

CHAPTER 4

A result-based comparative study of the suggested non-gradient method with the gradient descent method

4.1 Introduction

A lot have been discussed in Chapter 1 and 2 about the differences and effectiveness of gradient-based and gradientless/non-gradient/zero-order methods in the field of structural optimization. The current research proposes a zero-order method, and to assess its effectiveness relative to a gradient-based method, several basic structural shapes were optimized and the outcomes were compared to those generated by OptiStruct, a widely used software in the industry and academia for structural shape optimization. OptiStruct employs the Gradient descent method, also known as the Gradient Method, to locate the minimum value of the function, and utilizes the gradient value to perform local approximations assuming small changes in the design during each optimization step. To update the design, the solution of approximate optimization problems based on sensitivity data is used. The suggested approach (GSO) seems to

give a more industry-friendly and fabricable final optimized shape of structure compared to the OptiStruct.

4.2 OptiStruct

OptiStruct is part of the HyperWorks toolkit, as described earlier this is a finite element solver designed to solve linear and non-linear simulations. The pre-processing for OptiStruct is done using HyperMesh or HyperCrash and the post-processing is done using HyperView and HyperGraph. A structure can be optimised using a variety of techniques or algorithms. In OptiStruct, certain algorithms based on the Gradient Method are implemented. The design variables are aspects of a system that may change to enhance the system's performance. The kind of parameter or design variable specifies the optimization type for OptiStruct. Shape optimization in OptiStruct is an automated method for modifying the shape of the structure based on predetermined shape variables in order to determine the optimized shape. The geometric shape of the structure may be changed using design variables; on HyperMesh, HyperMorph is utilised to specify this parameter.

Any value or function that depends on the design variable and is assessed during the solution is referred to as a response for OptiStruct. In structural optimization, OptiStruct supports the use of various structural responses derived in a finite element analysis, or combinations of these responses, as objective and constraint functions. The Objective function can be maximised or minimised as a model response. In OptiStruct, there are two methods for declaring an objective. It is possible to minimise or maximise the highest or lowest value of a single response as well as the maximum or minimum values of a collection of normalised responses.

To handle the optimization problem, OptiStruct employs an iterative process referred to as the local approximation approach. With each optimization cycle, this method is predicated on the idea that only minor modifications to the design take place. There is a local minimum as a result. The majority of the changes occur in the initial iterations of optimization; therefore minimal system analysis is required in real-world applications. One of the most crucial components to going from a straightforward design variation to a computational optimization is the evaluation of design sensitivity for the structural responses. A rudimentary optimization problem that is created from the sensitivity data is solved to calculate the design update. The OptiStruct uses three distinct methodologies: (a) a primal feasible direction method, (b) the dual method, and (c) the optimality criteria method. The shape optimization in OptiStruct uses the primal feasible direction method, which is based on convex linearization of design space while the others are used in other forms of optimization.

4.2.1 Optimization procedure: OptiStruct

OptiStruct modifies the outside boundary of any given structure for its shape optimization. The grid point positions are used in finite element models to determine the shape. As a result, changes to shape affect those points. To address structural shape variations and their impact on the interior mesh and prevent mesh distortion, OptiStruct adopts a perturbation vector approach. The structural shape alteration is determined using a linear combination of perturbation vectors. Approximate probable shapes are at first defined as perturbations added to the vector of nodal co-ordinates (X_0 , Y_0) as represented by Equation 4.1 and shown in Figure 4.1. Using a linear combination of the perturbation vectors, the weights of the perturbation vectors may then be used to define the design variables for the optimization. Each shape vector has a single design variable.

The change in structural shape for the optimized shape is then achieved by determining the optimum set of the shape weights. The mesh nodal movement is given by Equation 4.2

$$X = X_0 + \Delta X \tag{4.1}$$

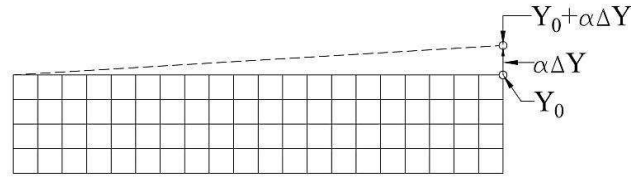


Figure 4.1: Description of shape design variable.

$$\left. \begin{aligned} X &= X_0 + \sum_{i=1}^n \beta_i \Delta X_i \\ Y &= Y_0 + \sum_{i=1}^n \alpha_i \Delta Y_i \end{aligned} \right\} \tag{4.2}$$

Where, X, Y is the vector of nodal co-ordinates for the changed shape, X₀, Y₀ is the vector of nodal co-ordinate for initial shape, n is the number of shape/ design variables, β and α are the magnitude of perturbation, ΔX and ΔY are the perturbation vector. For the present study weight is minimized under the constraint of maximum shear stress.

