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Design, Analysis and Fabrication of Automated Staircase-Climbing Load Carriage

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Abstract— Often we need to move heavy objects at home or workplace. There are many machines devised to fulfil this purpose. These machines work conveniently on flat surface and terrains with minor irregularities, but fail to serve the purpose on staircase. The conventional machines cannot be used on stairs since doing so will lead to several problems such as danger of toppling of load off the cart, inclined while climbing and damaging the staircase. These problems can lead to severe accidents which may cause serious injuries to the operator and those around. Hence there is need of an alternative mechanism which will enable the trolley to ascend stairs. The mechanism for climbing stairs are available but the need is to select one that is best suited for this application. In this project four staircase climbing mechanisms are compared on basis of criteria favorable for the application and the mechanism fulfilling mentioned criteria is selected for the application. The Blanco mechanism was selected since it fulfilled most of the criteria required for application. This work includes the design procedure for the load carriage based on Blanco Stair-Climbing system followed by fabrication and experimentation for the validation of the objectives.

Index Terms— Blanco Stair-Climbing system, criteria, design, experimentation, fabrication, mechanism, toppling.

1 Introduction

Transporting of goods is often needed in day to day activities. Various machines have been made to fulfil the need. In industries this need is met by conveyors, cranes, automatic guided vehicles, elevators and pallet truck. For domestic applications machines like hand trolleys of various types. But these conventional machines fail to serve on staircase. If these machines are used on staircase, there are a lot of problems conveying goods. The motion will be jerky giving rise to a danger of falling of the object off the trolley, the object will be inclined which is unacceptable in case of some cases, the trolley may fail since they are not designed for such type of application and the staircase and surrounding infrastructure might get damaged in process. The problems can lead to severe accidents causing injuries to the operator and those around. Hence there is a need of an alternative solution for safely carrying the load over stairs. The use of a staircase climbing mechanism for a hand trolley can be the solution of the problem. There are a number of mechanisms which climb the staircase such as simple wheel, dynamic ramp stair climber, Tri-Star mechanism and Blanco stair-climbing system. The Blanco mechanism scored more over the other mechanisms and was selected for this application. The load carriage designed uses Blanco stair-climbing system. A design procedure for the same is mentioned in the work followed by the analysis of critical components. The load carriage can ascend stairs of variable stair height, is able to retain the desired orientation of object for better stability while climbing for any inclination of staircase in addition to various safety features.

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2 Selection of a Staircase Climbing Mechanism [3]

During the design process, several different stair-climbing mechanisms were considered. The merits and faults of each approach were examined and some preliminary analysis was done. “Reference [3] had done comparative study of different stair-case climbing mechanisms to determine the mechanism which satisfies the criteria favorable for the given application.” Table 1 shows the results on the basis of which the mechanism for application was selected.

From table 1, it can be seen that Blanco mechanism scored more over the other mechanisms and was selected for this application. The load carriage designed uses Blanco stair-climbing system. A design procedure for the same is mentioned in the work followed by the analysis of critical components. The load carriage can ascend stairs of variable stair height, is able to retain the horizontal orientation of object while climbing for any inclination of staircase and has a mechanism to manipulate back roll of the carriage in addition to various safety features.

Table 1 Comparison of Various Mechanisms

Criteria	Large wheels	Dynamic ramp	Tri-Star	Blanco wheel
Quality of climbing	-	+	+	+
Ease of construction	+	-	0	+
Reasonable cost	+	-	0	+
Low weight	+	-	0	0
Familiarity	+	0	+	+
Total	3	-2	2	4

Symbols Used:-
“+” for acceptable, “-” for non- acceptable and “0” for neutral.

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3 DESIGN OF STAIRCASE ASCENDING LOAD CARRIAGE USING BLANCO STAIR-CLIMBING SYSTEM

As demonstrated in this document, the numbering for sections upper case Arabic numerals, then upper case Arabic numerals, separated by periods. Initial paragraphs after the section title are not indented. Only the initial, introductory paragraph has a drop cap. Fig. 1 shows solid modelling of staircase climbing load carriage in CATIA V5.

