STRUCTURAL DESIGN OF A LOAD TEST RIG AND DESIGN EVALUATION USING FEM

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***Abstract*— This paper deals with structural design and analysis of a test rig for testing of critical components used for aerospace applications. The loads on the components mounted in the test are applied through hydraulic actuator. The test rig is made of various structural members such as I-section, C-section, L-section, etc. Selection of sections for fabricating the test rig will be dictated by detailed load assessment of the test rig.**

***Index Terms*— design, finite element analysis, structural members**

I. INTRODUCTION

Dimensional model of the test rigs are worked out based on the space limitations. Then the loads experienced by the test rig is estimated. Based on this standard cross-sections with dimensions will be chosen. Apart from this load transfer between individual sections of the test rig also is to be studied. Depending on the requirement to supplement the loads getting transformed to the sections members like gussets will be added to the test rig. In addition to this mechanism of joining individual sections (Bolted joints, Welded joints, etc.) also required to be considered while designing the test rig. Sufficient design margins are required to be adopted in the design. Once the design configuration of test rig is completed detailed structural analysis will be carried out using Finite Element Method (FEM). Design adequacy will be assessed and available factor of safety will be calculated from FE analysis. Based on the analysis results the design of the test rig will be fine tuned if necessary. The out come of this project would be a structural design configuration of a load test rig, which can be used for structural testing of aerospace components.

Structural Elements

As structural design of a load test rig is taken up in this project, it is essential to understand about various aspects of structures. Especially attention is required to be focused on various structural elements. This chapter brings out various structural elements, which play a vital role in design of any structural test rig

Beams

A beam which is a structural element that is capable of withstanding load primarily by resisting bending. The bending force induced into the material of the beam as a result of the external loads, own weight and external reactions to these loads is called a bending moment.

Beams generally carry vertical gravitational forces but can also be used to carry horizontal loads (i.e., loads due to an earthquake or wind). The loads carried by a beam are transferred to columns, walls, or girders, which then transfer the force to adjacent structural compression members. In Light frame construction the joists rest on the beam.

Bending Of Beams

When a beam experiences a bending moment it will change its shape and internal stresses (forces) will be developed. The above figure illustrates the shape change of elements of a beam in bending. Note that the material is in compression on the inside of the curve and tension on the outside of the curve, and that transverse planes in the material remain parallel to the radius during bending.

I – BEAMS: I- are beams with an I- or H-shaped cross-section. The horizontal elements are flanges, while the vertical element is the web. The Euler-Bernoulli beam equation shows that this is a very efficient form for carrying both bending and shear in the plane of the web. On the other hand, the cross-section has a reduced capacity in the transverse direction, and is also inefficient in carrying torsion, for which hollow structural sections are often preferred (Figure 1)

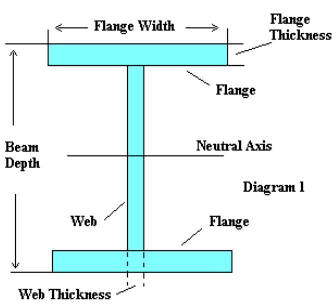


Fig 1: I – Beam

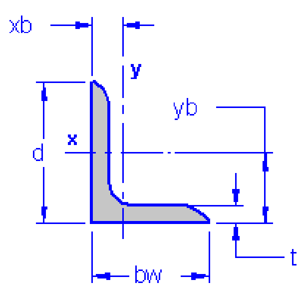


Fig 2: Angle section

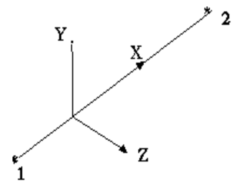
Angle Sections

Steel angle sections (Fig 2) are commonly used as beams to support distributed loads, which cause biaxial bending and torsion. However, the recommendations of many design codes are unnecessarily conservative when applied to the bending of angle section beams, or are of limited application, or fail to consider some effects, which are thought to be important. In this paper, consideration is given to the first-order elastic analysis of the biaxial bending of angle section beams including the effects of elastic restraints, and proposals are developed for the section moment capacities of angle sections under biaxial bending which approximate the effects of full plasticity in compact sections, first yield in semi compact sections, and local buckling in slender sections. Proposals are developed for the bearing, shear, and uniform torsion capacities of angle section beams in a companion paper. The proposals in this and the companion paper can be used to design steel angle section beams, which are laterally restrained so that lateral buckling or second-order effects are unimportant.

II. APPLICATION OF FINITE ELEMENTS IN STRUCTURAL ANALYSIS

Though wide varieties of elements are available discussion is limited to the following element, which is considered for the present problem.

1 – D linear two-nodded beam element



The element X axis is the beam centroidal axis and is directed from node 1 (the fore end) to node 2 (the aft end). The element Y and Z axes are the principal axes of the cross section.

