Automotive Chassis Sizing Optimisation for Modal and Distortion Criteria

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Abstract

Weight is one of the important design drivers of automotive members. In case of primary load bearing members, such as the chassis, the design process is driven by numerous manufacturing and performance requirements. As a result, weight saving efforts are typically taken up only in later design cycles rather than in the preliminary ones. In this paper, a robust optimisation approach that can be used in the early stages of design, and that results in weight saving, has been described..

The methodology developed has been applied to size optimisation of a typical chassis structure used in automotive application. Optimisation of the structure has been carried out with modal frequencies and frame deformation under static payload, as the constraint parameters. An in house code GENSIZ was used to carry out the optimisation runs.

Up to 20% weight reduction was achieved for the modal frequency constrained optimisation and for deformation constrained optimisation the weight saving schieved was in the range of 30 to 35%. With mass relocation, up to 17% reduction in the deformation of the structure was achieved . The cross assessment of modal thickness data analysed for distortion study showed a weight reduction of 19%, modal frequency reduction of 17% and a 1% reduction in deformation.

Key Words: Finite Element Analysis, Genetic Algorithm, Optimisation

Abbreviations

CG	Center of Gravity
FE	Finite Element
GA	Genetic Algorithm
SPC	Single Point Constraint
GENSIZ	Genetic Sizing

1. INTRODUCTION

With growing emphasis on light weighting vehicle, mathematical techniques like optimisation are being used in the product design and development process. Chassis is one of the key structural members of a vehicle. Every chassis design is a compromise between weight, size, performance requirements like torsional stiffness, bending stiffness, NVH requirements, packaging and cost. With so many competing requirements, use of mathematical models provides a suitable means for design assessment and improvement. Algorithms, well suited for multi-constrained optimisation, can be successfully applied for such designs to arrive at safer structural designs with improved performance and lower overall weight and cost.

1.1 Optimisation

Optimisation is a procedure of finding and comparing feasible solutions until no better solution can be found. When an optimisation problem involves only one objective function, the task of finding the optimal solution is called single objective optimisation. When an optimisation problem involves more than one objective, the task of finding one or more optimum solution is known as multi objective optimisation.

1.2 Optimisation Methods

Some of the algorithms developed for optimization are:

a) Gradient based algorithm
b) Heuristic based algorithm
c) Deterministic algorithm
d) Stochastic algorithm
e) Evolutionary algorithms this includes genetic algorithms, evolution strategy, evolutionary programming and genetic programming.

Till recently, optimisation related studies involved finding optimum value in the presence of constraints. More focus was on the theoretical aspects of optimality, convergence proofs, and special purpose optimisation algorithms for nonlinear problems, such as integer programming, dynamic programming, geometric programming, stochastic programming etc. Not enough emphasis was given to multi-objective optimisation. This is because majority of multi objective optimisation case studies avoided the complexities involved in a true multi objective optimisation problem and transformed multiple objectives into a single objective function by using some user-defined parameters.

Theories and algorithms for single objective optimisation can be applied to the optimisation of the transformed single objective function. However, there is a fundamental difference between single and multi objective optimisation which is ignored when using the transformation method. For example, faced with two optimal choices, 1 and 2, while selecting a car to buy, if one is willing to sacrifice cost to some extent from solution 1, one can probably find another car with a better comfort level than this solution. Here, the extent of sacrifice in cost is related to the gain in comfort. Similarly, the possibility of existence of a set of optimal solutions 1, 2, A, B and C, where a gain in one objective calls for a sacrifice in the other objective, exists. And, for proper decision making, knowledge of such multiple optimal solutions arising out of trade-offs between conflicting objectives, is important. It is not easy to decide which car to buy since it involves many other considerations such as the total finance available, distance traveled per day, number of passengers, fuel consumption and cost of running, social status and many other factors. Often such higher level in formation is non-technical, qualitative and experience-driven. If a set of many trade-off solutions are available, one can evaluate the pros and cons of each of these solutions based on these higher information and compare them to make a choice.

1.3 Genetic Algorithms

Genetic algorithm (GA) is a method, based on natural selection, the process that drives biological evolution, for solving both constrained and unconstrained optimisation problems. It repeatedly modifies a population of individual solutions. At each step, genetic algorithm selects individuals at random from the current population as the parents, and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution. GA can be applied to solve a variety of optimisation problems that are not well suited for standard optimisation algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear.

