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Topology Optimisation and Fabrication Aspects for Light Weight Design of an Articulating Beam of Article Launching System

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ABSTRACT

Light weight design of an articulating beam that is utilised for erection mechanism of heavy article (above 15-ton class) is quite challenging task considering high stiffness requirement at erection start mode. The research work presents structural topology optimisation of an articulating beam to obtain optimal material distribution within available space pertaining to required stiffness parameters and boundary constrains. Optimal weight of articulating beam structure is achieved using density optimisation technique aiming minimum compliance and volume. This study highlights problem formulation with solid isotropic material with penalisation optimisation technique with case study followed by discussion on various fabrication aspects for converting the topology results in to feasible design. As an outcome, optimal material design of the articulated beam is achieved that is converted into two feasible light weight designs considering manufacturing aspects. These designs are then validated for their structural adequacy with finite element analysis computing desired stiffness and strength parameters.

Keywords: Topology optimisation; Structural analysis; Finite element analysis; Solid isotropic material

1. INTRODUCTION

An articulating beam is main structural member of an erection mechanism that is used for articulation of an article (above 15-ton class) from horizontal condition to vertical condition. Topology optimisation technique is emerging as conceptualising light weight structural design for various industries without knowing the initial layout of required structure in advance. It is used for obtaining optimal material distribution within available design space defining material density as design variable. Topology optimisation technique implies more design freedom compare to size and shape optimisation techniques, which deal with thicknesses or cross-sectional areas as variables. For structural topology optimisation, solid isotropic material with penalisation (SIMP) is most favoured density based optimisation method which conceives each element as solid material or void followed by penalisation to force solutions to either zero or one (void or solid).

This study presents topology optimisation technique for achieving light weight design of articulating beam without compromising stiffness. An articulating beam of the four bar erection mechanism as shown in Fig. 1. Methodology for problem formulation of topology optimisation based on SIMP technique is presented with case study describing step wise procedure.

Optimal material distribution of the articulating beam is computed by defining minimum volume as objective along with material density as design variable and displacement and volume as state constrains. Based on the output of topology optimisation that reveals optimal material distribution profile, two feasible designs of the articulating beam are proposed. Major fabrication aspects of converting the conceptual design by the optimisation technique to feasible design considering manufacturing aspects are discussed. These proposed feasible designs are validated by finite element analysis (FEA) to check structural adequacy.

The SIMP method was originally developed by[1] fictitious material model defined with density variables are penalised with a basic power and reproduced onto material stiffness[2]. Recent techniques and advancement in topology optimisation are surveyed[3-4]. Continuum structure is considered as porous unit cells defining equivalent material constitutive behaviours e.g. elastic stiffness tensor of each unit cell are formulated with homogenisation. Topological solution is achieved by modifying the corresponding size variables of each unit cell iteratively by[5]

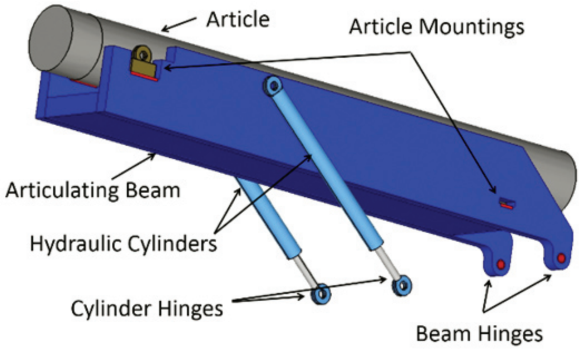

Figure 1. Four bar erection mechanism.

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Convergence properties of the density based SIMP method is discussed[6-7]. Presented an extended SIMP algorithm in which penalisation is applied on direct corner contact by reviewing various suppressing methods for corner contacts between solid elements in topology optimisation[8]. Presented a hybrid method by combining SIMP and Sum of the Reciprocal Variables (SRV) approaches, where SIMP is employed to generate an intermediate solution to initialize the design variables and SRV is then adopted to produce the final design that is claimed effective for topology optimisation problems[9].

