Technical Journal, University of Engineering and Technology (UET) Taxila, Pakistan Vol. 25 No. 2-2020
ISSN:1813-1786 (Print) 2313-7770 (Online)

Material Selection for the Support Columns of Universal Testing Machine (UTM) using Granta's Design CES EduPack Software

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Abstract- Material selection is the most critical and increasingly complex task in the product design process. Product life cycle is majorly dependent on the choice of material selected. Digital tools are extensively used in material selection phase. Among huge list of available materials, selection of most compatible material is challenging due to wide range of design properties. It is difficult and time consuming for engineers and designers to manually evaluate each material and to select best fit materials as per design requirement. More than three hundred digital tools are available for material selection such as MatMatch, MatWeb, IDES Prospector, idemat etc. Granta's design CES (Cambridge Engineering Selector) EduPack software is one of the software package used for materials ranking and selection. It has library of more than 4000 materials. It clarifies the product functional & design requirements and then select appropriate materials while considering certain design constraints. The purpose of this software-based study is to select the optimal choice of material for support columns of Universal Testing Machine (UTM) using CES EduPack software. Support columns are critical & major load bearing elements in UTM. Using CES software, suitable & best fit material is identified for support columns while considering functional and design requirements. It is revealed that stainless steel is the most promising material that meet the design requirement of UTM support columns.

Keywords- Product design, Materials Selection, CES EduPack, Universal testing machine, support Columns

I. INTRODUCTION

Granta's design CES Edupack is one of the material science software's which is extensively used in sustainability development model of products and material selection as per design requirements. This software is a powerful tool for material selection and is extensively loaded with various materials database. Along with general properties of a material, it also defines other attributes such as recyclability, CO_2 footprints, durability in different fluids etc. This software leads to select most promising small subset of materials from a bulk list of options as per problem statement [1], [2].

Compatibility of material used in product development plays a vital role for its safe functioning. In engineering design process, importance of suitable material can never be undermined. Moreover, avoiding the identification & selection of appropriate material in the product design & fabrication phase may increase the risk of failure. Therefore, material selection is very critical in product life cycle.

Design has certain constraints and has a set of absolute & relative properties which should be fulfilled such as cost, fracture toughness, stiffness, Density, yield strength, maximum & minimum service temperatures, product life and so on. Similarly, each material discovered with set of properties, which is called its "attributes profile" [3].

'Materials selection' is to search for best possible match between the design requirements & material property profile [4]–[8]. For a designer, it is difficult & time consuming to remember property profile for each known material. Among the list of more than 10000 materials, it is challenging to decide and select the best fit material as per design constraints. It is most probable to select inappropriate & unfit material among the discovered materials. Therefore, certain risks can be controlled and avoided if software-based selection is made for best fit material matches for the design requirements. This study focuses on software-based material hunt instead of using manual techniques. The methodology of software-based selection is thoroughly explained by M. F. Ashby in his work [8].

The Granta's design CES EduPack software compares various materials as per design requirements and constraints. This software shortlists those materials which fulfill the design requirements while considering the environmental credentials of materials. Metals, Glass, Polymers, Ceramics, Elastomers and Hybrids are major families listed in materials classification. CES software represent these families in different colors separation which is called envelopes and small bubbles lies inside these colors envelops shows members in respective family. Moreover, this software has three levels starting from level 1 to level 3. Bulk materials are placed in level 1 followed by higher number of listed materials in level 2 while level 3 covers almost all the materials exists [9]. Property charts comparison among materials plays a significant role in material selection process and decision of final candidate material. Besides, other factors also contribute in final choice of material i.e. taxation, material availability and geo-politics etc.

Afnan et al. used CES Edupack software to select an optimal material for plaque of radiant gas heaters. Seven different materials were shortlisted by software as per defined property constraint. These seven materials were further screened and ranked using property rating chart method. It is found that Cordierite is the best fit material for plague of radiant gas heaters [10]. Athil & Agadeer used the same software (CES Edupack) to select material for punch and dies. High speed steel was revealed the most promising material [11].