GA uses three main types of rules at each step to create the next generation from the current population. These rules select the individuals, called parents, who contribute to the population at the next generation. Crossover rules combine two parents to form children for the next generation. Mutation rules apply random changes to individual parents to form children.

GA have evolved over the last three decades to be recognized as a very powerful tool in obtaining solutions to non-engineering and engineering design optimisations. Simple GA is powerful, efficient and robust for structural design problems.

1.4 Working of Genetic Algorithms

A GA begins by creating a random initial population. It then creates a sequence of new populations. At each step, the algorithm uses the individuals in the current generation to create the next population. To create the new population, the algorithm performs the following steps. It scores each member of the current population by computing its fitness value. Then it scales the raw fitness scores to convert them into a more usable range of values. Next, members, called parents, are selected based on their fitness. Some of the individuals in the current population, that have lower fitness, are chosen as elite. These elite individuals are passed to the next population. From the parents children are either by making random changes to a single parent, mutation or by combining the vector entries of a pair of parents crossover. The algorithm then replaces the current population with the children to form the next generation. This process continues till one of the specified stopping criteria is met (Figure 1).

2. CHASSIS OPTIMISATION

Minimising weight of an automobile has always been, and remains, a goal for the automobile manufacturers. Chassis structure being one of the heavier components of an automobile has always attracted attention of the designers looking for potential weight savings. Availability of better optimisation algorithms and computing power has allowed designers to analyse chassis structure in more details and come up with designs that are lighter yet meet the performance criteria.

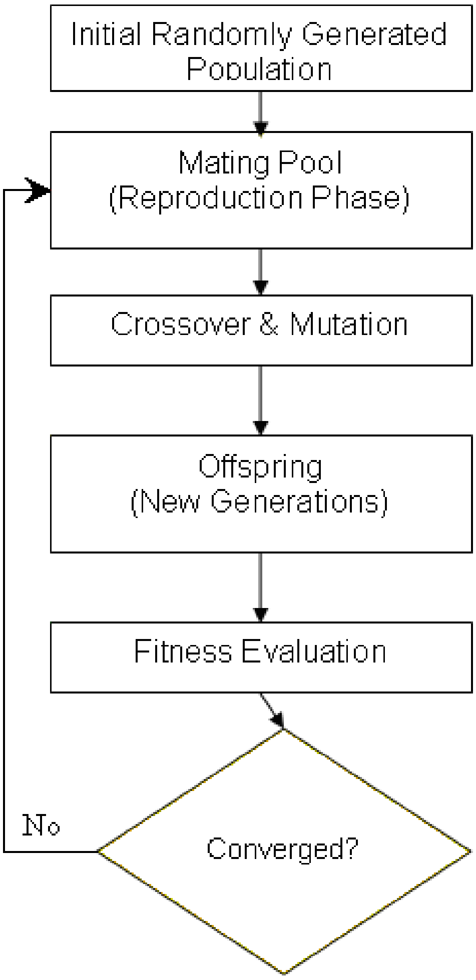


Fig. 1 Steps in a GA Based Optimisation Process

For anyone involved in the design of a ladder type chassis structure, publication by Richard L Exler [1] provides an excellent insight into how various structural members of different shapes and sizes when put together in a chassis meets the load carrying and stiffness requirements. The paper also identifies the strength and weakness of various members to provide direction for the optimisation exercise. References [2] through [5] also provide extensive information about automotive chassis design and performance.

Edmund F. Gaffney III et al [6] have explained the design methodology for Formula SAE suspension and frame design – a methodology that addresses the required compromise between stiffness, weight and packaging constraints.

Juan Pablo Leiva [7] has described the use of GENESIS program to solve structural optimisation problems of automobile designs. In this work the capability of GENESIS in solving different types of structural problems and carrying out sizing, shape and topology optimisation have been adequately demonstrated. Capability of GENESIS in optimizing composite pickup truck chassis structure has been used in the work by Naveen Rastogi [8].

Paper by Kazuhiro Saito et al [9] describes structural optimisation for linear static (stress and displacement), normal modes and eigenvalues. In this paper optimisation algorithms like nonlinear programming (NLP), meta-heuristic, reliability and robustness optimisation, and other special purpose algorithms are briefed. Geometry parameterization like size, shape and topology optimisation is covered in detail. It has been shown that these methods can provide very similar solution to mathematical programming methods with a lower computational cost.

