different yarn quality, yield force lies in the range of 10-20 N. Therefore, assuming a design factor of safety[13] as 2, warp thread load of 20 N is taken as the design load. All warp threads are wound uniformly over the upper beam (Fig. 1). Hence, they are modelled as uniformly distributed load. Since carpet knotting to weave about 150 mm carpet along the column height takes several days, structure is subjected to steady loading. Moreover, the beam is simply supported, and its rotation about the axis AB (Fig. 3) is restricted due to the presence of ratchet and pawl at A. Now, maximum resisting bending moment, M, and torsion, T, at any section x can be obtained as

$$M = \frac{wx(\lambda - x)}{2}\text{; and } T = \frac{w(x - \lambda)(\mathrm{d}+\mathrm{t})}{2} \quad \dots (1)$$

where x is distance along the beam from A; w is beam load per unit length due to the tension in the warps; d is mean diam; and t is thickness of the beam. The torsion, T, depends on design variables, d and t.

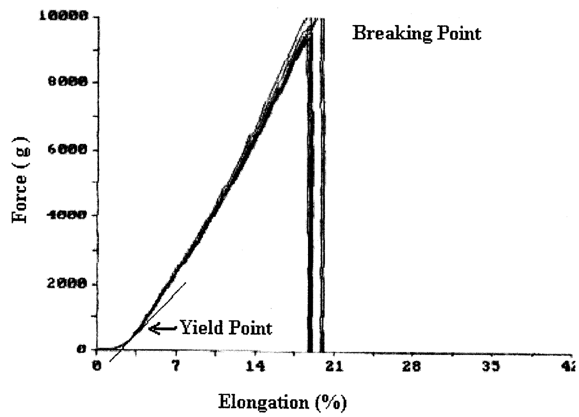


Fig. 2—Tensile test results of warp threads

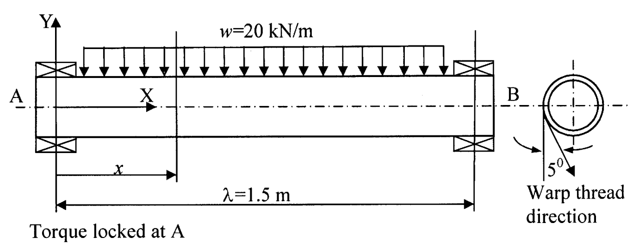


Fig. 3—Load diagram of the upper (warp) beam

Optimization Problem Formulation

To meet the constraints (Table 1), outer dimension of all the sections of beam lies in normal to the warp plane and should be uniform. This is maintained by choosing a circular beam of constant outer diam that keeps the cost also low. In order to reduce the weight and accordingly cost, a hollow circular beam of uniform thickness is considered suitable for such applications. For the failure criterion, one chooses the Distortion Energy Theory (DET)[13], and considers the beam material to be isotropic homogenous. Considering von Mises effective stress, the resultant stress is obtained in terms of bending (σ_x) and shear stress (τ_{xy}) as

$$\sigma = \sqrt{\sigma_x^2 + 3\tau_{xy}^2} \quad \ldots (2)$$

The maximum resultant stress occurs at, $x = \lambda / 2$, and the magnitude of maximum deflection of the beam, δ_{max}, is calculated as

$$\delta_{\max} = \frac{40 w \lambda^4}{384 \pi E \alpha t^4 (\alpha^2 + 1)}$$

where $\alpha \equiv d/t$, mean diam to thickness ratio and E is elastic modulus of beam material.

Optimization problem is then formulated as: Minimize the weight of the beam under simply supported loading that causes both bending and torsion. Mathematically, it is

$$\text{Minimize,} \quad W \equiv \rho \pi \lambda \alpha t^2 \quad \ldots (3)$$

$$\text{Subject to,} \quad \sigma_{\max} \leq S_y ; \quad \ldots (4)$$

$$\delta_{\max} \leq \delta_{\text{all}} ; \quad \ldots (5)$$

$$t \geq t_{\min} \quad \ldots (6)$$

where ρ is the density of the material, σ_{max} is the maximum von Mises stress, δ_{max} is the maximum deflection, and t is thickness of the beam. Moreover, S_y, δ_{all} and t_{min} are the yield strength of material of the beam, the allowable beam deflection so that carpet quality is not suffered, and the minimum available beam thickness, respectively.

