Published by :
http://www.ijert.org

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 10, October-2023

Design Optimization of Frame Cross Members for Truck Application

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***Abstract*—This Chassis frame is the most important part of a heavy duty vehicle. Its main function is to safely carry the maximum load under all designed operating conditions. Hence it should be rigid enough to withstand various forces coming on it like bending forces, lateral forces, twisting forces, vibrations and other forces.**

An important factor in chassis frame design is to have adequate strength as well as torsional stiffness for better handling characteristics. Therefore, maximum shear stress induced in the frame and deflections during various operating conditions are important criteria for the chassis frame design. Cross-member assist the side rails to overcome lateral, bending and mainly torsional loads

Cross- and side-members are joined together to form a rectangular one-piece frame. Open-channel sections are commonly used for cross members, but for special applications sometimes tube sections are also used. The individual channel members do not have adequate stiffness against twist, but when joined together they form a relatively rigid structure capable of withstanding both bending the torsional loading. The attachment of the cross-members to the side channels needs special attention, because the junction points are subjected to maximum bending as well as torsional stresses.

In this paper, a robust optimization approach that can be used for Design optimization of cross member without affecting frame performance criterion is described in detail.

Keywords -Chassis, Truck, Optimization, Stiffness, Frame Design

I. INTRODUCTION

The most important structural member of any commercial vehicle is its chassis frame. It is approximately a rectangular frame resembling a ladder. This type of chassis frame is often referred to as a ladder frame. It comprises of two side members also called long members joined by a series of cross members.

Along with the strength, an important consideration in the chassis design is to have adequate bending and torsion stiffness. Adequate torsional stiffness is necessary to have good handling characteristics. Commonly the chassis frames are designed on the basis of strength and stiffness. As per the conventional design procedure, the stiffness of the chassis is increased by adding cross members which results in overall increase of weight of chassis. This increase in weight of the chassis results in lowering fuel efficiency and increase in the overall cost due to extra material. Hence the design of the chassis cross members with adequate stiffness and strength is necessary. Fig.1 illustrates a chassis of truck application

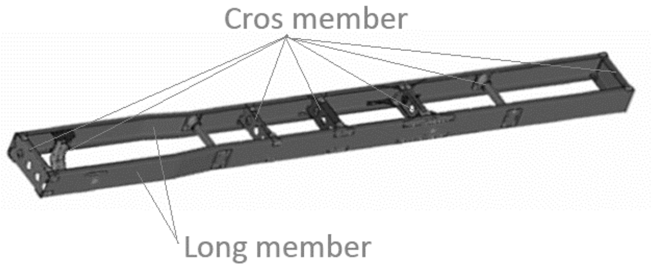


Fig 1- Truck Chassis

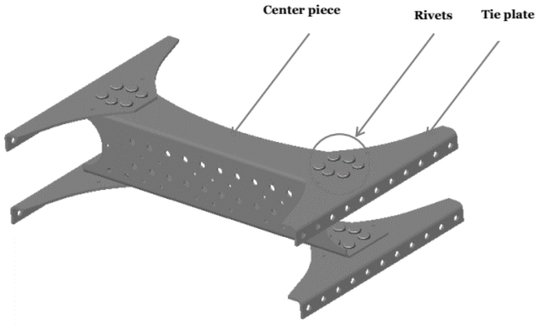


Fig 2 –Cross member

There are 7 types of cross members used in truck chassis frames

1) Front end or Bumper mounting cross member (Fig 2.1 A)
2) Engine mounting cross member (Fig 2.1 B)
3) Cabin mounting cross member (Fig 2.2 C)
4) Intermediate cross member (Fig 2.2 D)
5) Suspension cross member (Fig 2.1 E)
6) Spare wheel mounting cross member (Fig 2.1 F)
7) End cross member or closing cross member(Fig 2.1 G)

Fig 2.1A

Fig 2.1B

Fig 2.1C

Fig 2.1D

Fig 2.1E

Fig 2.1F

Fig 2.1G

II. CROSS MEMBER DESIGN FACTORE

The design of an automobile chassis cross member requires prior understanding of the kind of conditions the chassis is likely to face on the road. The chassis generally experiences four major loading situations, that include,

(i) Vertical bending
(ii) longitudinal torsion
(Hi) lateral bending, and
(iv) horizontal lozenging.