Modern topology optimisation algorithms are outcome of research efforts by[2,10,11]. Presently, many commercial organisations have implemented the topology optimisation algorithms which are interfaced with FE software to develop the structural optimisation. e.g, Optistruct by Altair, TOSCA by FE Design are more popular along with other analysis software having features of topology optimisation like MSC Nastran, ABAQUS, ANSYS, etc. Many optimisation problems are solved using the commercial software obtaining light weight designs[12-15].

Though adequate theoretical data is existing towards topology optimisation methods, practical solutions with topology optimisation of an articulation beam and kind structures are seldom available.

A general structural optimisation problem can be described by an objective function (f) that could either be maximised or minimised as in Eqn. (1).

$$\begin{cases} \text{min/max } x & f(x,\ y(x)) \\ \text{subjected to} & \begin{cases} \text{design constrain on } x \\ \text{state constrain on } y(x) \\ \text{equilibrim constrain} \end{cases} \end{cases} \tag{1}$$

Typically, volume or compliance (reciprocal of stiffness) is chosen as an objective function. design variable (x) represents density as state variable, (y) represents structural response that may be displacement or stress. The state variable depends on design variable $y(x)$. The overall objective function is set to minimise or maximise the state, subjected to design variables and constrains to get feasible optimal solution.

The objective function can also be formulated as combination of several objectives as in Eqn. (2).

$$\min x\, f\left(f_1(x,y), f_2(x,y), (x)..., f_n(x,y),\right) \tag{2}$$

A state function $g(y)$ represents the state variable. e.g. displacement in particular direction. This state function considered as a constrain to optimisation objective, which is defined as $g(y) \leq 0$. Defining $g(y)$ for any nodal displacement as $g(u(x))$. Then the nodal displacement is solved as in Eqn. 3 to get the state function.

$$u(x) = K(x)^{-1} F(x) \tag{3}$$

where K represents global stiffness matrix and F represents global force vector. Finally, the optimisation objective can be defined as in Eqn. (4)

$$\begin{cases} \min x & f(x) \\ \text{Subjected to} & g\left(u(x)\right) \leq 0 \end{cases} \tag{4}$$

The above equation is solved by computing derivatives of f and g with respect to x. For structural optimisation problem, x represents geometry data. Based the defined geometrical data, the optimisation can be classified as size, shape or topology optimisation.

1.1 Topology Optimisation Formulation

Computation of optimal material distribution is the method where the design or referenced domain Φ is discretised into void and solid elements by a FE discretisation. In mathematical terms we compute an optimal subset Φ_m pertaining to Φ .The design variable x can be presented by density vector ρ . The local stiffness tensor E can be formulated by incorporating ρ as in Eqn. (5).

$$E(\rho) = \rho(E)^0$$

$$\rho_e = \begin{cases} 1 & if\ e \in \Phi_m \\ 0 & if\ e \in \Phi/\Phi_m \end{cases} \tag{5}$$

And a volume constraint,

$$\int \rho d\Phi = Vol\left(\Phi_m\right) \leq V \tag{6}$$

V is the volume of initial design domain. Here, the gradient based optimisation solution method is considered in which Eqn. (6) is formulated as a continuous function such that density function can be defined between 1 and 0. The density function is then written as in Eqn. (7).

$$E = \rho^p E^0 \tag{7}$$

where, $\rho \in [\ \rho_{\min}, 1] p > 1$

$p =$ penalizing factor

The p, penalizes all elements having intermediate densities to get the value of either 1 or 0, $\rho_{\min}$ represents lower density value limit to avoid singularities. E.g. for any material having Poisson ratio $\upsilon = 0.3$, it is suggested to use $p \geq 3$. Typically, compliance and volume are defined as topology optimisation problem.