In the work of Scott A. Mitchell et al [10], Genetic Algorithm and Scoring Mechanism are shown to work effectively and faster than Grid Optimisation technique through their application on automotive suspension geometries.

Andreas Hoppe et al [11] have explained multidisciplinary optimisation (MDO) systems and requirements for automotive body. This paper covers optimisation examples of full car for crash and NVH load cases, restraint systems and pedestrian protection.. The aim of the multidisciplinary optimisation approach is to consider all participating disciplines that are defining constraints on the design in one single numerical optimisation procedure. The paper also highlights on parameters to be checked carefully before one can start a multidisciplinary optimisation as they have a large influence on the appropriate strategy.

3. CHASSIS ANALYSIS

A vehicle chassis is designed to carry the payload, weights of other structural components mounted on it and instantaneous loads like large pot-holes, kerb bumps, large bumps, panic braking, high 'g' cornering, high power train torque etc. The chassis has to withstand and give adequate performance under all these load conditions. The chassis stiffness and natural frequencies vary according to the load distribution on a chassis under above mentioned load conditions. The instantaneous requirement of chassis is strength, other performance requirements like frequency, distortion are considered for chassis.

The objective of the project is to carry out an analysis of the current chassis design, and carryout sizing optimisation for modal frequencies and distortion. The chassis geometry used was obtained from Mahindra & Mahindra Ltd. A Finite Element Model of the geometry was developed using HYPERMESH v 7.0 [12]. MCS/NASTRAN 2005 [13] was used for modal analysis and linear static analysis of the chassis under several vertical and cornering load conditions. Various critical regions like radiator, engine and transmission, front and rear suspension mounts, BIW mounts and fuel tank mounts were identified. The optimisation process was carried out using program Genetic Sizing (GENSIZ) [14].

3.1 Geometric Analysis

The geometric model of the chassis was used to develop FE models of the chassis. Mid surfaces of the structural components were extracted to mesh using shell elements. Two different models were developed -- one for modal analysis, and the other for static analysis. Considering the number of iteration required for optimisation process, the size of the model was limited so that the time required for iterations can be kept to a reasonable level.

The body structure was modeled using linear triangular and quadrilateral shell elements. Triangular elements were used only where made necessary because of the geometry of the components. Their use was minimized to avoid artificial stiffening of the structure. Rigid elements were used to connect nodes that are connected by joints in the actual structure. Bar and spring elements were used where necessary. The discretised model is shown in Figure 2.

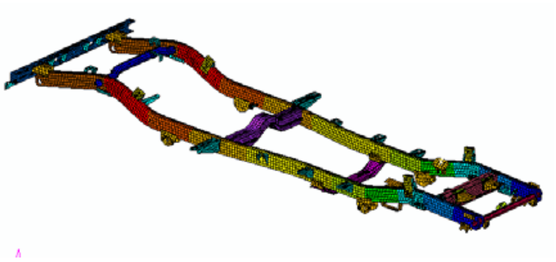


Fig. 2. FE model with all the Mounting Brackets

3.2 Mass Locations

Various components of the vehicle, like engine, body, suspension etc., were modeled using mass elements. Mass of the body was applied at a master node located at the center of gravity (CG) of the body and this node was connected to the ten body mounting points using rigid elements to distribute the weight of the body over the chassis. Similarly, the weights of engine, transmission, radiator and fuel tank were also modelled. The schematic of application of these weights is shown in Figure 3.

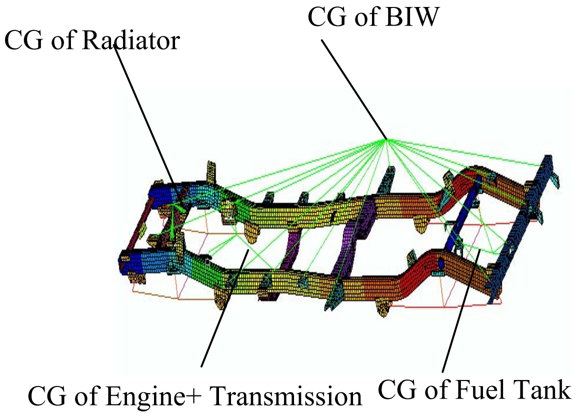


Fig. 3. Mass Distribution on Chassis

For the static analysis, the model was constrained at the axle centre points using Single Point Constraints (SPC), as shown in Figure 4. In the figure, number 1, 2 and 3 indicate constraints in X (along the length of the chassis), Y (towards the right side of the chassis) and Z (vertical) directions respectively.