Vertical Bending. Considering a chassis frame is supported at its ends by the wheel axles and a weight equivalent to the vehicle's equipment, passengers and luggage is concentrated around the middle of its wheelbase, then the side-members are subjected to vertical bending causing them to sag in the central region.

Longitudinal Torsion. When diagonally opposite front and rear road-wheels roll over bumps simultaneously, the two ends of the chassis are twisted in opposite directions so that both the side and the cross- members are subjected to longitudinal torsion (Fig. 21.2), which distorts the chassis

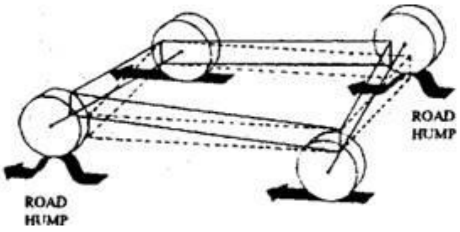


Fig. 21.2. Longitudinal torsion

Lateral Bending. The chassis is exposed to lateral (side) force that may be due to the camber of the road, side wind, centrifugal force while turning a corner, or collision with some object. The adhesion reaction of the road-wheel tyres opposes these lateral forces. As a net result a bending moment (Fig. 21.3) acts on the chassis side members so that the chassis frame tends to bow in the direction of the force

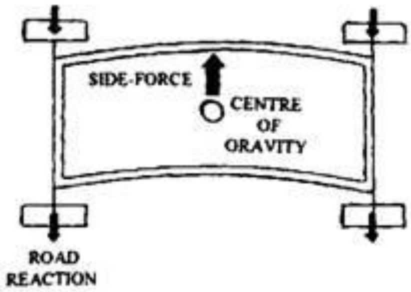


Fig. 21.3. Lateral bending

Horizontal Lozenging. A chassis frame if driven forward or backwards is continuously subjected to wheel impact with road obstacles such as pot-holes, road joints, surface humps, and curbs while other wheels produce the propelling thrust. These conditions cause the rectangular chassis frame to distort to a parallelogram shape, known as 'lozenging' (Fig. 21.4).

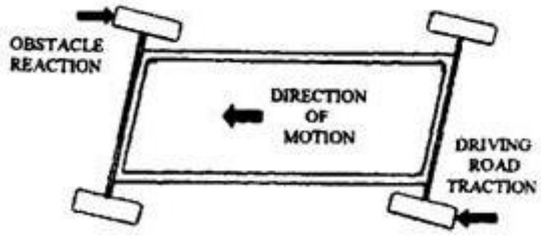


Fig. 21.4. Lozenging.

During movement of a vehicle over normal road surfaces, the chassis frame, is subjected to both bending and torsional distortion as discussed in the previous section. Under such running conditions, the various chassis-member cross-section shapes, which find application, include.

(i)Solid round or rectangular cross-sections,

(ii) Enclosed thin-wall hollow round or rectangular box-sections,

(iii) Open thin-wall rectangular channeling such as 'C, T, or 'top-hat' sections. Side-member bending Resistance.

The chassis side-members, which span the wheelbase between the front and rear axles must be able to take the maximum of the sprung weight. The sprung weight is the weight of the part of the vehicle supported by the suspension system. The binding stiffness of these members must resist their natural tendency to sag. The use of either pressed-out open-channel sections or enclosed thin-wall hollow round or rectangular box-sections can provide the maximum possible bending stiffness of chassis members relative to their weight.