To minimise compliance, equivalent strain energy of FE solution which yields higher stiffness can be defined as in Eqn. (8).

$$C(\rho) = (f)^T u \tag{8}$$

where $f = K(\rho)u \quad K(\rho) = \sum_{e=1}^{n} \rho_e^p \mathrm{K}_e^0$

K_e^0 represents elemental stiffness matrix. Volume constrain is also added to prevent the solution, ending up with total design volume to achieve minimum compliance.

2. TOPOLOGY OPTIMISATION OF ARTICULATING BEAM

Major components of the articulation/erection mechanism are shown in Fig. 1.The four bar erection mechanism is used for transportation (Fig. 2) and erection of heavy article from horizontal (0°) position to vertical (90°) position (Fig. 3).

Stepwise procedure for defining the topology optimisation of the articulation beam of a four bar mechanism is mentioned follows:

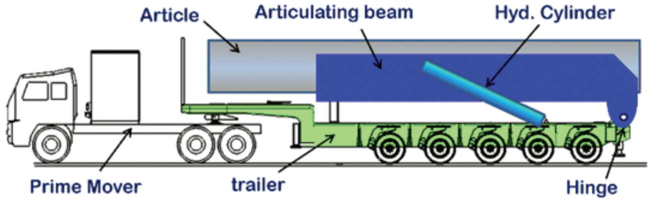

Figure 2. Four bar erection mechanism (transportation mode).

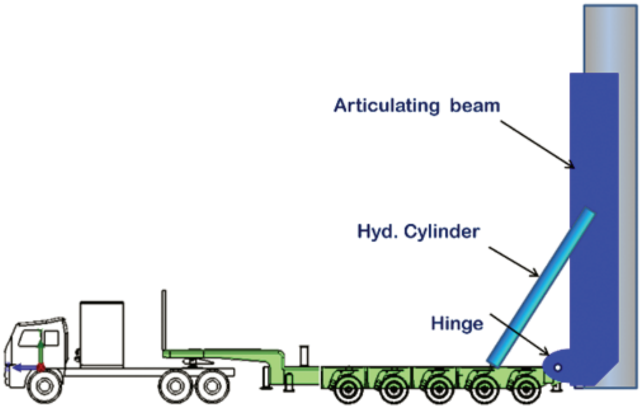

Figure 3. Four bar erection mechanism (erection mode).

(a) Recognition of most critical load cases out of various loading and boundary conditions. For this case study, articulation start mode (0^0) is recognised as most critical case since maximum deflection of articulation beam is observed. The study is carried out by FEA with linear static analysis for various cases. E.g. transportation mode, articulation modes from beam horizontal condition to vertical condition. (0^0 to 90^0).

(b) Assignment of available design space. Design space is defined by considering required space for mounting of article, hydraulic cylinders, lifting points, etc.

(c) FE modelling for the topology optimisation. This has been created for design and non-design space using 3D (solid) elements considering symmetric conditions along longitudinal axis. Detailed parameters of the FE model for optimisation are mentioned at Table 1.

Table 1. FE model parameters for topology optimisation

Parameter	Value
No. of HexagonalElements	39925 Nos.
No. of Pentagonal Elements	15 Nos.
No. of Nodes	50019 Nos.
No. of Rigid Elements	03 Nos.
No.of Degrees of Freedom	150812 Nos.
Average Element Size	40 mm

(d) Definition of boundary and loading conditions. Boundary and loading conditions are illustrated in Fig. 4. Beam hinge and cylinder hinge are defined as pin joints. Article load of 12 t and 3.35 t is applied at front and rear supports respectively. Payload details is mentioned at Table 2.

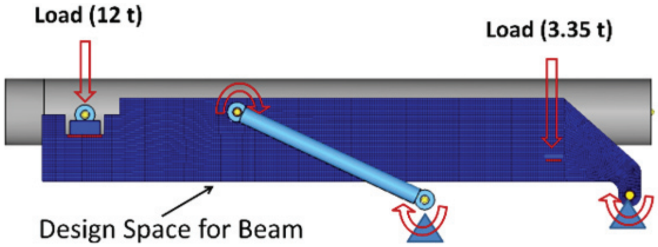

Figure 4. Boundary conditions and design space.

