Finite Element Analysis And Design Optimization of A Lifting Clamp For Different Materials

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Abstract- *A lifting clamp mechanism is most widely used for the lifting of heavy steel roll coils. The clamp grab has been used in the steel and iron industry for the last two centuries. Because of the clamp's simplicity, suitability for use in the worst mill duty environments, and long-term reliability, the clamp has a wide appeal to a large spectrum of users. Steel mills are used because they were designed in a way which can withstand high pressure and are not affected to electromagnetic interferences, and can also with stand the shock loads.*

The lifting clamp used to vertically lift the I-section beams is designed in this project. The working load limit of the lifting clamp considered is 2 Tons with a jaw capacity of 25 mm. Initially the design calculations are carried out using simple design equations and later the 3-Dimensional modeling of the lifting clamp is to be designed using Catia software. The 3d model is imported into Ansys software and structural analysis of the lifting clamp is carried out. The deflections and the stresses developed in the finite element analysis of the clamp are documented. The life estimation of the clamp is also calculated from the analysis, later the design optimization has to be performed along with varying the convectional material based on the results obtained from the CAE software. The best of the designs with the possible appropriate material has to be proposed.

Keywords- Lifting clamp, High pressure, Design calculations, Different materials, Fatigue life estimation, 2 tons weight.

I. INTRODUCTION

A clamp is like a attachment device which is used for holding objects very tight and also together to prevent moments or separation through the utilization of internal weight. Clamping prevents the part from being shifting or being pulled from the fixtures during the machining operation. Beam clamps are designed for connection between the lower flanges of structural steel beams to provide a semi permanent lifting point. This clamps are very easy and can be very quickly and attached via the screw type mechanism. This series of clamps are fitted with a spring type mechanism shackle allowing for very quick and easy attachment of the load.. These types of clamps can have a capacity of up to 10 Tons.

In general Beam Clamps have two principle uses, the first is as an ASME B30.20 Below the Hook Lifting device and the second as a structural fixed point to hang manual and powered hoists as described in ASME B30.16.These Lifting Beam Clamps are designed to the most severe design requirements: ASME B30.20 and its design document BTH-1. By doing this they provide a superior product in both function and safety.

As an ASME B30.20 rule a Lifting Device the Beam Clamp is only suitable for lifting and moving a I shaped structural beams also These include W-Shapes, M-Shapes, HP-Shapes and S-Shapes. Using a Beam Clamp as a temporary attachment point for manual or powered hook-suspended hoists is limited to vertical (90°) lifting. Each Beam Clamp includes a mechanical position lock for added safety of when in the closed position.

1.1 TYPES AND USES OF LIFTING CLAMPS

By definition, a clamp is a lifting device which is used for grabbing and lifting higher loads. It is used as a moving device to lift loads move from one place to other either horizontal or vertical . As per market trend there are different types of lifting clamps are available to ensure all lifting conditions which industries met.

1.2 TYPES OF LIFTING CLAMPS:

Beam Clamps: These type of clamps are mainly used in automotive and manufacturing industries which require lifting of heavy objects. For Examples for such heavy items are steel beams and vehicles.

Girder Clamps: Just like beam clamps, girder clamps are attached to beams and are used to lift objects vertically. These types of models are available in the market which can met and can used to lift any objects vertically. Usually used in heavy-usage industrial sectors.

Plate Lifting Clamps: These type of clamps are suitable lifting, moving and transferring loads like metal sheets.

Board Clamps: These are suitable only for lifting non-metal objects such as plywood, stone, fiber board or wood which has medium density..

Drum Lifting Clamps: These clamps are used in chemical manufacture industries which are used to lift oil drums and other circular shaped objects.

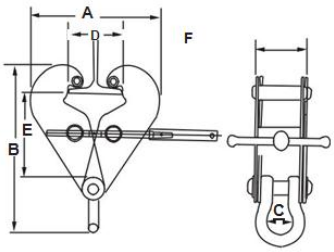


Fig1.1: 2D drawing of a Beam lifting clamp

II. PROBLEM DEFINITION

The main objective of the project is to design a lifting clamp for a working load limit of the 2 Tons with a jaw capacity of 25 mm. The lifting clamp should be useful to lift I-section beams vertically upwards. The project objective includes the design calculations using simple design equations initially and later the 3-Dimensional modeling of the lifting clamp is to be designed using NX-cad software. Once the design is finalized finite element analysis should be carried out to calculate deflections and stresses on the lifting beam clamp. The 3d model is imported into Ansys software and structural analysis of the lifting clamp is carried out. The analysis is carried out for Material Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316(marine).The objective of the project also includes life estimation of the clamp from the analysis and design optimization has to be performed along with varying the convectional material based. The deflections, stresses and life cycle is calculated and compared for all the materials. The best of the designs with the possible appropriate material has to be proposed.