A comparison of the bending stiffness's of different cross-sections having the same cross-sectional area and wall thickness is presented in Fig. 21.5A to F. Considering a stiffness of 1 for the solid square section, the relative bending stiffness's for other sections are,

Sr No	Type	Stiffness
1	Square Bar	1
2	Round Bar	0.95
3	Round Hollow Tube	4.3
4	Rectangular C-channel	6.5
5	Square Hollow Section	7.2

Practically, a 4 mm thick C-section channel having a ratio of channel web depth to flange width of about 3:1 are used as chassis side-members. This provides a bending resistance of 15 times greater than that for a solid square section with the same cross sectional area. For heavy-duty applications, two C-section channels may be placed back to back to form a rigid load-supporting member of I-section (Fig. 21.5H). To provide additional strength and support for an existing chassis over a highly loaded region (for example, part of the side-member spanning a rear tandem-axle suspension), the side-members may have a double-section channel. This second skin is known as a flitch frame or plate (Fig. 21.51).

Side-and Cross-member Torsional Resistance. The open-channel sections exhibit excellent resistance to bending, but have very little resistance to twist. Therefore both side and cross-members of the chassis must be designed to resist torsional distortion along their length. Figure 21.5C to F illustrates the relative torsional stiffness between open-channel sections and closed thin-wall box-sections. Comparisons firstly between the open and closed circular sections and secondly between the rectangular sections are made, considering the open section has a resistance of 1 in each case

Sr No	Type	Stiffness
1	Longitudinal split tube	1
2	Enclosed hollow tube	62.0
3	Open rectangular C-channel	1
4	Closed rectangular box-section	105

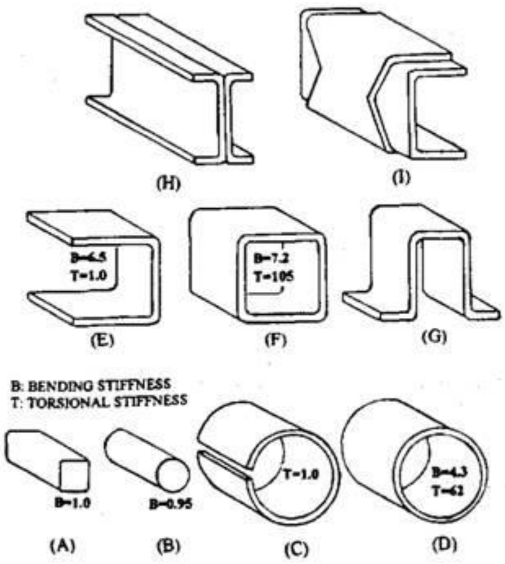


Fig. 21.5. Chassis-cross member sections.
A. Square solid bar.
B. Round solid bar.
C. Circular tube with longitudinal slit.
D. Circular closed tube.
E. C-section.
F. Rectangular box section.
G. Top-hat-section.
H.I-section.
I. Channel flitch plate.

This clearly explains the advantages of using channel sections over the hollow tube due to high torsional stiffness. The chassis frame, however, is not designed for complete rigidity, but for the combination of both strength and flexibility to some degree. End bracket joined directly to the side-member web. Tubular-section cross-members are specifically suitable for withstanding both bending and torsional stresses at concentrated points, such as spring shackle-hangers and tandem-axle suspension pivoting support

4. OPTIMIZATION METHODOLOGY

4.1. Cross Member Sizing Optimization

The first category in cross member design optimization techniques is sizing optimization. Without changing the general shape of the geometry an optimum relation between weight, stiffness and the dynamic behavior is found by optimizing sheet thicknesses. In early design phases a free sizing approach helps to get best indications for sheet partitioning and in later design phases the sizing optimization can lead to optimal thicknesses for all individual sheets in the structure.

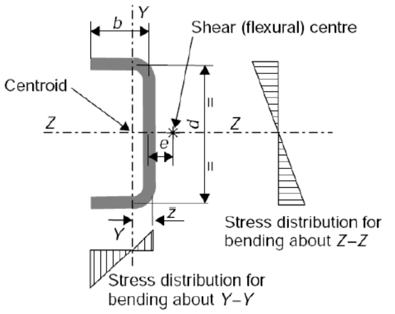
An example of sizing optimization is illustrated in the image below (Fig 4.1).