Solution

Optimization problem is a nonlinear two-dimensional constrained minimization problem as there are two variables (d and t). The problem of optimization is solved in two phases. In first phase, appropriate strength of the material is found for specified allowable deflection, δ_{all}, as follows: 1) Find thickness, t, using equality condition of Eq. (4) for a range of α and a material strength, S_y; 2) Calculate weight, W, from the objective function, Eq. (3), using α and t; and 3) Repeat steps 1 and 2 for other strengths. Similar procedure is adopted to generate weight data for deflection using Eq. (5). Weight requirement (Fig. 4) to satisfy both the constraints (δ_{all} =3 mm, S_y=100 Mpa) is always dictated by strength criterion (S_y=100 MPa). For other combinations (δ_{all} =3 mm, S_y=200 MPa), it is dictated by deflection criterion, while for S_y=150 MPa and δ_{all} =3 mm, both the curve intersect at α=30. Therefore, weight requirement for this combination is governed by deflection up to α=30. Beyond this point, no significant weight reduction is observed; there is equal influence of strength and stiffness criteria on the weight. Hence, the material strength (S_y = 150 Mpa) is chosen as optimal because α>30; it has no bias on the failure criterion, and one may choose either strength or deflection equation for the design equation. Accordingly, the optimal mean diam to thickness ratio, α, is taken as 30. The optimum values are denoted as, S_y^*=150 MPa and α^*=30.

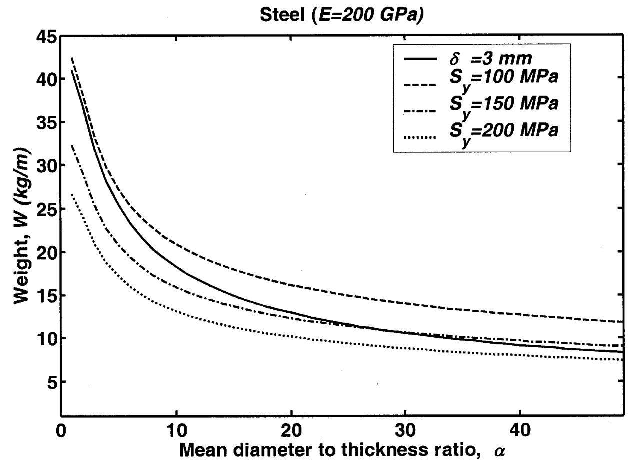


Fig. 4—Variation of beam weight, W, vs mean diameter-to-thickness ratio, α

In next phase, thickness, t, is evaluated by substituting, S^*_y, and, α^*, into Eq. (4). It is obtained as, t=3.8 mm and the value can be considered optimal if the third constraint, Eq. (6), is satisfied. The results obtained here using the proposed methodology, as presented above, can also be verified using any standard optimization technique[14] (Fig. 5).

Support Columns

Columns that support both the upper (warp) and lower (cloth) beams are under complex 3-dimensional loading. Locking moment (Fig. 6) due to locking of the beam, M_L, and axial compressive load, P, act on the columns, which support the upper and lower beams. Locking moment, M_L, causes torsion in the beam, whose magnitude depends on the diam of the beam and the locking device, i.e., ratchet-pawl at the upper beam. These loads are steady in nature during the carpet weaving process.

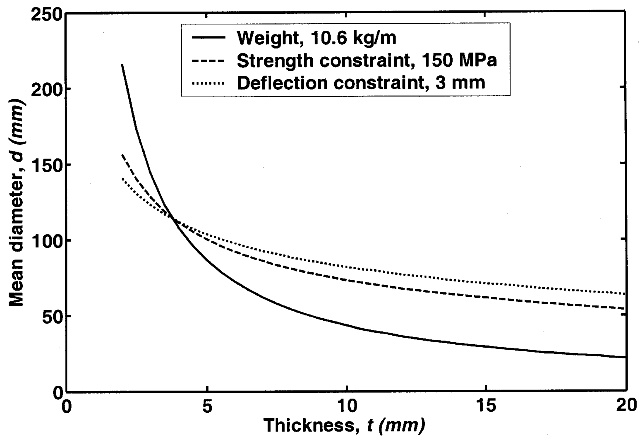


Fig. 5—Contour of objective function and the constraints in design variable space

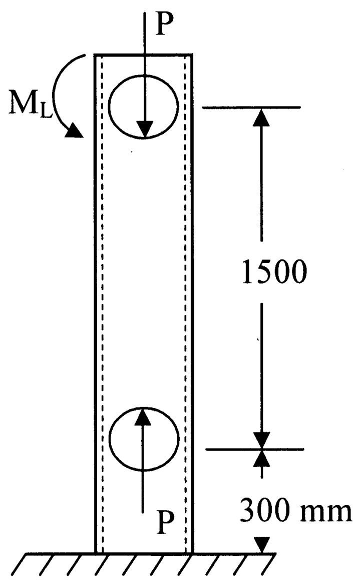


Fig. 6—Schematic diagram of left hand side supports

Load Modelling

The upper beam is locked at one end. Hence, locking moment, M_L, is equal to the total torque, T, applied on the beam, i.e., $M_L = w\lambda(d+t)/2$ from Eq. (1), where d is the mean diam, λ is the length and t is thickness of the beam. Compressive load is, $P = w\lambda/2$, where w is the beam load per unit length. Because loads are applied simultaneously, the locking moment, M_L, and compressive load, P, can be modelled together[15] as an eccentric load P acting at $e=d+t$, so that $Pe=M_L$. The length of the columns below the lower beam is small, and not under axial compression. Thus, the side support columns are modelled as one end fixed and the other end free with eccentric loading. Maximum compressive stress, σ_{max}, induced in the column can be obtained[15] as