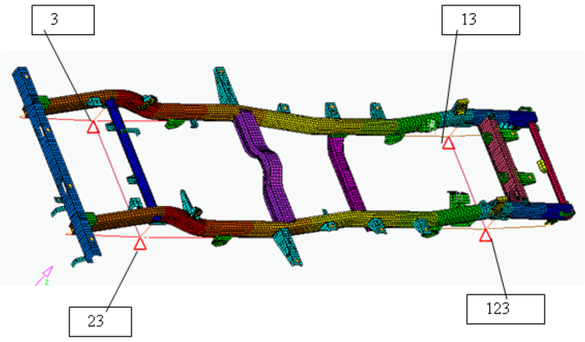


Fig. 4 Boundary Constraints Applied for the Static Analysis

Gravity (self weight) and acceleration loads (bump and cornering loads) were applied as body forces to the model. Acceleration loads of 3g vertical and 1g cornering were used in the static analysis.

For modal analysis, FE model without constraints and loads (Figure 2) was used. For static analysis, FE model with all the masses, loads and constraints was used.

4. BASELINE DESIGN ASSESSMENT

To form the basis for comparison for the optimised designs, modal and static analysis of the existing structure was carried out. Five critical locations on the structure were identified for the comparison of distortion. These locations are shown in Figure 5.

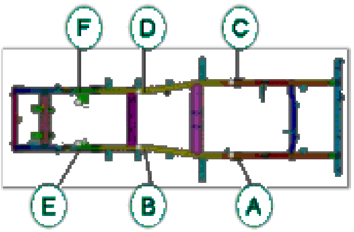


Fig. 5 Locations Used for Measurement of Distortions

The modal analysis for the chassis was carried out for free-free condition and without components like the radiator, engine, transmission, BIW, suspension, fuel tank etc. The first five frequencies of the structure, baseline values, are tabulated in Table 1 below. The modes shapes corresponding to the first three frequencies are presented in Figures 6 through 8. From the static analysis of the existing structure, distortions at six identified locations on the structure were obtained and used as a baseline parameter for assessing optimized designs. The distortion values are shown in Table 2.

Table 1 Natural Frequencies of Baseline Design

Mode No.	Frequency, Hz
1	29.4
2	32.1
3	36.5
4	49.5
5	53.5

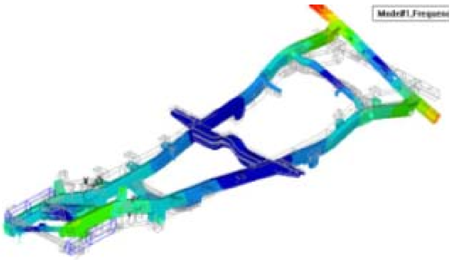


Fig. 6 First Mode of Baseline Design

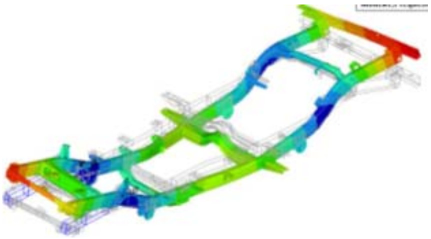


Fig. 7 Second Mode of Baseline Design

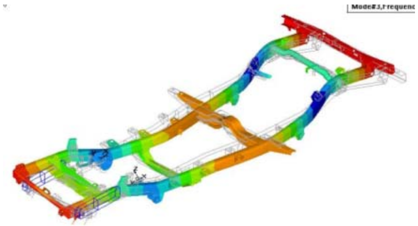


Fig. 8 Third Mode of baseline Design

Table 2 Baseline Design Distortions

Location	UX (mm)	UY (mm)	UZ (mm)
A	-0.26	1.14	-3.20
B	-0.18	1.51	-3.78
C	-0.09	1.15	-3.63
D	-0.07	1.46	-4.16
E	1.85	3.10	-1.59
F			-14.26

5. OPTIMISATION

5.1 GENSIZ

GENSIZ is a size optimisation program written in the versatile Gawk language. GENSIZ uses the genetic algorithm model for optimisation process. GENSIZ operates the FE solver, MSC/NASTRAN to obtain solution. The underlying objective function is a non-dimensional index that, when maximized, correspond to a high efficiency of the structural mass.