Cross member 5 mm Thickness- E36 Weight = 8 Kg
Cross member 4 mm Thickness – E46 Weight =6.4 Kg

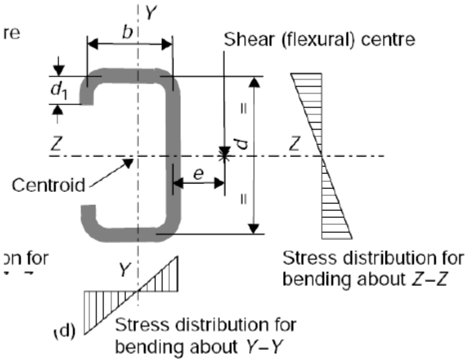
Fig 4.1 Cross member

4.2 CROSS MEMBER CROSS SECTION SELECTION

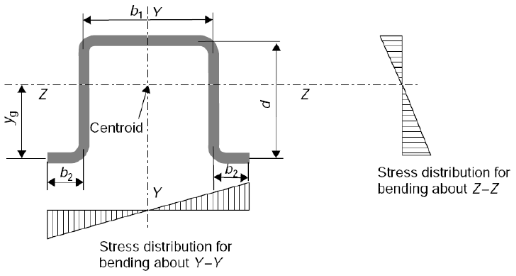
1) C Section-
Suitable for bending loads causing moments about the Z–Z axis. Care must be taken to ensure that the flange width ‘b’ is not excessive as this can lead to reduced allowable compressive stress



2) Lipped Section - The wide flange results in a low stress at which buckling occurs. Improvement in buckling stress can be achieved by adding a lip to the channel Suitable for cross.member.profile

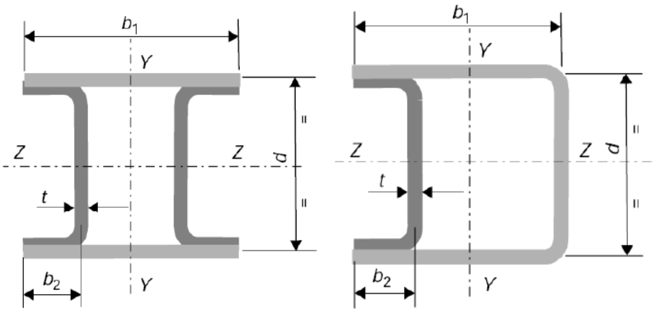


3) Hat Section –
Has good bending properties about both Y–Y and Z–Z axes provided the value of 2b2 is approximately equal to b1

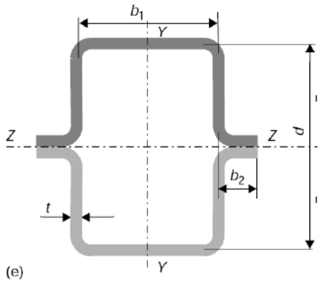


4) Two Channels Section –
Combination of two channels, one with wide and one with narrow flanges. These type of section suitable for Cross member mounting brackets and other supporting brackets.

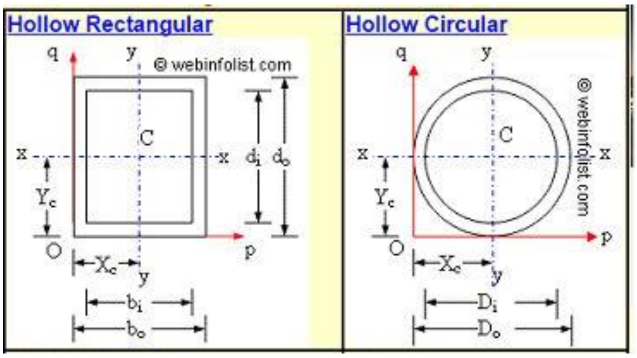
This combination avoids inclined principal axes and still has substantial second moments of area about Y –Y and Z–Z axes