4.2.2 Convergence criteria: OptiStruct

OptiStruct employs two types of convergence criteria, namely regular convergence and soft convergence. Regular convergence is attained when the constraint violation remains below 1% for two consecutive iterations, and the change in the objective function value is less than the objective tolerance. Regular convergence necessitates a minimum of three analyses since the convergence is based on a comparison of the most recent objective values. In contrast, soft convergence is reached when there is minimal or no

alteration in the design variable for two consecutive iterations, requiring one less iteration than regular convergence.

The working steps of OptiStruct are shown as flowcharts in Figure 4.2.

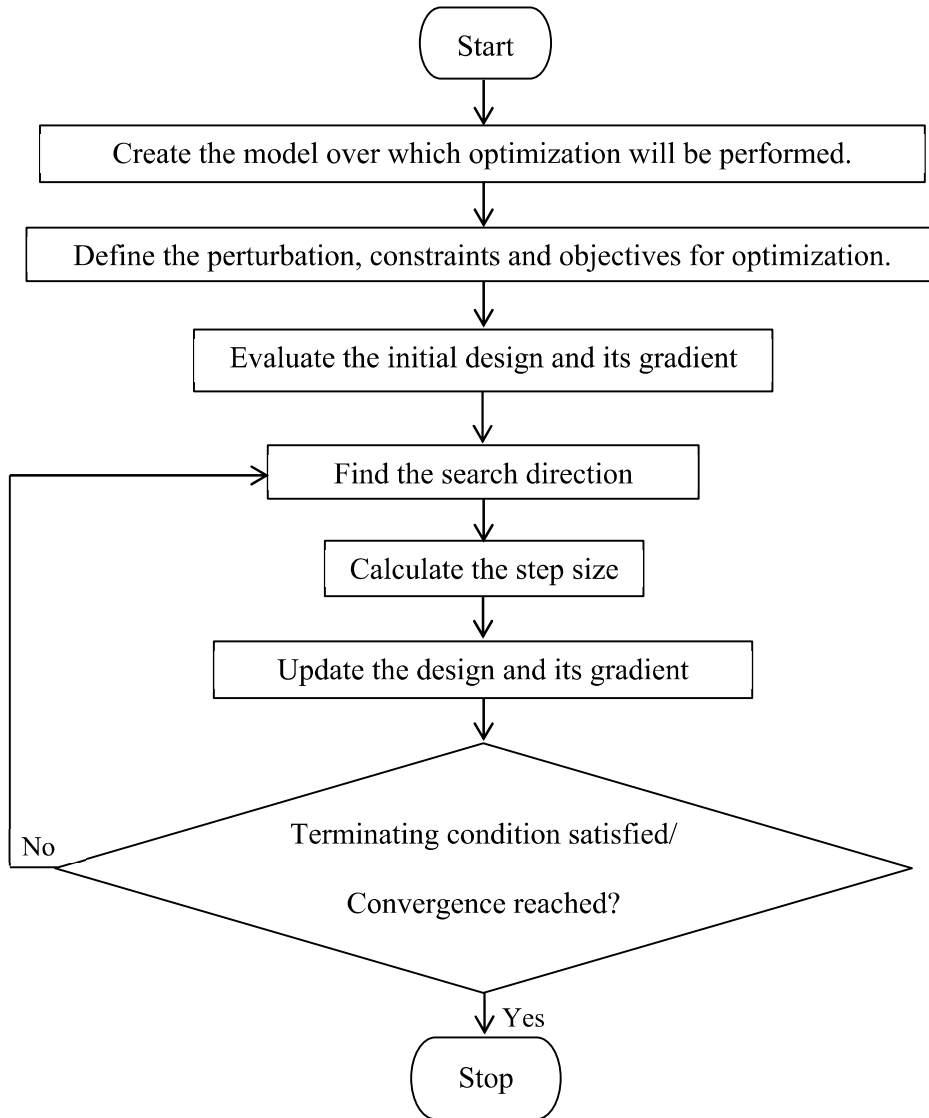


Figure 4.2: Working flowchart of OptiStruct

4.3 Mesh convergence and validation study.

A mesh convergence and validation study is being presented here to compare the convergence of OptiStruct to that of the GSO. This study will also serve to check the