III. METHODOLOGY

The methodology of the project includes the following:

- Requirement gathering by doing the literature survey.
- Perform Design calculations of the lifting clamp for Working Limit Load of 2 Tons.
- Create all the parts of lifting clamp using Catia software.
- Create assembly of lifting clamp using Catia software.
- Create manufacturing drawings of all the parts of lifting clamp using Catia software.
- Perform static analysis of the lifting clamp by applying the operating loads for four different materials (Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316).
- Tabulate and compare deflections and stresses obtained from static analysis for all the materials.
- Perform fatigue analysis of the lifting clamp for four different materials (Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316).
- Tabulate and compare life cycle obtained from fatigue analysis for all the materials.
- The best of the designs with the possible appropriate material has to be proposed.

IV. DESIGN AND ASSEMBLY OF LIFTING CLAMP

4.1 Numerical calculations of curved section of lifting clamp:

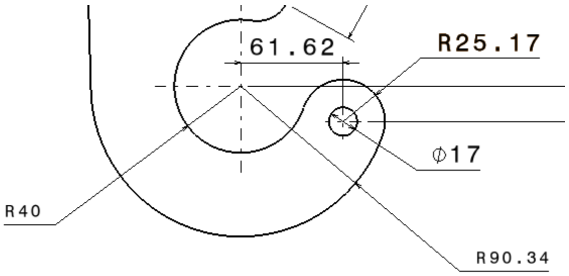


Fig4.1: 2d dimensions of c-clamp

Winkler-Bach Formula for Curved Beams:

Initially the study of bending of beam is carried out at curved section. The below figure explains the curvature.. This is possible when the beam section is symmetrical (Figure: 2) about the plane of curvature and the bending moment M acts in this plane.

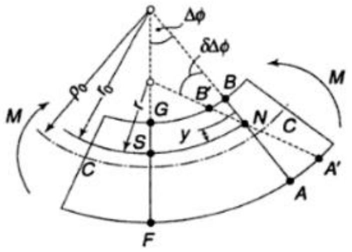


Fig4.2: C-clamp mechanism

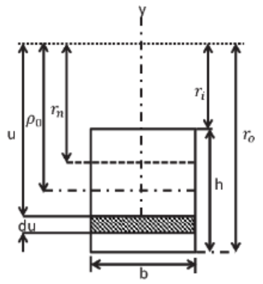


Fig4.3: Dimensions showing with each term

Winker-Bach formula for rectangular cross section curved beams

The stress acting on the curved beam is shown as

$$\sigma_X = (M*e /A*e) * (y / r_0 - y)$$

Bending Moment, $\mathbf{M = (P * \rho_0)}$

P= Weight * g where g= acceleration due gravity acting downwards = 9.8 mm^2

Then load P = 19600 N

$\mathbf{r_i}$ = inside radius of the curved clamp = 40 mm
$\mathbf{r_o}$= outside radius of the curved clamp = 90.34 mm
y= distance of neutral axis
h= height of the cross-sectional are = $\mathbf{r_o - r_i}$ **=** 50.34 mm
Area of rectangular cross –section, $\mathbf{A= b*(r_o-r_i)}$, where r_o=outer diameter of the cross-section =90.34 mm and r_i=inner diameter of cross-section= 40 mm
Then $\mathbf{A= 604.08\ mm^2}$
$\mathbf{R_O}$= Radius or curvature of centroidal axis $\mathbf{=A/\int dA/u = h/\ln(r_o/r_i)}$ = 61.84 mm
$\boldsymbol{\rho_o}$ = Initial Radius of curvature of centroidal surface $\mathbf{= r_i + h/2}$ = 65.17 mm