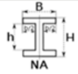
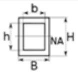
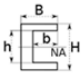
5) Two Hat Section –
Two hat sections are combined, both of these form effective structural members with good bending properties about Y –Y and Z–Z axes
This type of section suitable for cross member



5) Tubular Section –
Tubular sections are good at torsional stiffness



CROSS MEMBER SECTION COMPARISON
The Cross-section of a cross member determines the section modulus. Below is a comparison of various different sections applicable to a cross member with critical characteristics ranked with 1 being the Lowest and 4 being the Highest among the comparison of similar volume

Section	Section Modulus Formula	Section Modulus	Resistance to Bending Loads	Torsional Rigidity
	$S = \frac{B^2(H-h)}{6} + \frac{(B-b)^3 h}{6B}$	4	4	2
	$S = \frac{\pi(r_2^4 - r_1^4)}{4r_2} = \frac{\pi(d_2^4 - d_1^4)}{32d_2}$	1	2	4
	$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$	2	3	3
	$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$	3	1	1

(1 – Lowest Score to 4 – Highest Score)

4.3. CROSS MEMBER MATERIAL OPTIMIZATION

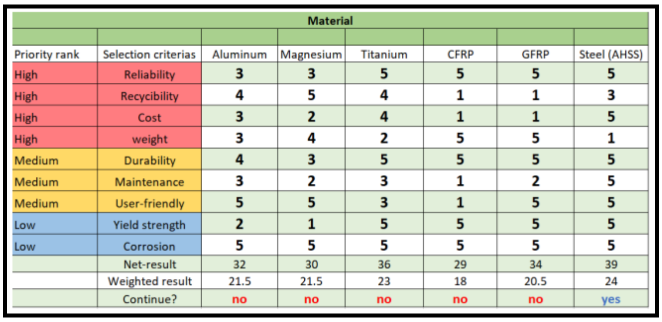
The materials are evaluated on nine different selection criteria which are placed in three different priority ranks.

The materials are given a score from 1-5 for each criteria.

The net results within each priority rank is then multiplied by a weight factor which is 1.0 for high priority, 0.5 for medium priority and 0.25 for low priority.

The score values for the criteria are defined as:

- Reliability: 1 (very low) · · · · · · 5 (very high)
- Recyclability: 1 (very low) · · · · · · 5 (very high)
- Cost: 1 (relatively expensive) · · · · · · 5 (relatively cheap)
- Weight: 1 (high weight) · · · · · · 5 (low weight)
- Durability: 1 (very low) · · · · · · 5 (very high)
- Maintenance: 1 (hard/cost ineffective) · · · · · · 5 (easy/ cost effective)
- User-friendly: 1 (easy to handle) · · · · · · 5 (very hard to handle)
- Yield strength: 1 (very low) · · · · · · 5 (very high)
- Corrosion: 1 (high risk) · · · · · · 5 (no risk).