Along with material selection, CES Edupack software is also used for eco-audit to determine product lifecycle assessment [12][13]. Gradin et al. used eco-audit tool of CES Edupack for life cycle assessment of novel car disk brakes [14]. Ikpe et al. used CES software to search material for automotive exhaust system & found that stainless is the most promising material in terms of cost and density [15]. Abdullah et al. used CES software to select alternative materials for hips prothesis and found that annealed and austenitic stainless steel is the best fit material in terms of bio-durability and micromotions [16].

Universal Testing Machine is used to test the axial strengths (Tensile & Compressive) and bending strength of the materials. It is majorly used for testing metals, alloys and ceramics to reveal its property profile for axial and bending loads. Support columns is the major load carrying elements in UTM during materials testing. In addition, the performance of UTM depends on the material used in fabrication of support columns. Therefore, the columns material should be carefully selected to avoid risk of failure as they are essential part of this machine tool. Consequently, in this report, optimal choice of material is identified for UTM support columns using CES Edupack software package.

II. Properties Considered in Materials Selection for UTM Support Columns

Each material has certain attribute profile i.e. cost, density, machineability, tensile and compressive strengths and other mechanical & physical properties which decide its applications [17]–[19]. UTM support columns are the most critical & supporting component in material testing. The following properties considered during materials selection process for UTM support columns includes;

A. Density

Mass per unit volume of a material is called its mass density (kg / m^3). In our case, comparatively low-density material should be preferred to reduce overall weight of the machine tool.

B. Young Modulus

It is the measure of ability of a material to withstand changes in materials dimension during tension or compression (Pa). Young modulus should be high for support columns.

C. Cost

Cost is measured in US $/kg. The cost should be as low as possible.

D. Machinability

The material used should have good machinability for making square threads.

E. Tensile Strength

The ability of a material to withstand the applied load in tension (Pa).

F. Compressive Strength

The ability of a material to withstand the applied load in compression (Pa).

III. Methodology

Level 2 in CES EduPack software is used to find suitable candidate materials for UTM support columns. First it is important to define the required *function, objective(s), constraints and free variables* for the UTM support columns.

- The basic function of these support columns is to support the axial load (both Tensile & Compressive).
- The objective is to select material which has lower cost, feasible and having optimum mass.
- The constraints considered for columns material are; No axial failure upon loading (High strength) --- up to 200 Tons or 2000 kPa, height of column is specified, circular geometry, no buckling failure upon compression, machineability and non-corrosive.
- Free variables include material choice and dimensions.

Using CES Edupack software, material properties charts are developed and suitable candidate materials were selected as per material requirements. The material requirements are shown in table I. Further screening is carried out analytically after material shortlisting using material rating charts. Material with higher rating value will be the preferred for UTM support columns.

TABLE I. MATERIAL REQUIREMENTS

Function	To support axial load
Constraints	• No axial failure upon loading (High strength) --- 200 Ton or 2000 kPa • Height of column is specified • Circular geometry • No buckling failure upon compression • Machineability • Price ≤ 8 US $/kg • Ductile
Objectives	Mass minimization Cost reduction
Free variables	Choice of materials Columns thickness and area

A. Mathematical modeling for Material Index (M)

First seek and develop the Objective function which will describe the quantities to be maximized or minimized,

$$M = A \times h \times \rho \quad \text{----- (1)} \quad \text{(Objective Function)}$$

where "h" is the height of the UTM support columns, 'A' is the area and '$\boldsymbol{\rho}$' is the mass density. 'M' is the Material index in equation 1.

As height is fixed & load is specified, therefore cross-section area & thickness of columns are free variables but area shouldn't be decreased beyond certain limit at which it can't sustain the axial load and buckle easily.

From Appendix B mentioned in the appendices, to avoid buckling of support columns while using small diameter, Euler formula is used;

$$F_{CRIT} = \frac{n^2 \pi^2 E I}{L^2} \text{ -------------- (2)}$$

where 'F_{CRIT}' is the critical force, 'I' is the moment, 'L' is the length & 'E' is the young modulus.