$$\sigma_{\max} = \frac{P}{A} + \frac{M_{\max}}{Z} \quad \dots (7)$$

where P is the compressive load; and A is the cross-sectional area; Z is the section modulus of the columns; and the maximum bending moment at fixed end, M_{max}, is given by

$$M_{\max} = Pe/\cos\left(\frac{L_{eq}}{2}\sqrt{\frac{P}{EI}}\right) \quad \dots (8)$$

where L_{eq} is equivalent length that is twice the actual length of column, L, and I is moment of inertia of the column section. The first term in the expression of M_{max}, Eq. (7), indicates direct compressive stress, and the second one is due to global buckling of the column. Hollow sections have higher area moment of inertia compared to the solid sections. Since, circular shape is not appropriate for the difficulties of mounting the tensioning and locking devices, hollow square box type section is chosen for the column structure.

Optimization Problem Formulation

Based on square cross section, optimisation problem is stated as follows: Minimize weight of the hollow square tube that is equally strong about its principal axes, i.e.,

$$\text{Minimize, } W \equiv 4\,\rho L \beta\, t^2 \quad \dots (9)$$

$$\text{Subject to, } \sigma_{\max} \le S_y; \quad \dots (10)$$

$$\sigma_{Buk} \le S_y; \quad \dots (11)$$

$$t \ge t_{\min} \quad \dots (12)$$

where, $\beta = b/t$; b being the mean width, ρ is the material density, t is the tube thickness, σ_{Buk} is the stress due to local buckling, S_y is the yield strength, and t_{min} is the minimum tube thickness allowed. Mean width-to-thickness ratio, β, is limited by the stress induced due to local buckling[10], σ_{Buk}, as,

$$\sigma_{Buk} \le \frac{4\pi^2 E}{12\,(1-\upsilon^2)\,\beta^2} \quad \dots (13)$$

where E is Young's modulus, and υ is Poisson's ratio of material under consideration.

Solution

Equality condition of local bulking, Eq. (13), for steel is plotted with Poisson ratio, υ=0.28, and Young modulus, E=200 GPa. The plot (Fig. 7) gives maximum ratio (β=54.54) corresponding to the local buckling stress (σ_{Bulk} =240 MPa). Weight data are then plotted by converting inequality of Eq. (10) into equality (Fig. 8). Optimal mean width-to-thickness ratio is then decided by equating the induced local buckling stress, σ_{Buk}, and the global buckling stress, σ_{max}, which must be less than the yield strength, S_y [10], i.e., $\sigma_{Buk} = \sigma_{max} \leq S_y$. Hence, for the material strength, S_y=240 MPa, optimum ratio, β is 54.54. Corresponding minimum weight (Fig. 8) is W=3.33 kg/m. One can find another set of optimum solution for different material strength, S_y. Also, there is no significant change in weight, W, beyond the mean width-to-thickness ratio, β=60 (Fig. 8). Table 2 provides the results for steel with two different yield values (S_y=240 and 150 MPa).