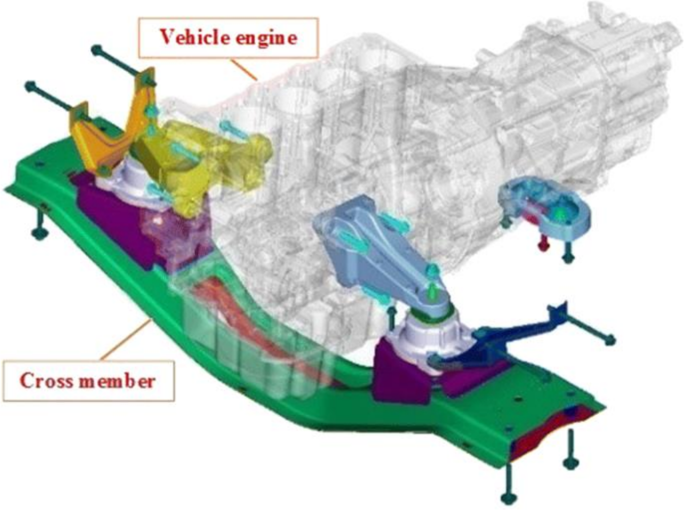


Material							
Priority rank	Selection criterias	Aluminum	Magnesium	Titanium	CFRP	GFRP	Steel (AHSS)
High	Reliability	3	3	5	5	5	5
High	Recycibility	4	5	4	1	1	3
High	Cost	3	2	4	1	1	5
High	weight	3	4	2	5	5	1
Medium	Durability	4	3	5	5	5	5
Medium	Maintenance	3	2	3	1	2	5
Medium	User-friendly	5	5	3	1	5	5
Low	Yield strength	2	1	5	5	5	5
Low	Corrosion	5	5	5	5	5	5
	Net-result	32	30	36	29	34	39
	Weighted result	21.5	21.5	23	18	20.5	24
	Continue?	no	no	no	no	no	yes

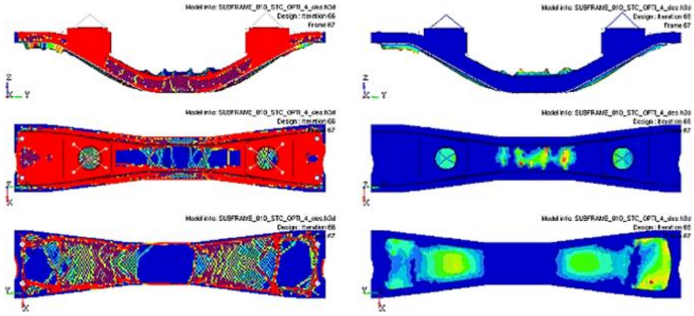
As it can be seen, AHSS has the highest score in terms of both net result and weighted results, hence the material will be selected for the fundamental base of the chassis. This does not mean that every component of the chassis will be produced in AHSS, this strictly concerns the high load carrying frame of the chassis.

4.4. TOPOLOGY OPTIMIZATION

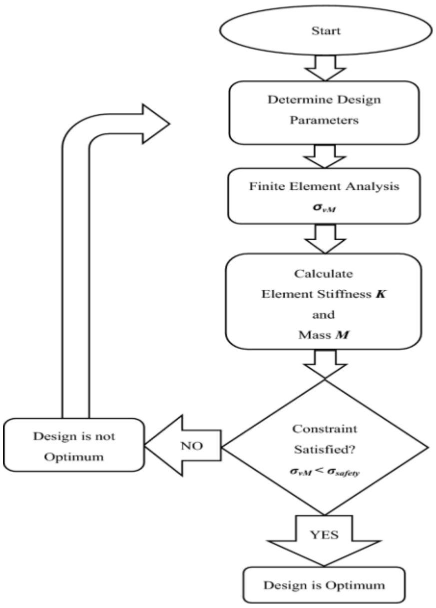
Topology optimization is one of the powerful tool to optimize any structure. It is used at the concept level of the design process so that a conceptual design proposal can be fine-tuned for performance and manufacturability. In automotive sector, design of chassis systems components is always challenging due to the heavy loads the system is exposed to and the long-life requirements for the total system for heavy transport vehicles. The design phase followed by analysis phase is very time consuming which leads to cost as well. The topology optimization helps to replace these time consuming and costly design iterations which reduces design development time and overall cost while improving design performance. Using 3D software topology optimization, one can find the best concept design that meets the design requirements. Topology optimization is based on the principle of finite element method



I Fig 5.4 A – Packaging constraints and space defining



TOPOLOGY OPTIMIZATION PROCESS



5. ALTERNATIVE MANUFACTURING PROCESSES

Replace the expensive and non-flexible manufacturing processes to unexpansive a flexible process. So modification and design change incorporation will easy and lead to faster product development cycle.

5.1) Press forming –

Expensive and very difficult process to adopt new design changes or modification requirement.

5.2) Roll Forming -

Less expensive, fast process for incorporate regular changes

5.3) Hot Forming – Expensive than Press forming but strength of material get improved due to process.