By using hollow columns, the mass can be sufficiently reduced without majorly effecting its strength. From equation (2), moment of inertia of support column is given by;

$$I = \frac{F h^2}{n^2 \pi^2 E} \text{ ---------------------(3)}$$

From fig. 1 snipped from Appendix A, for hollow circular section;

$$A = 2 \pi r t$$

$$I = \pi r^3 t \text{ -----------(4)}$$

Where 'A' is the area, 'r' is the radius and 't' is the thickness.
After simplifying we get;

$$A = \frac{2 I}{r^2} \text{ ---------(5)}$$

Putting equation (4) in (5) we get;

$$A = \frac{2 F h^2}{n^2 \pi^2 E r^2} \text{ ------ (6)}$$

Putting equation (6) in (1) we get;

$$m \geq \frac{2 F h^3 \rho}{n^2 \pi^2 E r^2}$$

$$m \geq \frac{2 F}{n^2 \pi^2} \times \frac{h^3}{r^2} \times \frac{\boldsymbol{\rho}}{\mathbf{E}} \text{ -------------- (7)}$$

Material index, $M = \frac{\rho}{E}$ ---------(Maximize 'M' to Minimize Mass or Density)

Property or group of properties that increase the performance value for a given design is called its material index, M. The shortlisted material choices for support columns will have greater value of E/ρ, where E is the young modulus and ρ is the mass density. Other two indices in equation 7 are associated with maximizing the performance aspects [7], [8].

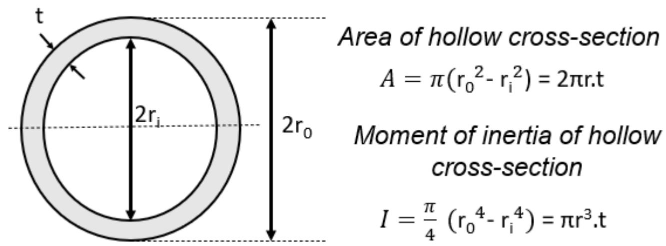

Fig. 1. Area (A) and Moment of inertia (I) for hollow cross section (Appendix A) used during mathematical modelling for UTM support columns

B. Slope for graph between Young Modulus (E) and Density (ρ)

From equation 7 in section IIIA, Material index is given by;

$$M = \frac{E}{\rho}$$

Taking log on both sides, we get;

$$\log(\rho) = \log(E) + \log(C) \text{ ------ (8)}$$

Solving and comparing equation (8) with straight line equation y = mx + c, we get;

Slope = 1

This is the slope value for CES software plot between E & ρ.

IV. Results and Discussions

Various properties limits shown in table I are applied to the material selection process and software selected materials accordingly which includes; Aluminum silicon carbide, Glass ceramics and Stainless steel. After applying limits, software shortlisted only 3 materials among bulky list of available materials. It is very hectic and time consuming to manually check property profile and then select after comparison. Further screening of the shortlisted materials is made on the basis of comparison of their various properties. Software analysis for material selection for support columns and their ranking are shown in fig. 2 to fig. 4

In fig. 2, the limits were applied in the limits section (stage 1) of CES Edupack software for cost which should be equal or less than 8 US $/kg. Others parameters in limits section includes tensile and compressive strength of support columns which has minimum strength limit of 10 MPa. In addition, one absolute property i.e. machinability is defined in the processability section.

The comparison of Young Modulus (E) and Density (ρ) is shown in fig. 3. In fig. 3a, the graph is plotted between E & ρ and slope value of 1 from section III.B is selected in the software.

After defining slope and limits in the software, the materials shortlisted were belong to Glass & Ceramics family (Aluminum silicon carbide, Glass ceramics) and Metal &

Alloys family (Stainless steel) as shown in fig. 3b. Shortlisted materials which fulfilled the design requirements are depicted in fig. 4 that includes Aluminum silicon carbide, Glass ceramics & Stainless steel.