Eccentricity of the radii of curvature, $\mathbf{e} = \boldsymbol{\rho_o} - \mathbf{r_o}$ = 3.33 mm
The from the obtained data we can calculate y, which is determined as

$\mathbf{y = \pm (R_o\ h^2/R_o^2 + h^2\ )}$, the negative and positive representation is taken in to consideration based on the placement of sectional area above or below of the centroidal axis, from the above calculations we get **y= ± 24.6 mm**

From the above calculations bending moment is given by

$\mathbf{M= P * \rho_O = 19600 * 65.17 =1277332\ N\text{-}mm}$

The compressive stresses is developed in the curved bar clamp, If the cross-sectional area is considered below the centroidal axis which is given by, $\boldsymbol{\sigma_x} \mathbf{= -180\ N/mm^2}$

The tensile stresses is developed in the curved bar clamp, If the cross-sectional area is considered above the centroidal axis which is given by, $\boldsymbol{\sigma_x} \mathbf{= 419\ \ N/mm^2}$

4.2 OBJECTIVE:

The objective of the project is used to generate a 3d model of each assembly component used in lifting clamp and generate manufacturing drawings. By using assembly techniques each component is assembled to for a full fledge of lifting clamp product. For the total above process reverse engineering techniques are used to generate 3d parts from non parametric model to parametric model.

The lifting clamp consist of 7 parts, each part is been listed below and by using above objective process the 3d model of each part is created.

1) c-clamp
2) Locking pin
3) stiffeners
4) Adjustable screw
5) crane hook
6) nut and bolt
7) clamp locking pins

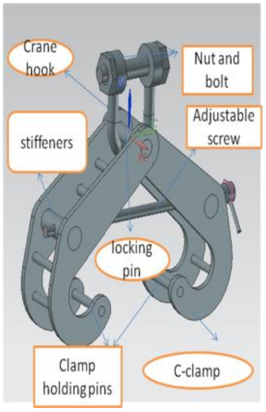


Fig 4.4: Geometric parts used in lifting clamp

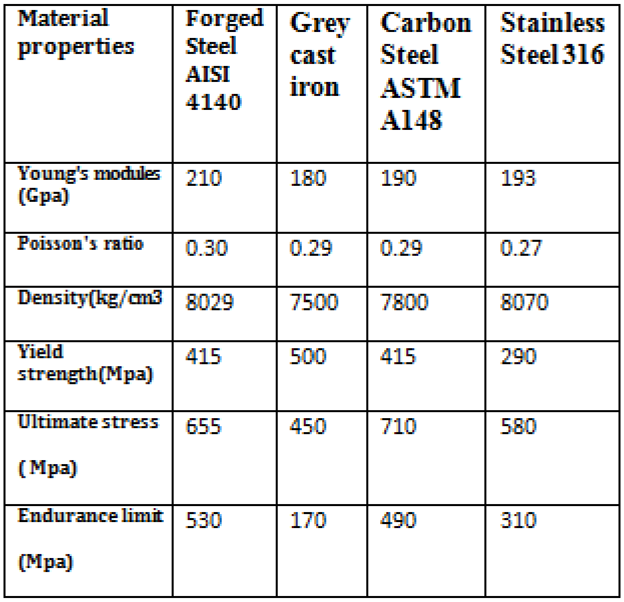
V. STRUCTURAL ANALYSIS OF LIFTING CLAMP

In this project the lifting clamp analysis is performed for different materials (Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316) by applying static loading to calculate stresses and deformations. This analysis is carried out for testing load limit of 2 tones. The lifting clamp used in this project is used to lift I section beams. Later the static results are used to calculate the fatigue life of lifting clamp, for this a good man diagram too was used to calculate the life of lifting clamp.

From the analysis results the stress, deformation and life of lifting clamp for different materials (Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316) are compared and the best one is proposed.

5.1 MATERIAL PROPERTIES:

The regular materials used in manufacturing lifting clamp are (Forged Steel AISI 4140, Grey cast iron, Carbon Steel ASTM A148, Stainless Steel 316). But in this project a study is being made to understand the best material for the application in terms of weight, deformation, stress, factor of safety and life of the material. The material properties for the above materials are tabulated below.