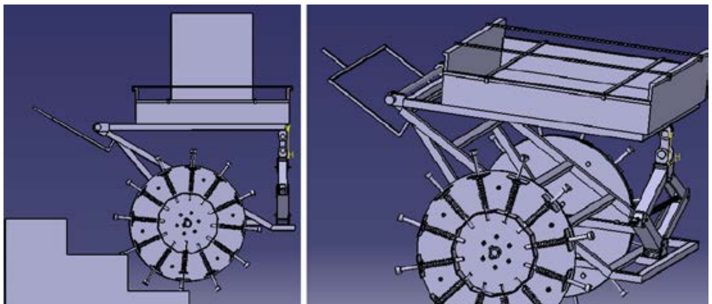


Fig. 1. (A) Orientation during ascention (B) Solid model of staircase climbing load carriage

3.1 Solid Modelling:

The solid modelling was done in CATIA V5. The assembly consists of the adjustable frame of load carriage supported by two Blanco-wheels mounted on axle and there is a jack screw incorporated for adjusting frame for variable staircase inclination as shown in Fig. 1.

3.2 Design procedure for spoke

Maximum Bending moment was found to be Mb = 36250 N-mm at point B. The diameter of spoke is calculated from formula based on strength (bending) consideration of shaft design. The diameter for spoke was calculated and chosen as 12mm (standard value). Fig. 2 shows free body diagram, shear force diagram and bending moment diagram of a loaded spoke.

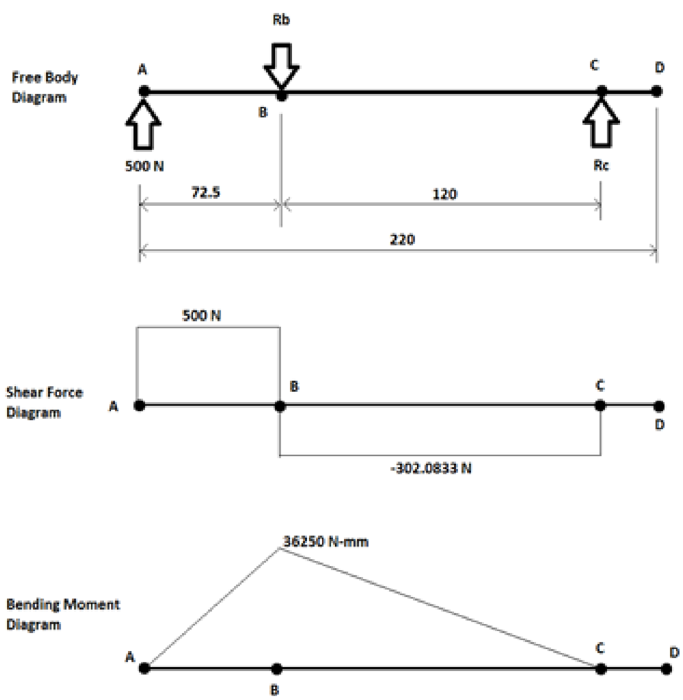


Fig. 2. Free body diagram of spoke

3.3 Design procedure for spring

The requirement was a spring of free length 100 mm and deflection 50 mm. According to space constraints,
Axial gap = 1 mm, spring wire diameter = 2.5 mm
The spring thus designed has the specifications as shown in Table 2.

TABLE 2 SPECIFICATIONS OF SPRING

Parameter	Value
Mean coil diameter	20 mm
Spring index	8
Modulus of rigidity	81370 N/mm2
Total number of turns	15
Stiffness	3.82 N/mm

3.4 Design procedure for shaft

Table 3 shows the distribution of shaft length for assembly. The shaft is to be designed for combined effects of bending and torsion. Fig. 3 shows shows free body diagram, shear force diagram and bending moment diagram of the shaft.