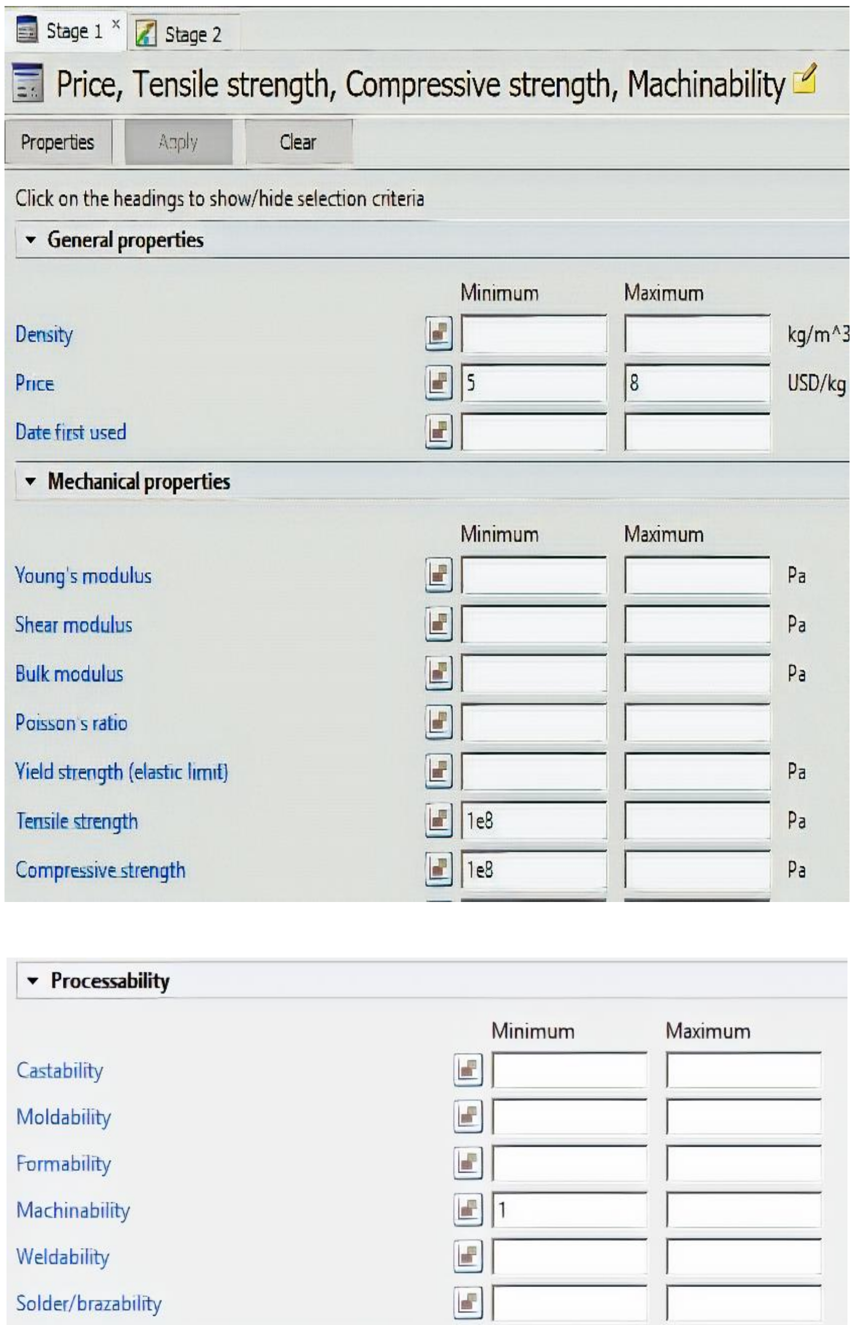

Fig. 2. Limits defined for UTM support columns in stage 1 of CES EduPack software for Cost (US $/ Kg), Tensile & Compressive strength (Pa) & Machinability