Table 2. Payload and available space

Total Payload of article	15.35 t
Space for Articulation Beam (Approx.) (LxWxH)	10.2 x 1.95 x 1.5 m (excluding article space)
Article C.G. (From front)	5.8 m

(e) Definition of topology optimisation parameters. Optistruct software is used as solver with pre-processing in Hyper mesh followed by post-processing in Hyper view. Various topology optimisation parameters are tabulated in the Table 3. For this kind of structure, maximum deflection in erection start mode (article horizontal condition) is critical constrain for overall design of an articulating beam that is to be determined based on allowable deflection of an article. For this case study, the authors have considered 10 mm maximum allowable deflection (in vertical downward direction)as constrain for defining the optimisation parameters.

Table 3. Topology optimisation parameters

Objective function	Minimise volume
Design variable	Element Density
State constrain	
Static deflection	10 mm (vertical downward)
Response load case	Static FE analysis
Response	Static deflection and Total volume

(f) Computational solution with FE solver. Solution is completed with specified optimisation parameters followed by solutions for other critical load cases. e.g. articulation at 20°.

3 OPTIMISATION RESULTS AND DISCUSSION

After convergence of the iterative functions by the solver, density plots are generated that describes distribution of material density over the design space. Figure 5 shows material density plot for given loading conditions for articulation start mode (0°). Similarly Fig. 6 shows material density plot for 20° articulation mode.

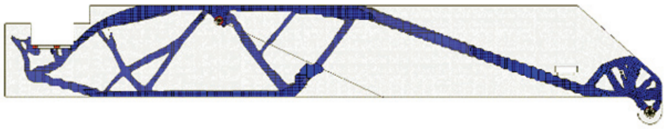

Figure 5. Material density plot for articulation start mode (0°).

Figure 6. Material density plot for articulation (20°).

The density plots describe optimised design in form of solid materials. The material distribution profile required to be converted in to feasible design, considering fabrication aspects. Accordingly, authors have proposed two feasible designs, design 1 (Fig. 7) having members with mainly circular sections and design 2 (Fig. 8) having members with rectangular sections. These two feasible designs are proposed with structural steel material having yield strength of around 450 N/mm^2 to 550 N/mm^2 depending on required factor of safety. The authors have proposed this two designs considering members with standard sections and steel plates with standard thickness available in market. This designs are claimed to be lightweight without compromising required stiffness parameter.

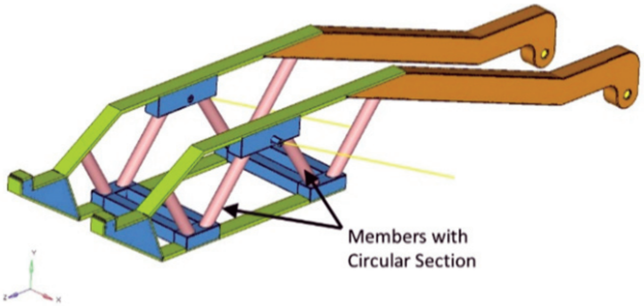

Figure 7. Design 1: Articulating beam with circular sections.

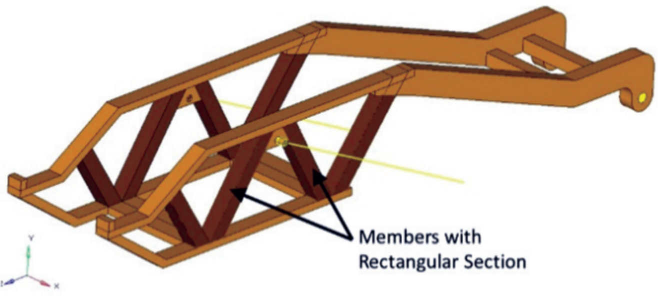

Figure 8. Design 2: Articulating beam with rectangular sections.