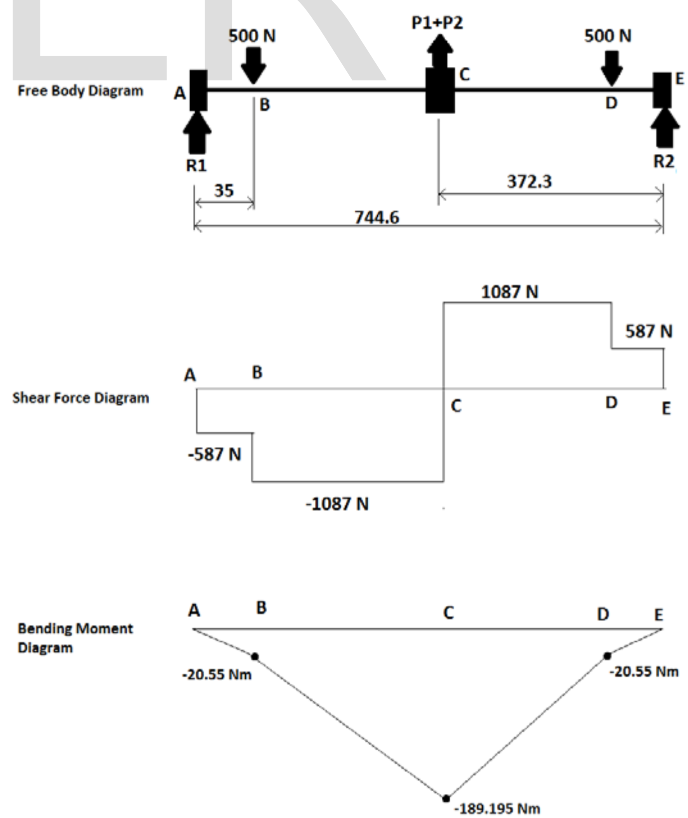


Fig. 3. Free body diagram of shaft

TABLE 3 DISTRIBUTION OF SHAFT LENGTH

Parameter	Value (mm)
Frame width including bearing	725
Clearance in frame and wheel	10
Shaft portion under wheel	20
Clearance for bush	20
Total Length	775

Maximum torque (Mt):

Total load = 1000N
Load shared by each wheel = 500N
Torque arm for each wheel = 0.285 m
Torque required at one wheel = 500 × 0.285 = 142.5 N-m
Assuming starting torque a 1.5 times of total torque, the total torque considering both wheels is Mt = 142.5 × 2 × 1.5 = 427.5 N-m

Maximum Bending moment (Mb):

Fig. 3 shows the loading condition of shaft in free body diagram during operation.
Assuming drive pulley diameter = 200 mm
Assuming co-efficient of friction = 0.5
Assuming angle of lap = 180°
Forces P1 and P2 can be calculated from basic pulley relations.
Applying conditions of equilibrium, we get reactions at bearings R1 = R2 = 587 N
Plotting Shear Force and Bending Moment diagrams:

Maximum Bending moment =190 Nm at point C

According to maximum shear stress theory, was used to determine the diameter of shaft:

Hence, selecting the diameter of shaft as 25.4 mm (Standard Value)

3.5 Design procedure for Rim Plate:

The dimensions of rim-plate were determined as follows:
The inner rim is at a radius 140mm. It was decided to install 12 spokes on wheel. Equation (1) is used to calculate the length of plate.

$$L=(\pi*\phi)/N$$

Where, L = length of rim-plate
ϕ = inner rim diameter
N = number of spokes

The breadth of rim plate is assumed as 42mm with length 70mm and thickness 2mm due to space and functional considerations. The plate is made of mild steel. The rim plate undergoes bending in two different situations, when the spoke is receded within the wheel and when the spoke is lifting the weight acting as moment arm.

Finite Element Analysis of rim-plate:

The plate was checked for bending stresses in FEA for both the conditions and the results were as follows:

When the spoke is receded within the wheel. The force of 500N acts on plate through the spring in totally compressed position.

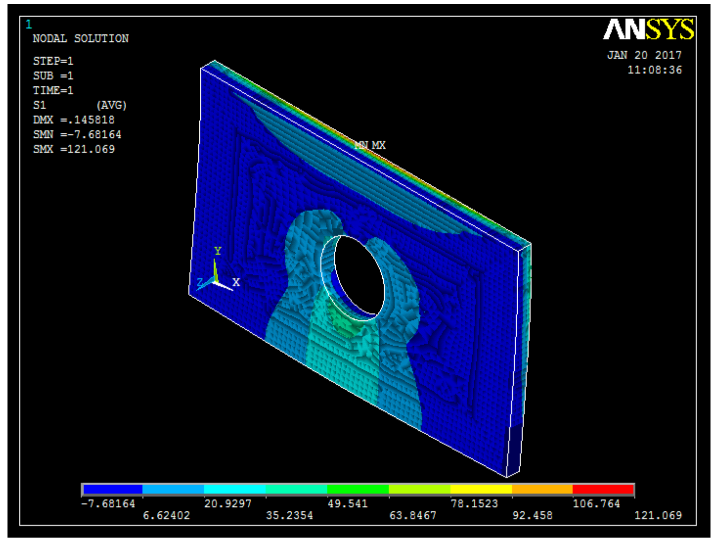
Element type: Solid Brick 8 node 185 –A 3D 8 node element gives high accuracy for stress calculation. Since the loading condition is bending, element 185 is used. Also the part geometry matches with the chosen element, hence fine and uniform meshing can be obtained.