Cross sectional properties:

Stiffness properties: area	Cross-section area Y & Z area moments of inertia Y & Z shear area ratios
Stiffness properties: torsional	Torsional constant Warping constant Warping restraint factor
Stiffness properties: eccentricities	Y & Z eccentricities
Stress recovery data	Y & Z stress recovery distances Effective radius in torsion
Nonlinear properties	Plastic section modulus about element Y or Z axes Plastic torsional section modulus

Beam geometric data:

Orientation node / angle
Elastic foundation stiffness in Y and/or Z direction
Fore and aft rigid links (end offsets)
Fore and aft end releases

Output:

- Displacements
- Strains
- Elastic strain energy
- Plastic strains (nonlinear structural)
- Creep strains (nonlinear structural)
- Reaction forces
- Element forces
- Stresses

Physical Properties

Nonstructural Mass

Use nonstructural mass to model mass effects (such as an attached structure) which are independent of element volume. Use nonstructural mass only when inertia loadings are present.

Yield Function Constants (Nonlinear Structural Analysis Only)

In a plasticity analysis, the beam is treated as elastic until a plastic hinge forms. This hinge forms when one of the following yield function equations is satisfied.

For non-circular cross sections:

$$C_1 \left|\frac{P}{P_m}\right|^{C_2} + C_3 \left|\frac{M_y}{M_{Py}}\right|^{C_4} + C_5 \left|\frac{M_z}{M_{Pz}}\right|^{C_6} + C_7 \left|\frac{T}{T_P}\right|^{C_8}$$

For circular cross sections:

$$C_9 \left|\frac{P}{P_m}\right|^{C_{10}} + \left[\left|\frac{M_Y}{M_{Py}}\right|^2 + \left|\frac{M_z}{M_{Pz}}\right|^2 + C_{11} \left|\frac{T}{T_P}\right|^2\right]^{C_{12}} \geq 1.0$$

Where

P = axial force

M_y = bending moment about Y axis

M_z = bending moment about Z axis

T = torque

P_m =Y * A

M_{Py} = plastic moment about the Y axis = Y * Z_y

M_{Pz} = plastic moment about the Z axis = Y * Z_z

T_P = plastic torque = Y * Z_t

Y = yield stress

A = area of cross section

Z_y = plastic section modulus about the X axis

Z_z = plastic section modulus about the Z axis

Z_t = plastic torque

C_1 - C_{12} = user definable constants

C_1-C_{11} default to 1.0. C_{12} defaults to 0.5.

Material Type

Isotropic :

Use material density to model the mass effects of the beam element volume.

Stiffness Properties: torsional

Torsional constant is a value which satisfies the following equations:

$$\text{Rotation (in radians)} = \frac{\text{Applied torque * Length}}{\text{Shear Modulus * Torsional Constant}}$$

$$\text{Dimensions of Torsional Constant} = (\text{Length})^4$$

III. STRUCTURAL ANALYSIS OF LOAD TEST RIG USING FEM

A load test rig is designed based on stiffness based design. To begin with basic dimensional model of the test rig is worked out considering the dimensional constraints. Standard sections like C – section, I – section and L – section are considered as load bearing members for the load test rig. Various design configurations are evolved by varying the dimensions of these sections. The objective behind varying the dimensions is to arrive at an optimized configuration i.e. configuration having high stiffness to weight ratio. Structural analysis is carried out using Finite Element Method (FEM) to evaluate stiffness to weight ratio for all the configurations. As the proposed design is stiffness based design displacement is calculated for each configuration against the actuator load, which the test rig is supposed to hold. As the displacement inversely varies with stiffness, configuration which exhibits less displacement with least weight is preferred for fabrication. This chapter brings out the details of finite element analysis and subsequently the results.

Construction of load test rig

The load test rig is basically a frame type of construction. The overall dimensions of the test rig are considered to be 5000 mm x 5000 mm x 5000 mm based on the space constraints. It is modular in nature and consists of two modules equispaced along one dimension. Standard sections are considered as load bearing members. For top member from which Actuator of 100 KN load will be suspended I – section is considered. L - Section is considered for all bottom members. For all other members C – section is considered. However bottom plate portion on which unit under test will be positioned is not considered for analysis as no part of load gets transfers to it. Test rig will be grouted at its bottom. Wire frame model (Dimensional model of test rig without sections) and Solid model (Test rig with sections) of the test rig is shown in Figure 3

Material properties:

Material	Young's modulus (E)	Poisson's ratio (μ)	Density (ρ)
Medium Steel	2.1 x 10^{11} MPa	0.25	7820 Kg/m^3

Boundary conditions& Loads:

Analysis of test rig (C – 400, I – 400 & L – 100)

Dimensions of sections considered for this configuration are given below:

Sl. No.	Dimension of the section	C - section mm	I - section mm	L - section mm
1.	Depth, H	400	400	100
2.	Width, W	100	140	100
3.	Thickness of flange, Tf	15.3	16	6
4.	Thickness of web, Tw	8.6	8.9	6

IV. RESULTS AND DISCUSSIONS

Displacements obtained using FEM along with the weights for various configurations with sections having different dimensions are summarized.