Material properties	Forged Steel AISI 4140	Grey cast iron	Carbon Steel ASTM A148	Stainless Steel 316
Young's modules (Gpa)	210	180	190	193
Poisson's ratio	0.30	0.29	0.29	0.27
Density(kg/cm3	8029	7500	7800	8070
Yield strength(Mpa)	415	500	415	290
Ultimate stress (Mpa)	655	450	710	580
Endurance limit (Mpa)	530	170	490	310

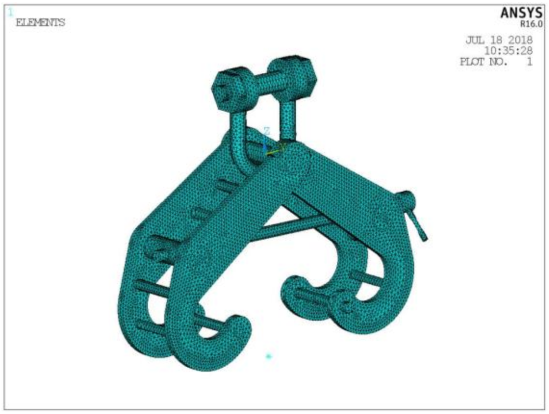


Fig 5.1: Meshed Ansys model of Total lifting clamp Assembly

5.2 BOUNDARY CONDITIONS:

The boundary conditions used for the static load conditions for lifting clamp are shown below.

1) The crane hook end is fixed in all degrees of freedom.

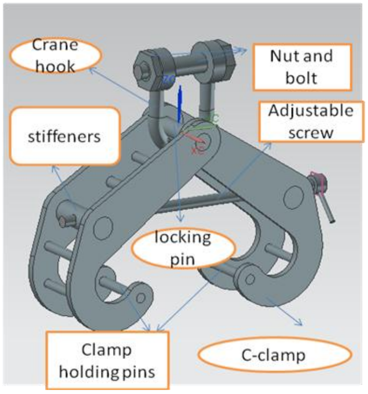


Fig 5.2: different parts of lifting clamp

Fig 5.3: Boundary condition of displacement applied on end of crane hook.

2) LOADING:

The loading conditions applied for the static of lifting clamp are shown below.

a) Mass of 2 tones is applied on the lifting clamp shown in below figure 5.4.

Fig 5.4: loading condition of mass of 2 tones.

b) Inertia load(gravity) is also applied to simulate self weight of the clamp shown in below figure.

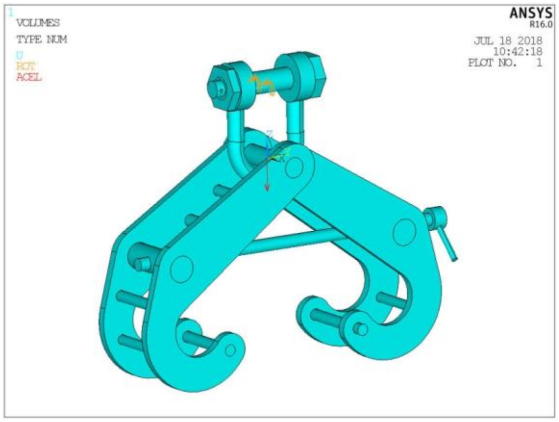


Fig 5.5: loading condition of inertia (gravity).

5.3 RESULTS

1) Forged Steel AISI 4140:

Finite element analysis is carried out for the above material forged steel and the results obtained are shown below.

a) DEFORMATIONS:

The maximum deformation observed is 24.77 mm as shown in the figure. The directions deformations are also consecutively plotted below.

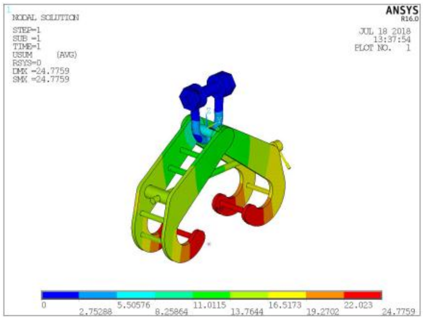


Fig 5.6: Total deformation obtained on lifting clamp for material forged steel.

B) STRESSES:

For this process the maximum VonMises stress theory is followed to understand the failure of the material. For that reason VonMises stress results are plotted for each part as shown below.

The maximum stress observed on lifting clamp is 541.4 Mpa as shown in the below figure.