Element size: 1

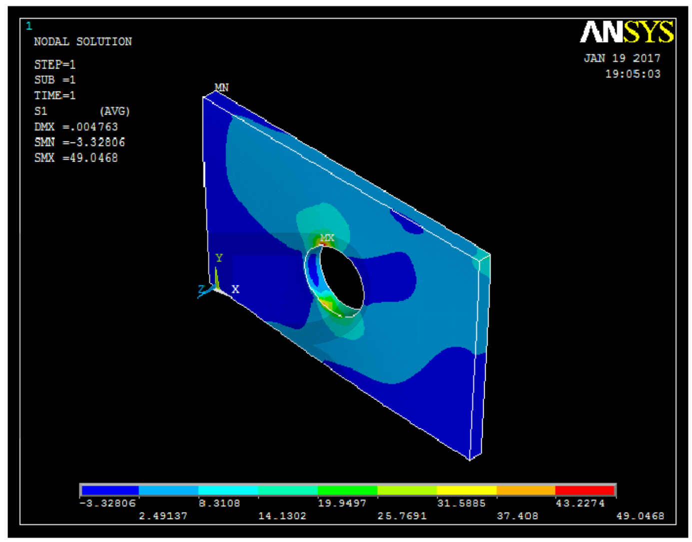
Meshing: Hex (sweep) – Hex meshing is used for achieving high accuracy in less number of nodes and since geometry is simple. Sweep mesh is selected because the part to be analyzed is simple. Sweep mesh is selected because the part to be analyzed is thin.

Fig. 4(A) shows the stress induced is 121.069MPa while yield stress for the plate material is 380 MPa. Hence, the bending stress within the plate are within permissible limits, the plate is safe for given loading condition.

When the spoke jams into rim-plates and is lifting the weight



(A)



(B)

Fig. 4. Finite element analysis in APDL (A) When spoke recedes into rim (B) When spoke jams in the rim plates

acting as moment arm. The force of 761N acts on plate due to the spoke.

Element type: Solid Brick 8 node 185 – A 3D 8 node element gives high accuracy for stress calculation. Since the loading condition is bending, element 185 is used. Also the part geometry matches with the chosen element, hence fine and uniform meshing can be obtained.

Element size: 1

Meshing: Hex (sweep) – Hex meshing is used for achieving high accuracy in less number of nodes and since geometry is simple. Sweep mesh is selected because the part to be analyzed is thin.

Fig. 4(B) shows the stress induced is 49.0468MPa while yield stress for the plate material is 380 MPa. Hence, the bending stress within the plate are within permissible limits, the plate is safe for given loading conditions.

3.6 DESIGN CALCULATIONS FOR BRAKES

Design torque = 430 N-m

Selecting standard size disc considering space available in the assembly

Disc radius, Rd = 75 mm

Based on disc dimensions the pad dimensions are selected as

Outer radius, Ro = 70 mm

Inner radius, Ri = 30 mm

Coefficient of friction between standard disc and pad material, μ = 0.35

Number of pads = 2

Torque absorbed by each pad, Mt = 430/2 = 215 N-m = 215000 N-mm

Actuating Force, P = 11663.57 N

Let, A = Area of pad

A = 5831.78mm2

From area of pad, the angular dimension of the brake pads can be found out. Let θ be angular dimension of the pads,

θ = 2.91c = 167°

TABLE 4 FINAL DIMENSIONS OF BRAKE ASSEMBLY

Hence, table 4 shows final dimensions of critical components

Brake pads (x2)	
Angular dimension (θ)	167°
Outer radius (R_o)	70 mm
Inner radius (R_i)	30 mm
Brake disc	
Outer radius (R_d)	75 mm

of brake assembly.

3.7 SELECTION OF BEARINGS

Shaft diameter D = 25.4 mm

Radial load, Fr = 500 N

Running life in hours, L10h=8000 hrs (for industrial, lifting application)

L10 = 840 million revolutions

Dynamic load, C = 4717.7 N

Based on inner diameter (shaft diameter) and dynamic load the bearing selected is 6205. Bearings used for axle shaft, motor and lay shaft are same.

4 FABRICATION AND ASSEMBLY OF STAIRCASE-CLIMBING LOAD CARRIAGE

4.1 Blanco Wheel

This sub-system consists of two Blanco wheels and an axle. The Blanco wheel assembly consists of spokes, springs, rim-plates, 2mm mild steel circular plate and circular plywood. The wooden plank was reinforced with the circular plate by using bolted joints. The partially fabricated model is shown in Fig. 5. Rim plates were welded on inner periphery of the wheel as shown in Fig. 5. Then finally the spokes where installed as per the assembly.