5.4) Hydroforming –

Tube hydroforming allows engineers to optimize their designs through cross sectional reshaping and perimeter expansion. Combined with the ability to inexpensively

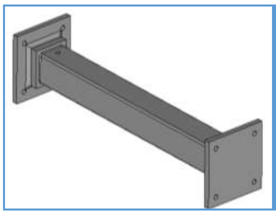
Create the holes that are required for vehicle subsystem interfaces, hydroforming has become a critical technology for structural components in mass-produced vehicles.

6.5) Press break –

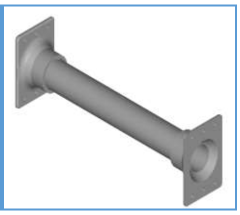
Press breaking is efficient and cost-effective compared to the other options, but only at small volumes and with shorter part lengths. Larger orders get expensive very quickly, as the break forming process is labor intensive. Break presses are also unable to handle longer parts.

6. SHAPE OPTIMIZATION

FE analysis of Chassis Frame with Hollow Square Cross Member



Rectangle Section CM



Round Section CM

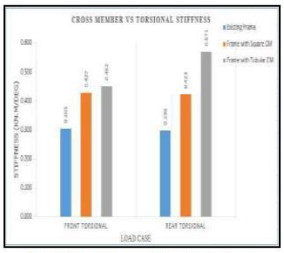


Fig.13: Comparison of Torsional Stiffness.

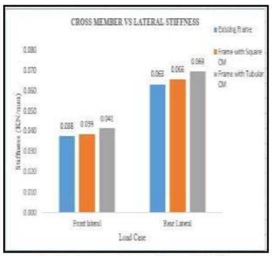


Fig.14: Comparison of Lateral Stiffness.

Fig.15 and Fig.16 show the Strain energy contribution of existing C-section cross member, hollow square cross member and tubular cross member respectively in front and rear torsion load cases.|

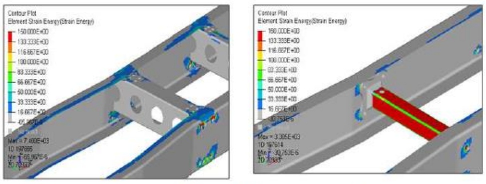


Fig 15: Strain energy contribution of 3^{rd} cross member in front torsion load case

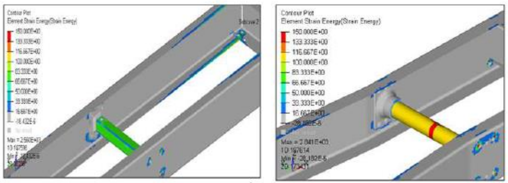


Fig 16: Strain energy contribution of 7^{th} cross member in rear torsion load case

Conclusion of above study

The existing heavy vehicle chassis of 25 tonnage model is analyzed with different cross sections. After Stiffness analysis a comparison is made between three different cross member sections with respect to torsional Stiffness of the chassis. From the analysis results, it has been observed that the hollow square section and tubular Sections is superior to the existing C-Section. Torsional stiffness of the chassis by using hollow square cross Member is increased by 29% and lateral stiffness by 3.80%. Although this adds additional weight of 7.8 kg to the chassis frame. Chassis frame with tubular cross members provides 47% increment in torsional stiffness and 0.7 kg. Hence from the analysis it is concluded that the tubular section is best for improvement of torsional stiffness of the chassis frame under consideration 8.86% increment in lateral stiffness. Also the weight increment by using Tubular cross member is very small

7. CONCLUSIONS

Weight of cross member can be optimized min5-10% with changing low strength material to high strength material and thickness. In this method less modification or tooling cost to be involved

Communization and carry over less weight part providing the advances for maximum optimizing weigh and cost

Redesign of major contributor component can be change by validating through CAE and getting maximum benefit of weight saving

Through CAE validation optimization of chassis components deletion can be achieved.

Replace the expensive and non-flexible manufacturing processes to unexpansive a flexible process. So modification and design change incorporation will easy and lead to faster product development cycle

ACKNOWLEDGEMENT

We wish to express our sincere thanks to K Anbarasan Sir for their help and guidance given time to time

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