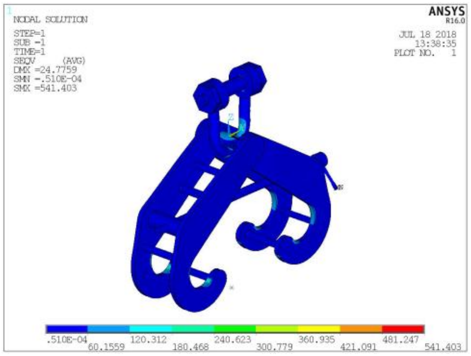


Fig 5.7: VonMises stress obtained on lifting clamp for material forged steel.

The maximum von misses stress founded on each Assembled component used in lifting clamp are shown below.

Table 5.1: Von Mises stress and factor of safety of each part of lifting clamp for material forged steel.

RESULTS OBTAINED (forged steel)	C-CLAMP	CRANE HOOK	CLAMP HOLDING PINS	STIFFNERS	ADJUSTABLE SCREW	LOCKING PIN	NUT & BOLT
VonMises stress (Mpa)	235	157.76	15.61	58.57	31.74	292.11	176.42
Factor of safety	1.76	2.63	26.58	7.08	13.07	1.42	2.35

Table 5.2: Results showing Total deformation and directional deformation of lifting clamp.

RESULTS OBTAINED (forged steel)	LIFTING CLAMP
Total deformation (mm)	23.5
X-Directional deformation (mm)	2.81
Y-Directional deformation (mm)	3.44
Z-Directional deformation (mm)	.01

2) GREY CAST IRON:

Finite element analysis is carried out for the material grey cast iron and the results obtained are shown below.

a) DEFORMATIONS:

The maximum deformation observed is 28.89 mm as shown in the figure. The directions deformations are also consecutively plotted below.

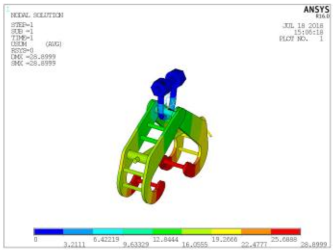


Fig 5.8: Total deformation obtained on lifting clamp for material grey cast iron.

B) STRESSES:

For this process the maximum VonMises stress theory is followed to understand the failure of the material. For that reason VonMises stress results are plotted for each part as shown below.

The maximum stress observed on lifting clamp is 544.76 Mpa as shown in the below figure.

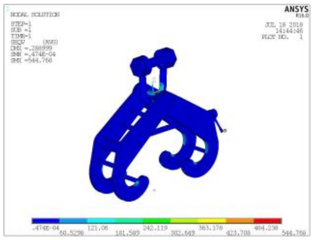


Fig 5.9: VonMises stress obtained on lifting clamp for Grey cast iron.

Table 5.3: Von Mises stress and factor of safety of each part of lifting clamp for material grey cast iron.

RESULTS OBTAINED (Grey cast iron)	C-CLAMP	CRANE HOOK	CLAMP HOLDING PINS	STIFFNERS	ADJUSTABLE SCREW	LOCKING PIN	NUT & BOLT
VonMises stress (Mpa)	235.72	205.82	15.54	58.84	31.77	294.29	198.74
Factor of safety	2.12	2.42	32.17	8.49	15.73	1.69	2.51

Table 5.4: Results showing Total deformation and directional deformation of lifting clamp.

RESULTS OBTAINED (Grey cast iron)	LIFTING CLAMP
Total deformation (mm)	28.89
X-Directional deformation (mm)	3.28
Y-Directional deformation (mm)	4.07
Z-Directional deformation (mm)	.01

3) CARBON STEEL ASTM A148:

Finite element analysis is carried out for the material Carbon Steel ASTM A148 and the results obtained are shown below.

a) DEFORMATIONS:

The maximum deformation observed is 27.40 mm as shown in the figure. The directions deformations are also consecutively plotted below.

Fig 5.10: Total deformation obtained on lifting clamp for material Carbon Steel ASTM A148.

The maximum stress observed on lifting clamp is 544.72 Mpa as shown in the below figure.