Fig. 5. Fabrication of Blanco wheel and shaft

4.2 Frame

After the manufacturing of the Blanco wheels, we then pushed towards the fabrication of the frame of the load Carriage. In the manufacturing of the frame, hollow rods of square cross section 1”×1” of various lengths are used. The material of the rods is mild steel which is decided according to the design consideration. The Frame is divided in two Parts:

- Upper Frame
- Lower Frame

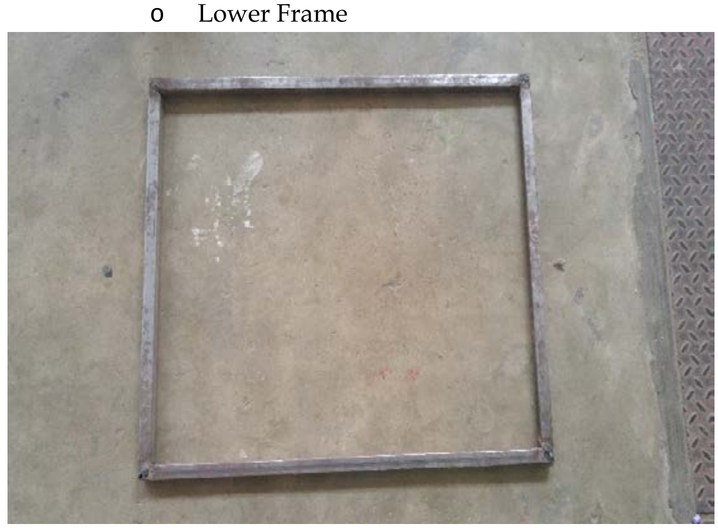


Fig. 6. Fabrication of upper frame

In the Upper frame the hollow rods are welded as designed

Fig. 7. Fabrication of lower frame

and the box over which the load is to be carried is fixed with the upper frame using bolts. The box is made out of plywood. The box was fixed on to the upper frame by nails. Thus, a fabricated upper frame is shown in fig. 6.

In the Lower frame also the hollow rods are welded as designed and the screw jack is also welded with it. The screw jack head is attached with a rectangular cross section hollow rod to increase the height of lift by screw jack for adjusting the level of the upper frame in horizontal position. Also, the caliper of the brake was attached as shown in the image.

These two frames are fixed with each other by using door hinges so that there will be some relative motion between them required for horizontal alignment. A fabricated lower frame is shown in fig. 7.

4.2 Shaft

Fig. 8. Fabrication of shaft

Fig. 10. Staircase climbing load carriage

A bar of mild steel (diameter 25.4mm, required length) was procured for use as axle for the load carriage. The ends of the shaft were turned to press-fit bearings on to the shaft. Since a standard bearing was selected of which inner diameter was 25 mm. Fig. 8 shows a fully fabricated shaft assembled into frame and wheels with a brake disc mounted at its centre.

Fig. 9. Force measuring instrument

4.3 Total Assembly

Fig. 9 shows a fully fabricated model of staircase climbinf load carriage with LPG cylinder loaded on it. The cylinder is constrained with the help of the elastic ropes with hooks at their ends. Also, it can be seen that the desired orientation of the object is retained so that the load and the load carriage remain stable while climbing the stairs.

5 TESTING

5.1 Instrument for measurement of force

For finding the force required to pull the cart over the stairs, an instrument is constructed. This instrument is based on the principle of parallel springs. In this instrument, three springs

of equal stiffness are used. The springs are mounted a rod by means of metal rings as shown in image above. The rings are equidistant from each other and the ends for even force distribution. The other ends of the springs are also connected to metal rings. This other end of the springs is hooked to handle of load carriage by S-shaped hooks as shown in fig. 10.

5.2 CALCULATIONS

This analysis is done for a particular stair case with a specific angle of inclination i.e. 30° as in this case.

Stiffness of each spring, K = 3.5 N/mm

Hence, stiffness of instrument is, Keq = (3.5+3.5+3.5) = 10.5 N/mm

The measured value of deflection, x = 21 mm

Hence, pulling force, F = 220.5 N

5.3 ANALYSIS OF THE RESULTS

Determination of Reduction factor:

Self-weight of the load carriage = 48.14 kg

Pull force, F = 220.5 N = 22.5 kg

Reduction Factor, G = F/T

Where, T = T = Total mass = Pay load mass + self-weight of the load carriage.