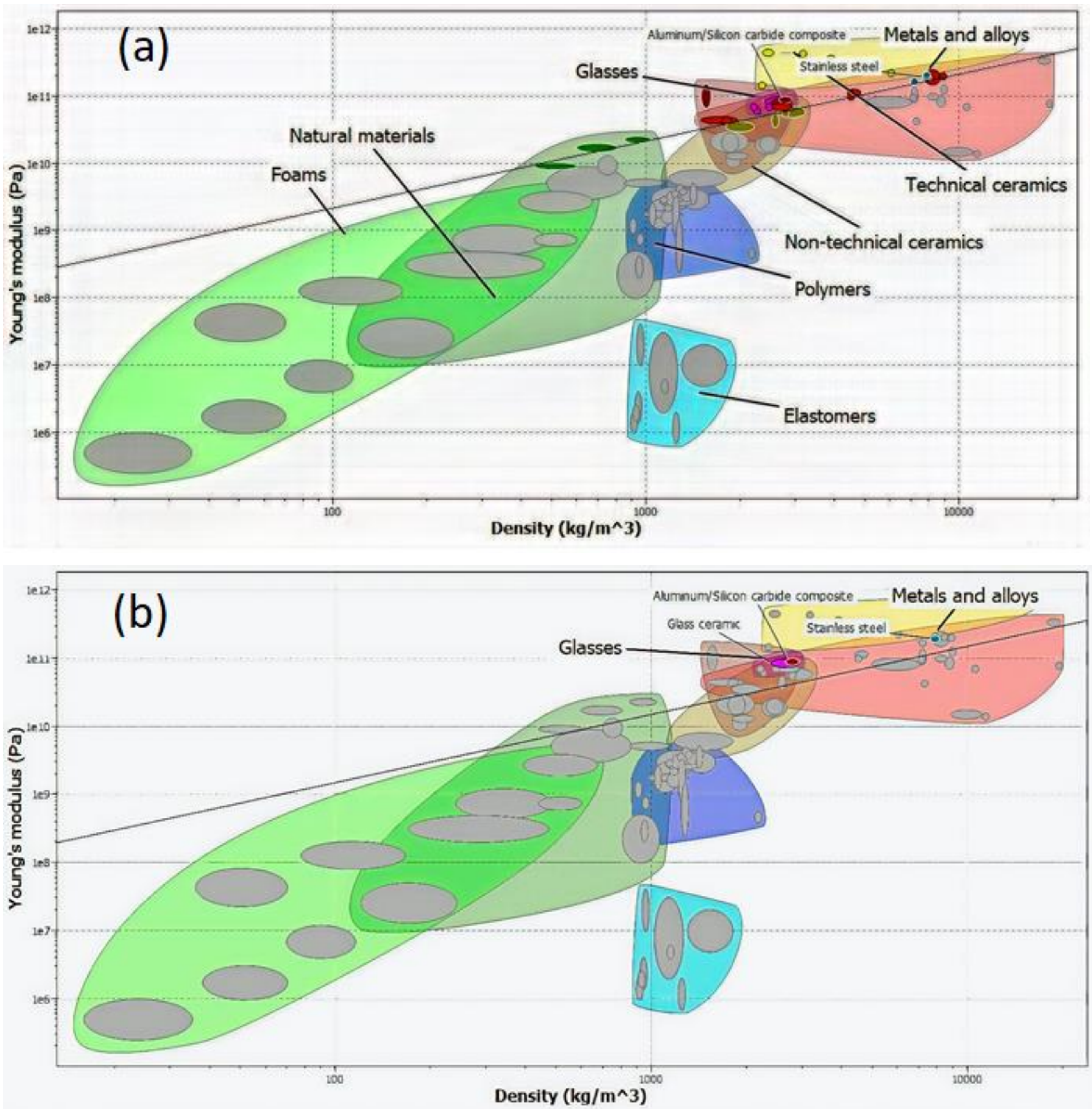

Fig. 3. (a) Plot between Young's Modulus (Pa) vs Density (kg / m^3) labeled with material kingdom using slope value of 1 (b) Young's Modulus (Pa) vs Density (kg / m^3) labeled with shortlisted material classes (Glass, Glass ceramics, Metal & alloys)