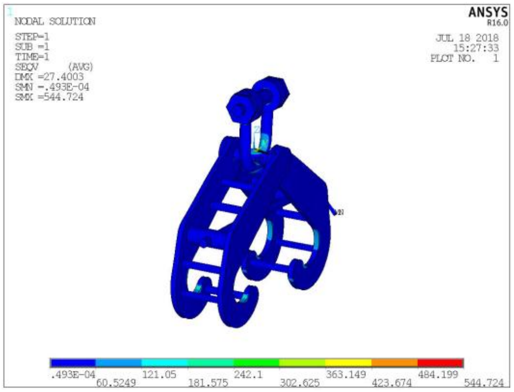


Fig 5.11: VonMises stress obtained on lifting clamp for Carbon Steel ASTM A148.

Table 5.5: Von Mises stress and factor of safety of each part of lifting clamp for material carbon steel.

RESULTS OBTAINED (Carbon Steel ASTM A148)	C-CLAMP	CRANE HOOK	CLAMP HOLDING PINS	STIFFNERS	ADJUSTABLE SCREW	LOCKING PIN	NUT & BOLT
VonMises stress (Mpa)	235.73	147	106.85	58.85	106.85	294.55	198.82
Factor of safety	1.76	2.82	3.88	7.05	3.88	1.40	2.08

Table 5.6: Results showing Total deformation and directional deformation of lifting clamp.

RESULTS OBTAINED (carbon steel)	LIFTING CLAMP
Total deformation (mm)	27.40
X-Directional deformation (mm)	3.11
Y-Directional deformation (mm)	3.82
Z-Directional deformation (mm)	.01

4) STAINLESS STEEL 316(MARINE):

Finite element analysis is carried out for the material Stainless Steel 316(marine) and the results obtained are shown below.

a) DEFORMATIONS:

The maximum deformation observed is 19.05 mm as shown in the figure. The directions deformations are also consecutively plotted below.

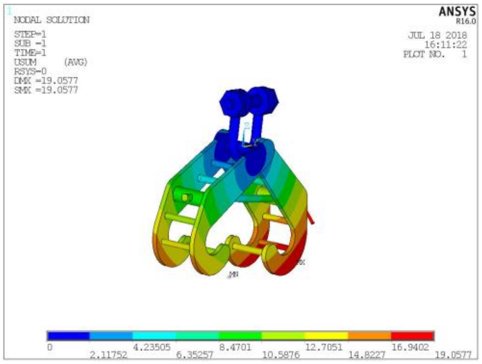


Fig 5.12: Total deformation obtained on lifting clamp for material Stainless Steel 316(marine).

The maximum stress observed on lifting clamp is 549.66 Mpa as shown in the below figure.

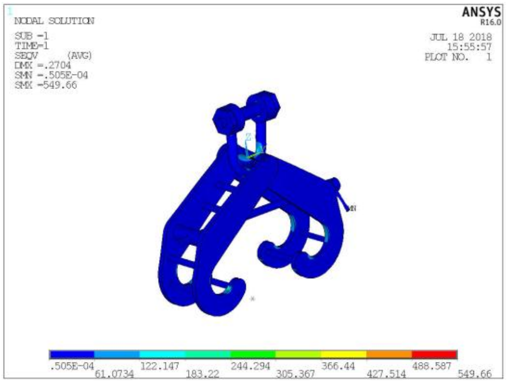


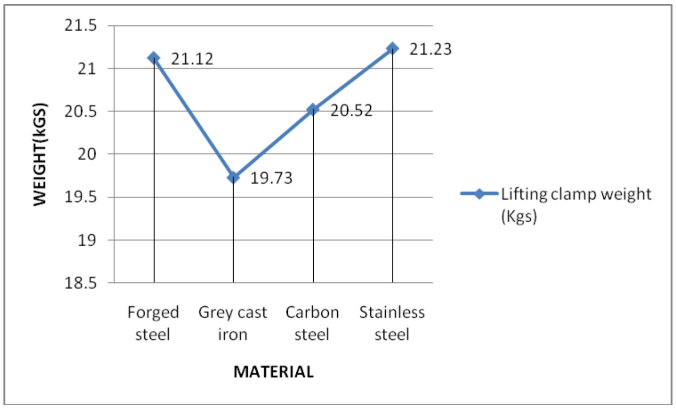
Fig 5.13: VonMises stress obtained on lifting clamp for Stainless Steel 316(marine).

Table 5.7: Von Mises stress and factor of safety of each part of lifting clamp for material Stainless Steel 316(marine).