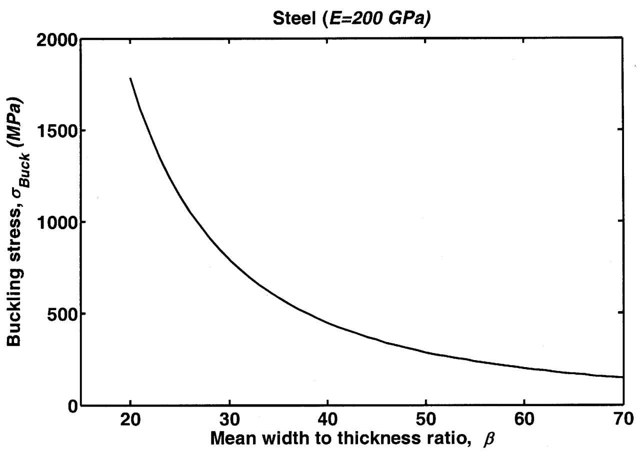


Fig. 7—Local buckling stress, σ_{Buk}, vs mean width-to-thickness ratio, β

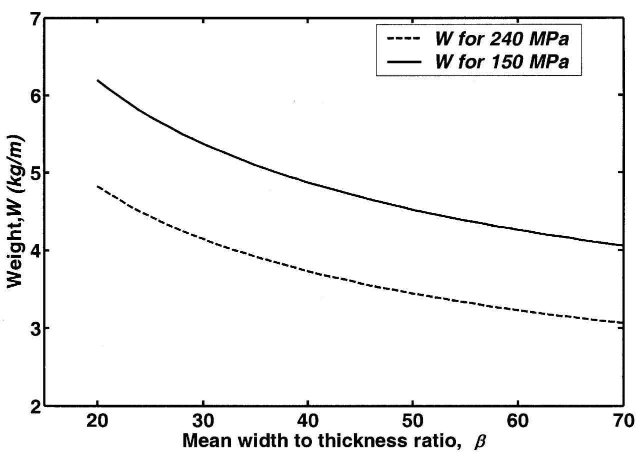


Fig. 8—Weight vs mean width to thickness ratio, β

Results and Discussion

For the typical loom for the carpet (width, 1.2 m; uniform wrap threads load, w=20 N/mm; beam length, 1.5 m; column height, 1.5 m), optimal dimensions were analyzed (Table 3). The results of the proposed analytical method verified by the standard finite element analysis (FEA) tool ANSYS 7[16] under more realistic boundary conditions. For example, portion of the column below the lower beam (Fig. 6) was not considered for the column buckling. However, for FEA[17], it also included as extended portion of the column by 0.3 m.

von-Mises effective stress contour of the FE model (Fig. 9) shows that maximum stress of 146.48 MPa is induced in the middle nodes of the beam. Moreover, stress of 235.91 MPa is induced at joint 6 of the column, at the gear end (Fig. 1). The maximum stresses are computed analytically by assuming the beams as simply supported, and the columns as fixed-free. The results (Table 4) are close, which not only verifies the correctness of the FE and analytical results but also validates optimised dimensions obtained from the given materials of certain strengths. The comparison of beam and column dimensions[4] (Table 5) shows substantial weight saving (34.5% for beams, 83.8% for columns).

Table 2—Comparison of optimum values

Yield strength, S_y, MPa	Optimum ratio, β	Optimum t, mm	Optimum b, mm	Minimum W, kg/m
150	69	1.37	94.53	4.07
240	54.54	1.41	76.90	3.33

Table 3—Optimized specifications for the carpet loom (1.5 m × 1.8 m)

Component	Material	Shape of section	Yield strength, S_y, MPa	Size ratio	Dimensions, mm	Weight kg/m
Beam	Carbon steel	Hollow circular	150	d/t=30	d=114, t=3.8	10.6
Column	Carbon steel	Hollow square	240	b/t=54.54	b=76.90, t=1.41	3.33

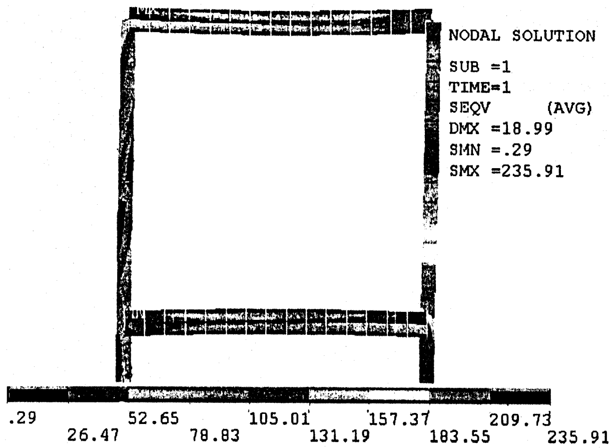


Fig. 9—The von-Mises effective stress contours in the beams and columns

Table 4—Comparison of stresses

Components	Maximum von-Mises effective stresses (ANSYS 7), MPa	Maximum analytical stresses, MPa
Beam	146.48	151.05
Column	235.91	234.55

Table 5— Comparison of optimised components

Components		Saha *et al*[4]	Optimized
Beam	Section	Hollow circular	Hollow circular
	Sy, MPa	360	150
	δ_{all}, mm	5	3
	d, mm	135	114
	t, mm	5	3.8
	W, kg/m	16.2	10.6
Column	Section	Channel 200×75	Hollow square
	S_y, MPa	240	240
	b, mm	-	76.9
	t, mm	-	1.4
	W, kg/m	20.6	3.33

Conclusions

A metallic carpet loom developed to overcome difficulties of existing wooden looms is reported. In order to reduce its weight and cost, optimisation of beams and columns was carried out. For realistic estimation of loads, tensile test of warp thread was conducted to obtain load-deformation curve. Optimisation of the beams and columns indicates substantial savings in the weight. Finite element analysis of the loom is critical when the realistic conditions are difficult to implement in analytical form, as was the case for columns. There is a total saving in the weight of the beams (34.5%) and columns (83.8%), which is expected to reduce the price of a loom of 1.5m×1.8m by about 20-25 percent.

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