The following major fabrication aspects are discussed for the feasible designs of the articulating beam:

(a) Based on the material density plots (Figs. 5 and 6), many designs of the articulating beam are possible using various longitudinal and cross members of solid section, I-section, C-section, circular section, box section, etc. however the density plots clearly gives the idea for numbers and configuration of various members for designing the articulating beam.

(b) Considering overall dimensions (10200 mm x 1950 mm x 1500 mm) of the beam, overall weight and joining of various members with each other, the authors have proposed to consider box (tubular) sections instead of solid sections for designing longitudinal and cross members.

(c) It is observed by the density plots that rear article mounting support is optimised with minimum material due to lesser article load at rear in erection start mode. However, it is recommended to provide sufficient support for rear mounting support considering other articulation modes (vertical condition).

(d) It is observed that span of the members of the beam is increasing for articulation (20°) (Fig. 6) compare to articulation at (0°) (Fig. 5).

(e) Design 1(circular sections) has more welding difficulties for connecting longitudinal members with cross members and at article mounting supports compare to design 2 (rectangular section).

(f) Design 2 (rectangular sections) enables unique characteristic for fabrication of all longitudinal members from single metal sheets minimising welding in longitudinal plane which is important aspect for minimising welding failures.

(g) Design 2 provides easy mounting arrangement of hydraulic cylinder and other supports compare to design 1 reducing weight of these mounting brackets.

(h) It is observed that design with box sections members results in lesser weight compare design with circular section members.

4 DESIGN VALIDATION

Both the derived designs of the articulation beam are validated with FE analysis for structural adequacy and maximum deflection parameters.

4.1 FE Analysis of Proposed Designs

Linear static FE analysis of the proposed two designs has been carried out by creating FE models using mainly 2D shell elements with suitable connection elements. Detailed parameters of the FE models for design 1 and design 2 are mentioned at Table 4.

Table 4. FE model parameters for proposed designs

Parameter	Design-1 (circular)	Design-2 (rectangular)
Quad. elements	267300	143546
Tria. elements	22	730
Nodes	267101	142637
Rigid elements	6	6
DOF	1602568	855770
Average element size	12 mm	15 mm

4.2 Verification of FE Results

The FE results of the linear static analysis of the proposed designs are summarised at Table 5. To verify the FE analysis, the following two computational criteria are considered: -

(a) Reaction forces
(b) Mesh conversion study

The vertical reaction forces (Table 5) are computed by FE analysis and compared with the applied forces (weight of article and articulating beam). It is observed that applied forces are matching with reaction forces.

Table 5. FE results summary

	Max. deflection (mm)	Max. stress (MPa)	Beam weight (t)	Reaction forces x 10^5 (N)	
				Beam hinge	Cylinder hinge
Design 1	6.7	373	8.4	-1.08	4.92
Design 2	6.6	290	5.4	-1.07	4.61

Mesh convergence study is carried out by varying element size of the FE models particularly at high stress regions for both designs as tabulated in Table: 6. Graphical representation of the stress conversation study is plotted at Fig. 9.

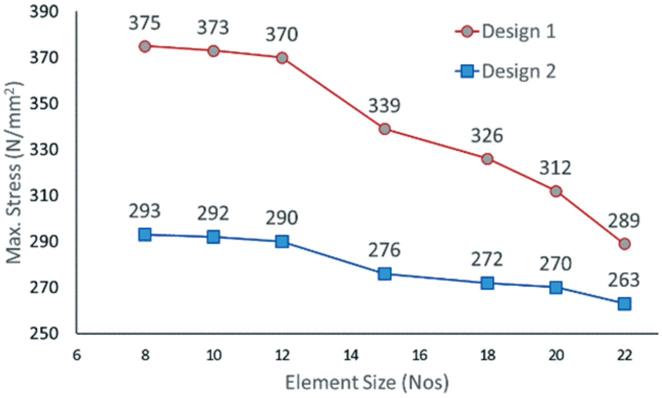

Figure 9. Stress conversion chart.