GENSIZ can handle,

- An unlimited population size.
- Strings of any length.
- Any number of P-Groups.
- Thin-walled, flat and curved structures of built-up nature (PSHELL).
- Liner, isotropic materials.
- MSC/NASTRAN solution types for eigenvalues and distortion. (SOL 101, 103 &105).

The working procedure of GENSIZ is shown in Figure 9 below.

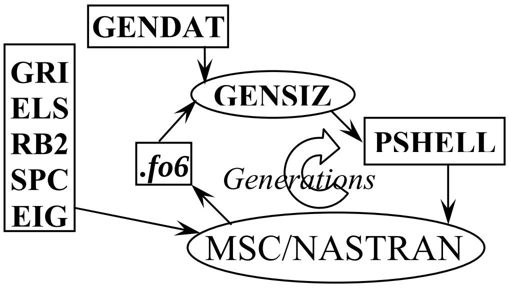


Fig. 9 GENSIZ Operation

5.2 Size Optimisation of Chassis Components

The FE model of the chassis was sub divided into 20 groups (P-groups), as shown in Figure 10 such that different thickness can be assigned to the components of different groups. For the purpose of optimisation, thickness and thickness variation information was fed into GENDAT file and the thickness values were optimised to control the mass of the chassis.

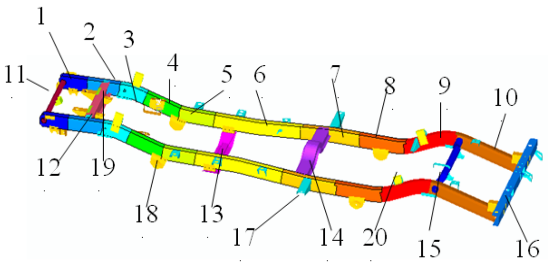


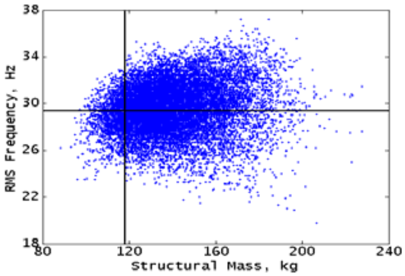
Fig. 10 Chassis Segment Groups (P-groups)

In the GENDAT file the thickness values for the 20 P-groups were varied from 2-8 mm in steps of 1 mm. 3 bits were allocated for each group segment. The number of design solution for this particular arrangement is 2^{60}. In this huge search space GENSIZ searches for results in the region of the fittest values. Two optimisation runs were carried out on the chassis structure. The first was to improve the size with respect to natural frequencies of the system while the second run was carried out to improve the sizes with respect to distortion values. The optimisation was carried in Pentium 4 [2.8 GHz] processor with 1 GB RAM. The results of the optimisation are discussed below.

6. RESULTS AND DISCUSSIONS

6.1 Case #1, N=1, Modal Optimisation

The first optimisation run was carried out to improve the natural frequencies of the chassis structure while reducing the mass of the chassis



Description	Baseline	Best Designs			Worst Designs		
		1	2	3	1	2	3
RMS Freq, Hz	29.4	26.2	26.3	26.5	27.6	30.7	25
Structural Mass, Kg	117.8	88.4	93	94.8	227.5	223.3	223

Fig. 11 Cloud Plot of Case #1, N=1 Archive Designs and Design Comparisons Chart

The cloud plot in Figure 11 shows the 16662 designs accumulated in the fitarchive.

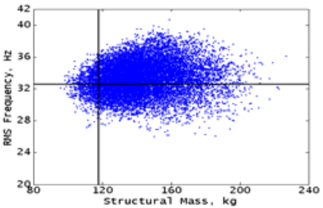
The best design comes out to be about 25% lighter (88.4 kg) and this structure's natural frequency is about 11% lower (26.2 Hz) than that of the baseline design.

The design with the lowest natural frequency, 23.5 Hz, weighs 96 kg, while the structure with the highest frequency, 37.2 Hz, weighs 171.7 kg.