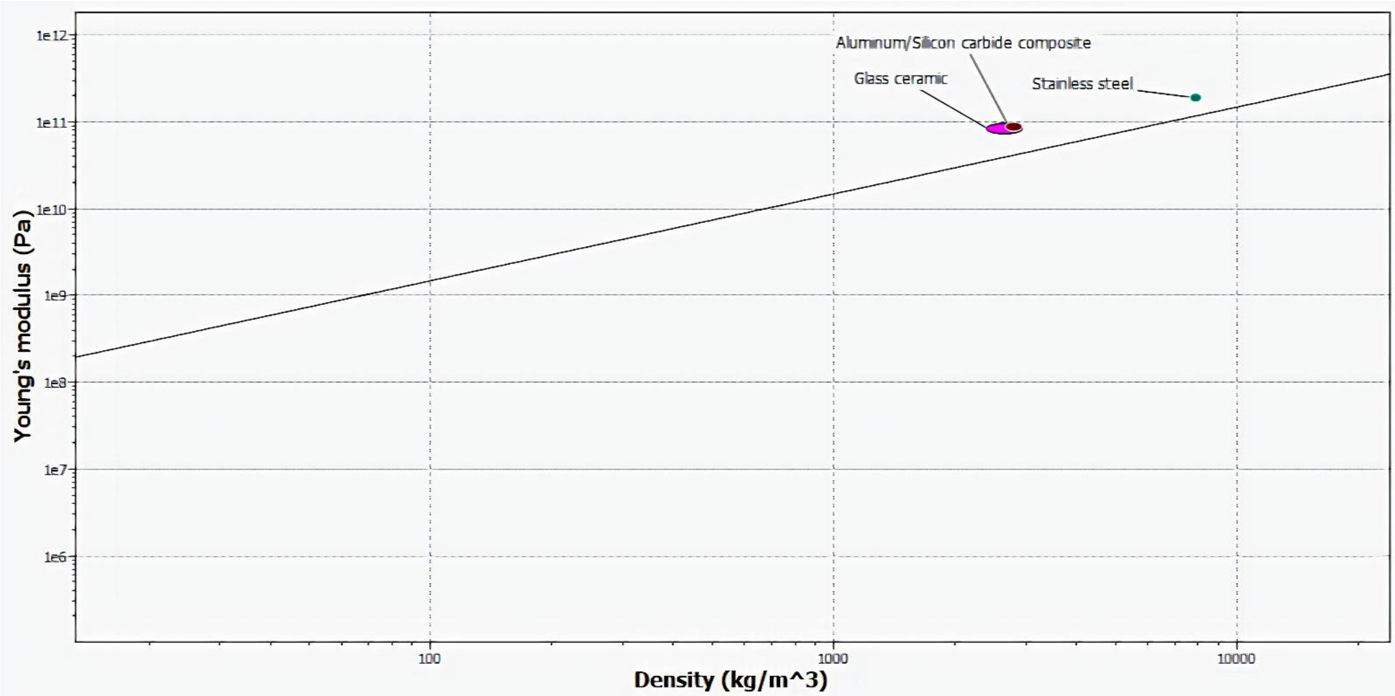

Fig. 4. Shortlisted qualified materials for UTM support columns which include Aluminum silicon carbide, Glass ceramics & Stainless steel

A. Materials Rating Chart

As charts and graphs created using CES software package are shown in fig. 2 to fig. 4 [20] Among three candidate materials, Stainless steel seems most suitable material to meet the design requirements and will be appropriate selection for the support columns of UTM. Moreover, Aluminum silicon carbide and Glass ceramics are also shortlisted to be used for the columns of UTM. But for further scrutiny and verification, screening is made using materials rating chart method depicted in table II, III & IV.

In table II, all defined properties in material requirements were assigned weight factor 'r' (1 to 5) according to their importance in the application. Property rating index 'R' (1 to 5) depicted in table III shows the importance of material response against each property defined in table I. The material should be machinable and that is assigned as Go-No-Go property mentioned in property rating chart.

From table IV, it can be seen that Aluminum silicon carbide and Glass ceramics has rating value of 3.1 and 2.96 out of 5 respectively, which is the minimum rating value among the three candidate materials. Stainless steel has maximum rating value among the candidate materials which is 4.35 out of 5.