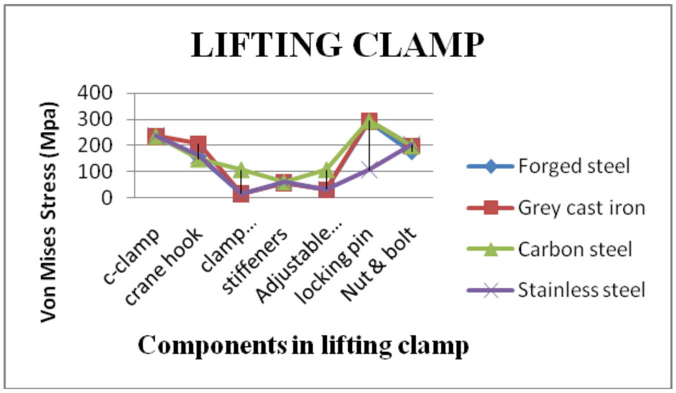
RESULTS OBTAINED (Stainless Steel 316(marine))	C-CLAMP	CRANE HOOK	CLAMP HOLDING PINS	STIFFNERS	ADJUSTABLE SCREW	LOCKING PIN	NUT & BOLT
VonMises stress (Mpa)	236.26	162.06	15.45	59.29	31.87	106.37	202.99
Factor of safety	1.22	1.78	18.77	4.89	9.09	2.72	1.42

Table 5.8: Results showing Total deformation and directional deformation of lifting clamp.

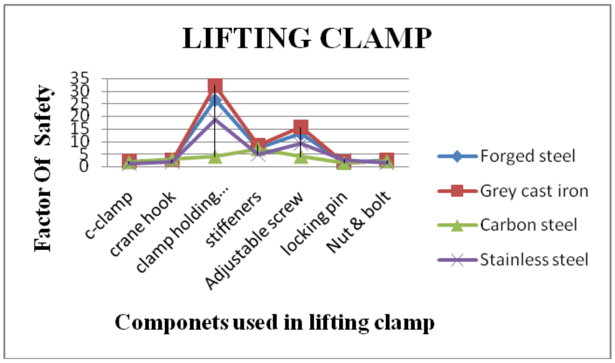
RESULTS OBTAINED (Stainless Steel 316 marine)	LIFTING CLAMP
Total deformation (mm)	19.05
X-Directional deformation (mm)	.72
Y-Directional deformation (mm)	2.42
Z-Directional deformation (mm)	11.15



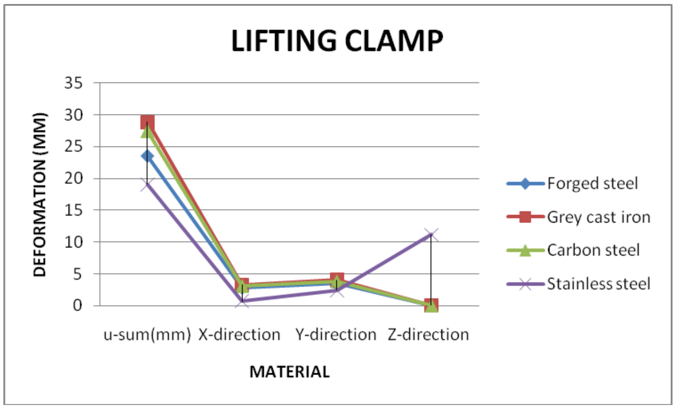
Graph 5.1: Comparison of mass with each different material used in manufacturing of lifting clamp



Graph 5.2: Comparison of Von Mises stress with each different material used in manufacturing of lifting clamp



Graph 5.3: Comparison of factor of safety with each different material used in manufacturing of lifting clamp



Graph 5.4: Comparison of deformation and directional deformation with each different material used in manufacturing of lifting clamp

VI. FATIGUE ANALYSIS OF LIFTING CLAMP

As a result of cyclic stress the fatigue failure of component can be established. The failure occurs on the material in three phases: crack initiation, crack propagation, and catastrophic overload failure. The duration of above three phases depends on many factors including mechanical material characteristics, applied stresses, processing history, etc.