Table 6. Mesh conversion study

Element size	Design 1 (Circular sections)		Design 2 (Rectangular sections)	
	Max. stress (N/mm^2)	Maximum displacement (mm)	Max. stress (N/mm^2)	Maximum displacement (mm)
22	289	6.87	263	6.69
20	312	6.85	270	6.68
18	326	6.85	272	6.68
15	339	6.81	276	6.65
12	370	6.77	290	6.62
10	373	6.76	292	6.62
8	375	6.76	293	6.62

Both the designs are compared in graphical chart representation as shown in Fig. 10.

4.3 Discussion of FE Results

Displacement and stress plots of the derived design 1 (circular sections) are presented in Figs. 11 and 12, respectively for the articulation start mode. Similarly, displacement and stress plots of the derived design 2 (rectangular section) are presented in Figs. 13 and 14, respectively.

The linear static FE results are summarised at Table 5. It is observed from the displacement plots (Figs. 11 and 13) that both the designs provide required stiffness indicating maximum deflection around 6.7 mm is within limit (less than 10 mm). Stress plots (Figs. 12 and 14) shows both the designs are safe for structural strength considering yield strength of 450 N/mm^2 for the beam material. Design 1 provides factor of safety of around 1.2 compare to factor of safety of around 1.6 of design 2. However max stress could be further reduced with local stiffening at high stress regions. Clearly, design 2 provides lesser weight 5.4 t against 8.4 t of design 1. Hence design 2 is recommended for this kind of articulating beam structures.

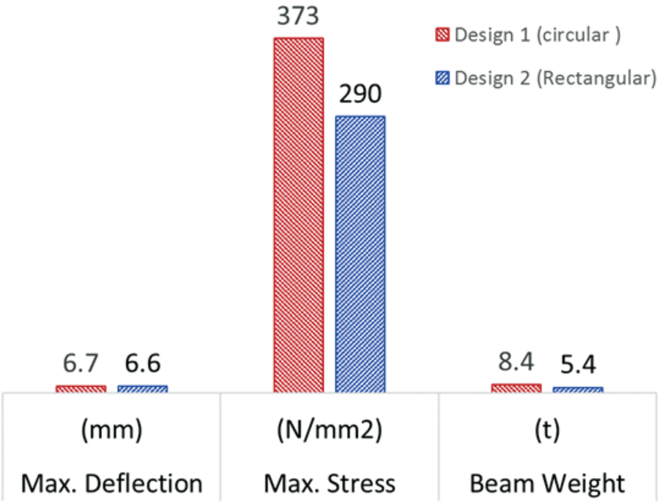

Figure 10. FE results summary of Design 1 and Design 2.

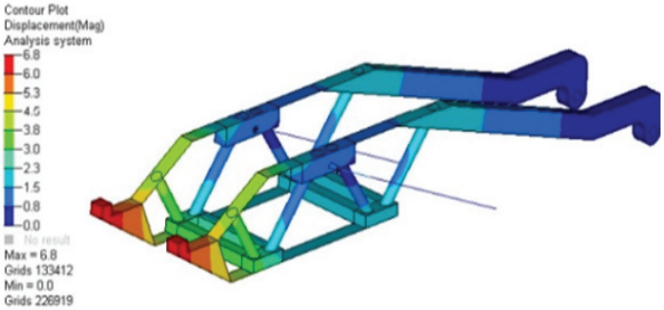

Figure 11. Displacement plot Design 1 (Circular sections)

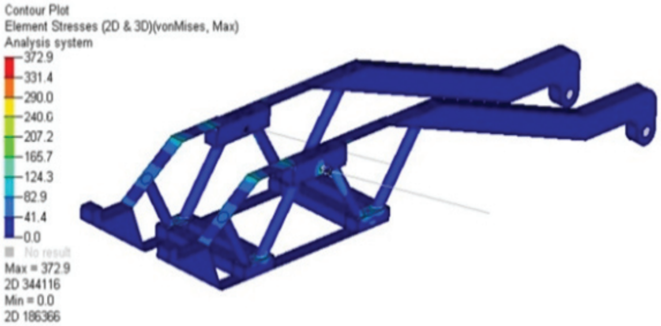

Figure 12. Stress (Von Mises) Design 1 (Circular sections).