Hence reduction factor, G = 0.4673

Determination of critical loading point:

For determining the critical loading point, i.e. the point from where the pulling force of the load carriage required is less than the mass of the payload, set of payload masses are taken and are plotted against the difference between the payload mass and the pulling force (found by multiplying total mass with reduction factor). Table 5 shows readings for pulling force measured for given payload masses highlighted by orange color. The reduction factor was found out based on these two readings the analysis was extrapolated by using this reduction factor for different payload masses.

TABLE 5 DETERMINATION OF CRITICAL LOADING POINT

Payload mass in kg (P)	Total mass in kg (T)	Pulling force in kg (F)	Reduction factor (G)	Difference (p-f)
0	48.14	22.5	0.46738679	22.5
5	53.14	24.8369339	0.46738679	19.8369339
10	58.14	27.1738679	0.46738679	17.1738679
15	63.14	29.5108018	0.46738679	14.5108018
20	68.14	31.8477358	0.46738679	11.8477358
25	73.14	34.1846697	0.46738679	9.18466971
30	78.14	36.5216037	0.46738679	6.52160365
35	83.14	38.8585376	0.46738679	3.85853760
40	88.14	41.1954715	0.46738679	1.19547154
45	93.14	43.5324055	0.46738679	-1.46759452
50	98.14	45.8693394	0.46738679	-4.13066057
55	103.14	48.2062734	0.46738679	-6.79372663

Refering table 5, it can be seen that the difference between paload mass and pulling force turns negative between payload mass 40 and 45 kg, i.e. the critical loading factor lies between these values. Also from fig. 11, it can be seen that the critical loading point is in between the payload massed 40 kg and 50 kg. Exact value of the critical loading point is found by linear interpolation and is equal to 42.7554 kg payload mass. Hence, above machine is effective above payload mass 42.7554 kg.

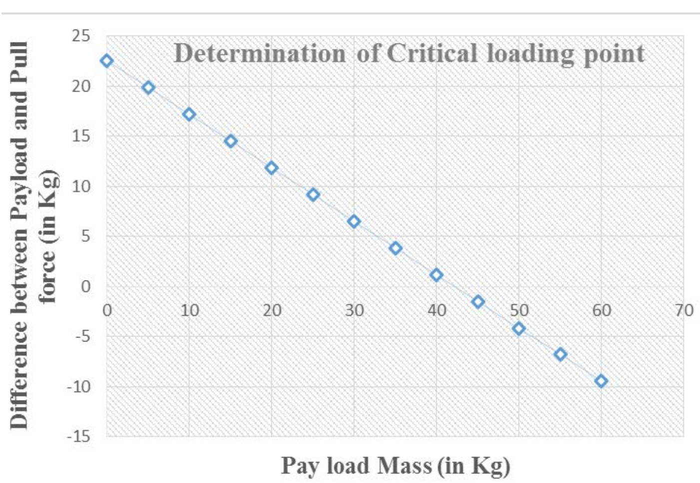


Fig. 11. Determination of critical loading point

6 CONCLUSIONS:

- On the basis of comparative study of mechanisms, Blanco mechanism is the best suited mechanism for the given application and chosen for this project.
- The working of the Blanco mechanism is validated.
- The handcart is equally applicable for smooth and flat terrain.
- During ascending or descending of the carriage the shocks are absorbed by the springs that are mounted on the wheels via spokes are damped by the frame itself preventing the load on it. Hence, making the operation stable and safe.
- The object remains horizontal while climbing.
- The operation is controlled using brakes which makes it more safe and convenient.
- The carriage can be turned left or right using the castor attached to it.
- From critical loading point analysis the point beyond which the pulling force of the carriage is less than the payload is determined.
- The critical loading point shows that the carriage is useful and efficient for heavy loads up to design limit (50 kg)

7 FUTURE SCOPE

- Use of a lighter metal for manufacturing of this product can be done to reduce the self-weight and cost substantially.
- Weight reduction of the Blanco wheel can be done by optimizing the design of the laser cut wheel plate. (i.e. By making slots on the wheel plate)
- This Handcart can be motorized for automated operation.
- A mechanism to prevent accidental back roll can be incorporated in the carriage.
- The load carriage can be designed for more than 50 kg by using motors with suitable reductions.
- The Blanco wheel mechanism can be applied to wheel chairs with suitable modification.

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