As the lifting clamp is subject to cyclic stress due to its operation, it is important to calculate the fatigue life of the lifting clamp due to cyclic stress. The maximum principle stress obtained from the static analysis is given as input to the Goodman diagram tool to estimate the fatigue life of the lifting clamp.

6.1 Goodman Relation:

Good man relation is an equation used to specify the stresses altering on fatigue life of material. A graph indicates of (linear) mean stress vs. (linear) alternating stress which shows the failing of material for number of cycles. The experimental data is showed by a scatter plot by a parabola which is called as Gerber line.

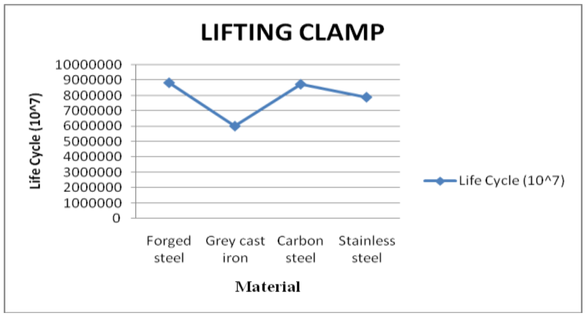
The Goodman relation can be represented mathematically as:

$$\sigma_{\mathbf{a}} = \sigma_{\mathbf{fat}} \times \left(1 - \frac{\sigma_{\mathbf{m}}}{\sigma_{\mathbf{ts}}}\right).$$

Where $\sigma_{\mathbf{a}}$ is the alternating stress, $\sigma_{\mathbf{m}}$ is the mean stress, $\sigma_{\mathbf{fat}}$ is the fatigue limit for completely reversed loading, and $\sigma_{\mathbf{ts}}$ is the ultimate tensile stress of the material. The general trend given by the Goodman relation can be explained with increasing mean stress for a level of applied stress. The safe cyclic loading can be explained by a relation which says if the coordinate of a mean stress and the applied stress lies under the curve , than the component can sustain. If the coordinate is above the curve, then the part will fail for the given stress parameters.

6.2 Steps involved in Goodman diagram

- Identifying the critical locations in the component.
- Maximum Principal stress extraction for the entire cycle.
- OObtaining the max (σ_{max}) and min (σ_{min}) values of maximum principal stress from entire cycle.
- SStress range(σ_{range}) = σ_{max}- σ_{min}
- SStress amplitude (σ_{amp}) = (σ_{max}- σ_{min})/2
- MMean Stress(σ_{mean})= (σ_{max}+ σ_{min})/2
- UUltimate Strength of material=σ_{ut}
- EEndurance limit=σ_e
- LLocating the point in Goodman's diagram using the coordinate (x = σ_{mean} , y = σ_{amp}).Of the point is within the Goodman's line then component has infinite life. If it is on or above the line then component will fail.
- MMargin of Safety for alternating stress (MS) = y^1/y.



Graph 6.1: Comparison of life cycle of total assembly of lifting clamp

VII. RESULTS

From the above graph 5.2 it is found that the VonMises stress developed on all the components used in manufacturing and assembling to build lifting clamp are not beyond the yield strength of the material and there are within the limits as when coming real environment the von mises stress is considered as 2/3rd of the original stress. Though the graph shows comparison of each material all are suitable to used to manufacture lifting clamp, But factor of safety has its own unique characteristics which helps selecting of the material. From the comparison of factor of safety with each material from graph 5.3 it is found carbon steel has better factor of safety limits than comparing other materials and by weight comparison(graph 5.1) it is found that carbon steel can sustain better loading condition in lifting I beams and also the project deals with the life estimation of the material used in manufacturing of lifting clamp, it is found that carbon steel material is good in sustaining larger loads and Better life time.

VIII. CONCLUSIONS

From the above analysis carried out on lifting clamp it has been found that the material carbon steel can sustain better loading conditions in terms weight, stress developed and the life cycle than comparing forged steel, grey cast iron and stainless steel, also as per the buying cost of material per kg in India, the carbon steel makes the lesser amount than comparing other 3 materials. So, the manufacturing cost also can been decreased by 55% if we choose carbon steel. In further study lifting clamp can be carried out by dynamic analysis to find out the natural and resonance frequencies of lifting clamp by doing modal and harmonic analysis to know the vibration characteristics of each functional part of lifting clamp.

IX. ACKNOWLEDGEMENT

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