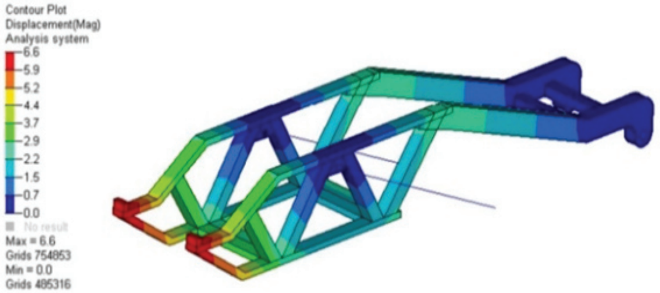

Figure 13. Displacement plot Design 2 (Rectangular sections).

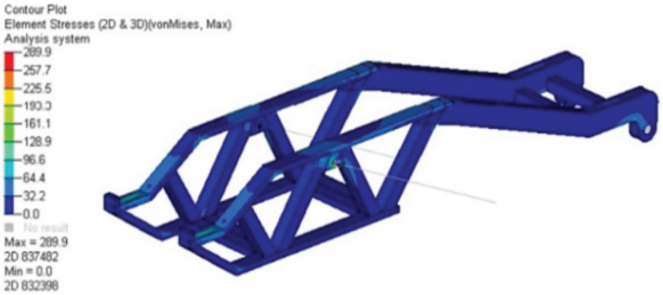

Figure 14. Stress (Von Mises) Design 2 (Rectangular sections).

5 CONCLUSIONS

A computational approach for lightweight design of an articulating beam kind of structure is introduced by topology optimisation with FE analysis that eliminates manual design iterations. Various optimisation parameters are discussed with applicable boundary and loading conditions for defining the topology optimisation problem. Results of the output density plots are discussed and converted in to two feasible designs considering various manufacturing aspects. The feasible designs are validated by linear static FE analysis. The following major observation are derived by the research work:

(a) Topology optimisation provides optimal material distribution layout for initial design of an articulating beam without manual iterations.
(b) It is recommended to consider box (tubular) sections instead of solid sections (as computed by topology optimisation) for various longitudinal and cross members considering manufacturing and cost aspects.
(c) Since optimisation output varies with varying boundary and loading conditions, it is recommended to consider effect of all critical load cases for freezing the optimal design rather than considering only worst load case.
(d) It is compared that design with circular sections have more welding difficulties for connecting longitudinal members with cross members and other mounting supports compare to design with rectangular box sections.
(e) Beam design with box sections enables unique characteristic for fabrication of all longitudinal members from single metal sheets that avoids welding in longitudinal plane which is important aspect for minimising welding failures.
(f) Beam design with members of box sections results in lesser weight compare to members with circular sections.

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In the present work, he has carried out topology optimisation analysis, various fabrication aspects for converting optimised design to feasible design and validation of the optimised design through FE analysis.

Mr Vinaykumar Rokade obtained his MTech (Mechanical Engineering) (Armament/combat vehicles) from Defence Institute of Advanced Technology, Pune, in 2014. Currently he is working as Scientist ‘E’, at Specialist Vehicle Division, DRDO-Vehicles Research and Development Establishment, Ahmednagar. His research interests are in the areas of design and development of article launching systems.

In the present work, he was involved in validation of the optimised design through FE analysis and fabrication aspects of the designs.