With proper distribution of the thickness of the structural elements, a structure with the same mass as the baseline structure can be designed with natural frequency about 11% higher than that of the baseline structure.

6.2 Case #2, N=3, Modal Optimisation

The cloud plot shown in Figure 12 shows the 15822 designs accumulated in the fitarchive.



Description	Baseline	Best Designs			Worst Designs		
		1	2	3	1	2	3
RMS Freq, Hz	32.6	32.1	32.0	33.6	32.2	32.0	29.2
Structural Mass, Kg	117.8	95.9	98.1	98.2	222.1	222.7	205.0

Fig. 12 Cloud Plot of Case #2, N=3 Archive Designs and Design Comparison Chart

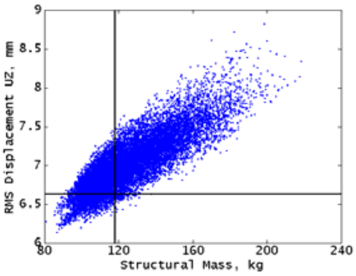
The best design comes out to be about 19% lighter (95.9 kg) and this structure's natural frequency is about 2% lower (32.1 Hz) than that of the baseline design.

The design with the lowest natural frequency, 27.3 Hz, weighs 111.9 kg, while the structure with the highest frequency, 40.7 Hz, weighs 158.9 kg.

With proper distribution of the thickness of the structural elements, a structure with the same mass as the baseline structure can be designed with natural frequency about 11% higher than that of the baseline structure.

6.3 UX - Optimisation

The main objective in this optimisation run was to maximize the performance to weight ratio, the performance parameter here is to reduce displacement due to the applied load.



Description	Baseline	Best Design					Worst Design		
		1	2	3	4	5	1	2	3
RMS distortion Ux, mm	0.79	0.66	0.68	0.67	0.66	0.70	1.36	1.22	1.20
Structural Mass, mm	117.8	79.6	80.0	80.3	81.7	82.0	234.8	226.5	223.0

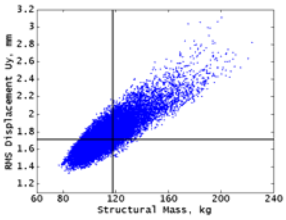
Fig. 13 Cloud Plot UX – Distortion and Design Comparison Chart

The cloud plot in Figure 13 shows the 17507 designs accumulated in the fitarchive.

The best design comes out to be about 32.4% lighter (79.6 kg) and for this structure distortion in the x-direction is 16.5% less than for the baseline design

6.4 UY – Optimisation

The cloud plot in Figure 14 shows the 16782 designs accumulated in the fitarchive. The vertical and horizontal lines indicate baseline design mass and UY distortion values respectively.



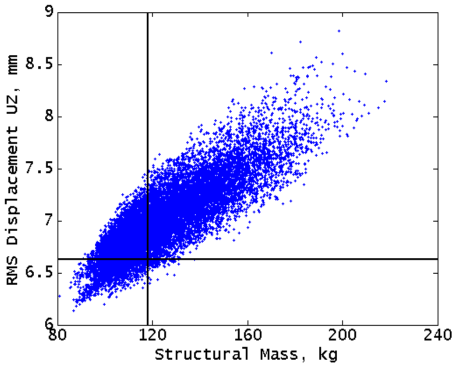
Description	Baseline	Best Design					Worst Design		
		1	2	3	4	5	1	2	3
RMS distortion, mm	1.71	1.42	1.39	1.42	1.42	1.43	2.83	2.64	2.53
Structural Mass, kg	117.8	76.99	78.88	79.04	79.12	79.13	223.51	220.87	214.78

Fig. 14 Cloud Plot UY – Distortion and Design Comparison Chart

The best design comes out to be about 34.6% lighter (76.99kg) and for this structure distortion in the y-direction is 17% less than for the baseline design

6.5 UZ – Optimisation

The cloud plot in Figure 15 shows the 16782 designs accumulated in the fitarchive. The vertical and horizontal lines indicate baseline design mass and UY distortion values respectively.