Influence of varying dimensions of C – section

Displacements obtained along with the weights for different sizes of C – section are summarized in the following Table 1.

Observations:

1. With increasing the size of C – section stiffness to weight ratio got increased. Reason for this can be attributed to the fact that C – section is contributing more to the stiffness than to the weight.
2. Maximum stiffness to weight ratio obtained with C – section for size of 400 mm is observed to be 0.034.
3. With increasing the size of I – section stiffness to weight ratio almost remain unchanged. Reason for this can be attributed to the fact that contribution of I – section towards stiffness and weight is identical.
4. With increasing the size of L – section stiffness to weight ratio got decreased. Reason for this can be attributed to the fact that L – section is contributing more to the weight than to the stiffness.

Table 1: C-Section FEA results

S. No	C mm	I mm	L mm	Displacement (mm)	Wt. Kg	stiffness to wt ratio
1.	100	100	100	331	823	0.004
2.	200			57.4	1529	0.011
3.	300			19.6	2273	0.022
4.	400			9.87	3011	0.034

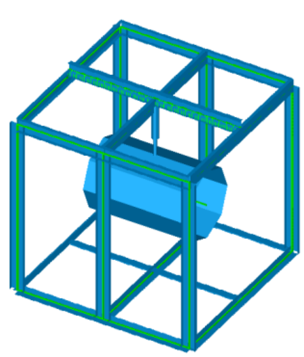


Fig 3 Solid Model of Test Rig

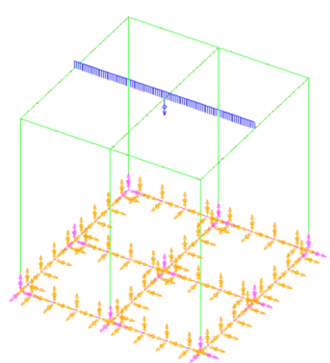


Fig 4 FE model of test rig

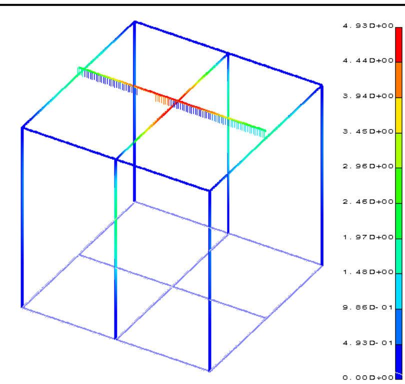


Fig 5 FEA result

Table 2: I-Section FEA results

S. No	**C** (mm)	**I** (mm)	**L** (mm	**Displacement** (mm)	**Wt.** (Kg)	**Stiffness to wt ratio**
1	100	100	100	331	823	0.004
2		200		213	892	0.005
3		300		195	984	0.005
4		400		191	1071	0.005

Table 3: L-Section FEA results

Sl. No	C mm	I mm	L mm	Displacement mm	Wt Kg	Stiffness to wt ratio
1	100	100	100	331	823	0.004
2			200	331	1642	0.002

Table 4: Overall summary

Sl. No	**C mm**	**I mm**	**L mm**	**Displacement (mm)**	**Wt (kg)**	**Stiffness to wt ratio**
1	100	100	100	331	823	0.004
2	100	100	200	331	1642	0.002
3	100	200	100	213	892	0.005
4	100	200	200	213	1711	0.003
5	100	300	100	195	984	0.005
6	100	300	200	195	1803	0.003
7	100	400	100	191	1071	0.005
8	**400**	**400**	**100**	**4.93**	**3259**	**0.062**
9	400	400	200	4.93	4078	0.049

V. CONCLUSIONS

A test rig is designed based on stiffness based design, which will act as a basic load-supporting platform for hydraulic actuators will be used to simulate desired loads on aero space components. To begin with basic dimensional model of the test rig is worked out considering the dimensional constraints.

Standard sections like C – section, I – section and L – section are considered as load bearing members for the load test rig. Various design configurations are evolved by varying the dimensions of these sections. The objective behind varying the dimensions is to arrive at an optimized configuration i.e. configuration having high stiffness to weight ratio. Sufficient design margins are required to be adopted in the design. Structural analysis is carried out using Finite Element Method (FEM) to evaluate stiffness to weight ratio for all the configurations. As the proposed design is a stiffness based design displacement is calculated for each configuration against the actuator load, which the test rig is supposed to hold. As the displacement inversely varies with stiffness, configuration which exhibits less displacement with least weight is preferred for fabrication.

An optimum configuration (C – section of 400 mm size, I – section of 400 mm size and L – section of 100 mm size), which is evolved based on stiffness to weight ratio as figure of merit obtained from structural analysis is recommended for fabrication of load test rig.

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