TABLE II. WEIGHT FACTOR RATING OF EACH PROPERTY

Property	Weight Factor rating, r
Compressive strength (CS)	5
Tensile strength (TS)	5
Young Modulus (E)	5
Price	5
Ductility (D)	4
Density ρ	4

TABLE III. PROPERTY RATING INDEX

Grade	Property Rating Index, R
Excellent	5
V. Good	4
Good	3
Fair	2
Poor	1

TABLE IV. PROPERTY RATING CHART FOR CANDIDATE MATERIALS

Materials	Go- No-Go	Relative Rating Number, R = property rating index x weighing factor rating						$\sum R$	$\sum r$	$\frac{\sum R}{\sum r}$
	Machinability	CS	TS	E	D	$1/\rho$	Price			
Aluminium Silicon Carbide	Satisfactory	2 x 5	2 x 5	4 x 5	3 x 4	5 x 4	3 x 5	87	28	3.10
Glass Ceramics	Satisfactory	5 x 5	1 x 5	3 x 5	2 x 4	5 x 4	2 x 5	83	28	2.96
Stainless Steel	Satisfactory	4 x 5	5 x 5	5 x 5	5 x 4	3 x 4	5 x 4	122	28	4.35

V. CONCLUSION & RECOMMENDATIONS

Materials for UTM support columns are selected using Granta's design CES Edupack software. Shortlisted materials are Aluminum silicon carbide, Glass ceramics and Stainless steel. All candidate materials fulfill the required criterion for the support columns in one way or another. But for better results, further screening is made through comparison of different properties of these materials using property rating chart method. It is concluded that Stainless steel is the best fit material for the UTM support columns. Moreover, property rating chart in table IV also endorses the findings with highest rating value of 4.35 for Stainless steel. The results further reveal that Aluminum silicon carbide and Glass ceramics cannot be considered as preferred choices for the support columns of UTM. Software and analytical result shows that Stainless steel is the most recommended material for the UTM support columns

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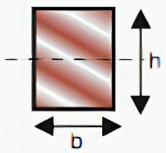
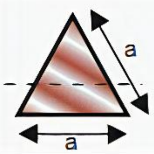
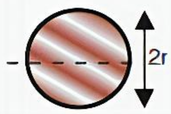
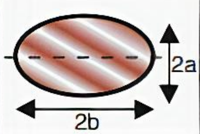
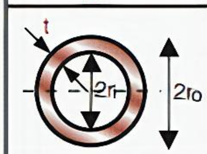
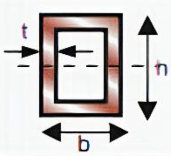
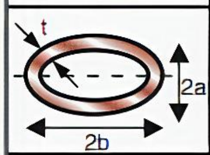
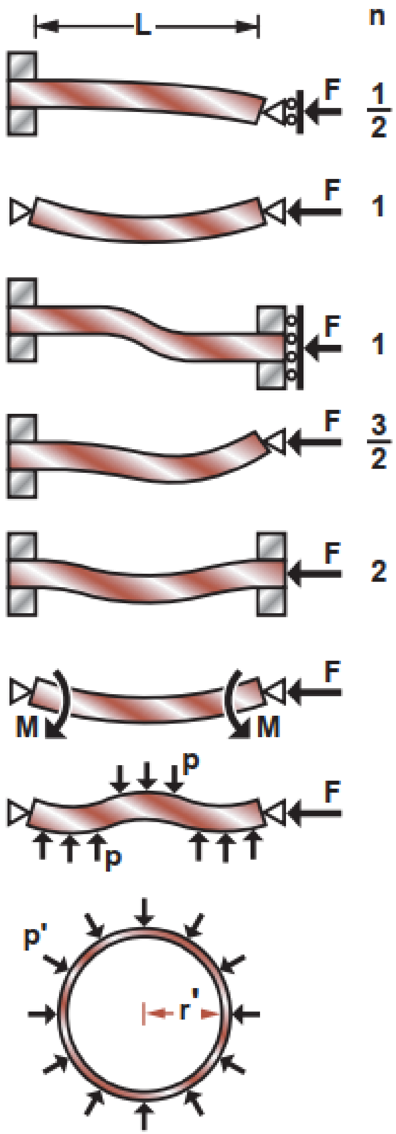
ISSN:1813-1786 (Print) 2313-7770 (Online)