Description	Baseline	Best Design					Worst Design		
		1	2	3	4	5	1	2	3
RMS distortion, mm	6.63	6.28	6.36	6.36	6.41	6.24	8.34	8.15	8.08
Structural Mass, kg	117.8	80.97	85.34	85.80	85.86	86.76	218.33	217.65	215.20

Fig. 15 Cloud Plot UZ – Distortion and Design Comparison Chart

The best design comes out to be about 31% lighter (80.97kg) and for this structure distortion in the z-direction is 5% less than for the baseline design

6.6 Assessment of Buckling

In buckling the eigenvalues are scale factors that multiply the applied load in order to produce the critical buckling load. In general, only the lowest buckling load is of interest, since the structure will fail before reaching any of the higher order buckling loads. So, the assessment of buckling for baseline design and optimised designs are considered as given below.

The fitness best design #1 thickness data from Case # 2, N=3 is used to assess the buckling load for optimum design w.r.t baseline design.

The eigenvalues extracted for baseline design and one of the fitness best design are shown in Table 3 below.

Table 3 Buckling Load Factors for Baseline and Optimum Design

Mode	Load Factor	
	Baseline design	Optimum design
1	23.29	23.29
2	26.35	26.35
3	27.58	27.58
4	-33.45	-33.45
5	36.17	36.17

The optimum design load factor is same as baseline design; hence the optimum design is adequate from buckling criteria with respect to the baseline design.

6.7 Assessment of Buckling

Based on the optimisation study for modal and distortion, best design 1 from Case #2 and best design 5 from Case 1 distortion UZ were selected for cross assessment. The cross assessment is to study the design adequacy of modal optimisation data for distortion and distortion optimisation data for modal.

The cross assessment shows reduction in mass, distortion and frequency with respect to the baseline design, as shown in Figures 16 and 17 and Table 4 below.

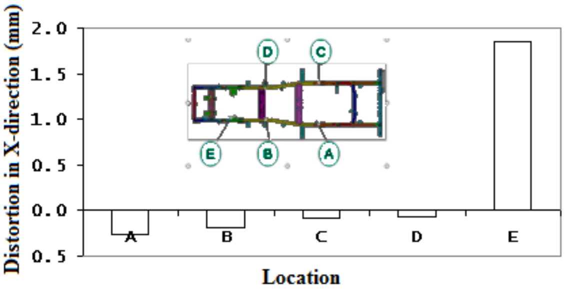


Fig. 16 Cross Assessment Results of UX-Distortion

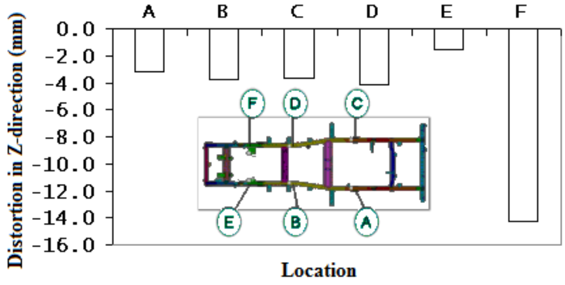


Fig. 17 Cross Assessment Results of UZ-distortion

The cross assessment for UZ distortion shows 1% reduction with respect to the baseline design.

The cross assessment for frequency shows 7% frequency reduction with respect to the baseline design.

Table 4 Cross Assessment of Frequency

Modes	Baseline design freq, Hz.	Cross assessment design frequency, Hz	RMS Freq. deterioration
1st	29.23	26.81	2.36 Hz (7%)
2nd	32.1	27.86	
3rd	36.1	35.34	
RMS	32.60	30.24	

7. CONCLUSIONS

The present study shows that GENSIZ can yield thousands of robust mass-efficient designs from modal and distortion criteria. The modal optimisation run resulted in a structural mass reduction of up to 20% from the baseline, with improved frequencies.

Distortion optimisation runs resulted in reductions of chassis mass by 32.4%, 34.6% and 31% for UX, UY, and UZ-components respectively with respect to the baseline design.

Distortion- optimisation runs resulted in reductions of distortion norms by 16.5%, 17% and 5% for UX, UY, and UZ respectively with respect to the baseline design.

The modal-optimum design was seen to even perform well for distortion criteria, with a 1% reduction in distortion norm., 7% in frequency and 19% in mass.

The chassis frequency can be increased upto 11% without increasing the baseline design mass and distortion

The above case studies have shown that by using optimisation it is possible to considerably improve structural designs. Improvements can be in terms of satisfying design requirements or in the objective functions themselves or in both.

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