APPENDICES

Appendix A: Moments of Sections

Section shape	Area A m	Moment I m^4	Moment K m^4	Moment Z m^4	Moment Q m^4	Moment Z_p m^4
	bh	$\frac{bh^3}{12}$	$\frac{bh^3}{3}(1\text{-}0\ 58\frac{b}{h})$ $(h > b)$	$\frac{bh^2}{6}$	$\frac{b^2h^2}{(3h+1\ 8b)}$ $(h>b)$	$\frac{bh^2}{4}$
	$\frac{\sqrt{3}}{4}a^2$	$\frac{a^4}{32\sqrt{3}}$	$\frac{\sqrt{3}\,a^4}{80}$	$\frac{a^3}{32}$	$\frac{a^3}{20}$	$\frac{3a^3}{64}$
	πr^2	$\frac{\pi}{4}r^4$	$\frac{\pi}{2}r^4$	$\frac{\pi}{4}r^3$	$\frac{\pi}{2}r^3$	$\frac{\pi}{3}r^3$
	πab	$\frac{\pi}{4}a^3b$	$\frac{\pi a^3b^3}{(a^2+b^2)}$	$\frac{\pi}{4}a^2b$	$\frac{\pi}{2}a^2b$ $(a<b)$	$\frac{\pi}{3}a^2b$
	$\pi(r_o^2 - r_i^2)$ $\approx 2\pi rt$	$\frac{\pi}{4}(r_o^4 - r_i^4)$ $\approx \pi r^3 t$	$\frac{\pi}{2}(r_o^4 - r_i^4)$ $\approx 2\pi r^3 t$	$\frac{\pi}{4r_o}(r_o^4 - r_i^4)$ $\approx \pi r^2 t$	$\frac{\pi}{2r_o}(r_o^4 - r_i^4)$ $\approx 2pr^2 t$	$\frac{\pi}{3}(r_o^3 - r_i^3)$ $\approx \pi r^2 t$
	$2t(h+b)$ $(h,b >> t)$	$\frac{1}{6}h^3t(1+3\frac{b}{h})$	$\frac{2tb^2h^2}{(h+b)}(1-\frac{t}{h})^4$	$\frac{1}{3}h^2t(1+3\frac{b}{h})$	$2tbh(1-\frac{t}{h})^2$	$bht(1+\frac{h}{2b})$
	$\pi(a+b)t$ $(a,b >> t)$	$\frac{\pi}{4}a^3t(1+\frac{3b}{a})$	$\frac{4\pi(ab)^{5/2}t}{(a^2+b^2)}$	$\frac{\pi}{4}a^2t(1+\frac{3b}{a})$	$2\pi t(a^3b)^{1/2}$ $(b>a)$	$\pi abt(2+\frac{a}{b})$

Appendix B: Buckling of columns, plates and shells



$$F_{CRIT} = \frac{n^2 \pi^2 EI}{L^2}$$

or $$\frac{F_{CRIT}}{A} = \frac{n^2 \pi^2 E}{(L/r)^2}$$

I = See Table A2 (m^4)
F = Force (N)
M = Moment (Nm)
E = Youngs modulus (N/m^2)
L = Length (m)
A = Section area (m^2)
r = Gyration radius $(I/A)^{1/2}$ (m)
k = Foundation stiffness (N/m^2)
n = Half-wavelengths in buckled shape
p' = Pressure (N/m^2)

$$F_{CRIT} = \frac{\pi^2 EI}{L^2} - \frac{M^2}{4EI}$$

$$F_{CRIT} = \frac{n^2 \pi^2 EI}{L^2} + \frac{kL^2}{n^2}$$

$$p'_{CRIT} = \frac{3EI}{(r')^3}$$