validity of results obtained by GSO while analysing the structural elements. For the mesh convergence and validation study, a fixed beam having linear-elastic properties ($E=2.1 \times 10^5 \text{ N/mm}^2$, $\nu=0.3$ and $\rho = 7.85 \times 10^{-5} \text{ N/mm}^3$), dimensions as (1000x150x100) mm with a point load of 100 kN at the centre is taken. The model is prepared in both OptiStruct and GSO with varying average element sizes from 200 to 5 and is compared with the bending stress (Φ) calculated using the conventional formula (Formula A) $\Phi = M/Z$. The result of the study is presented in Figure 4.3. It is noticed that the OptiStruct model converges at an average element size of 10 whereas the GSO model gets converged early at a relatively bigger average element size of 50. The average element size of 10 and 50 is now used successively hereafter for the present analysis in OptiStruct and GSO respectively.

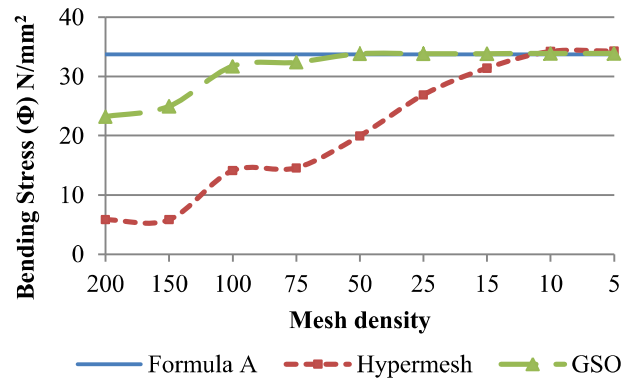


Figure 4.3: Mesh convergence and validation

4.4 Numerical illustrations and discussion

After conducting validation and mesh convergence studies, the present study compared the optimized shape of several problems using different optimization parameters under two different approaches. The objective was to achieve the target maximum shear stress while altering the overall weight for the final optimized shape. Four structures were

considered: three different types of beams (B1, B2, and B3) and a circular plate with a square cut-out (CC). The structures were also checked for permissible deflection criteria as per IS 456:2000, to ensure that the obtained final optimized shape does not fail the serviceability criteria.

The B1 beam is a straight beam with simple support on its edges and a concentrated point load at its centre. It was optimized with a design constraint of keeping the top flat. In the GSO approach, only the design nodes on the bottom face of the beam were allowed to move, while in OptiStruct, only the design variables on the bottom face were given.

The B2 beam is a curved beam with fixed ends and two concentrated point loads placed asymmetrically. It was optimized from both top and bottom to compare the effect of asymmetric loading on the optimized shape obtained by the two different methods.

The circular plate (CC) was loaded with a uniformly distributed load along its circumference. Due to the symmetry of the circular plate, only a quarter part was considered and analyzed for shape optimization. The shape of the cut-out was optimized and compared in this illustration.

The material properties used for further studies in this chapter, unless stated otherwise, are $E = 2.1 \times 10^5 \text{ N/mm}^2$, $\nu = 0.3$, and $\rho = 7.85 \times 10^{-5} \text{ N/mm}^3$. Table 4.1 shows the number of iterations and system time taken by GSO and OptiStruct to obtain the optimized shape of B1, B2, and CC, along with the percentage weight reduction. The final optimized shape obtained for B1, B2 and CC by GSO and OptiStruct is shown in Table 4.2.

Table 4.1: Parameters for B1, B2 and CC with iterations, runtime and percentage weight reduction to reach the optimized shape.

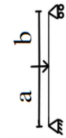

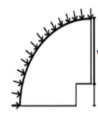
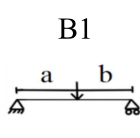
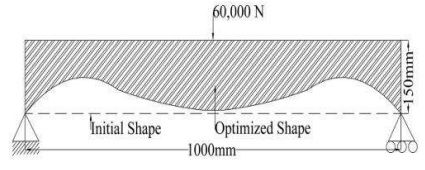
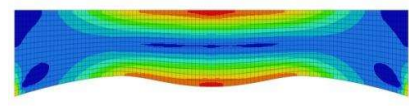

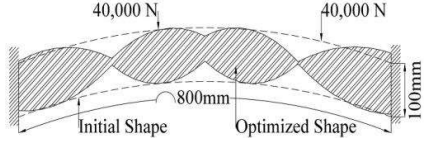
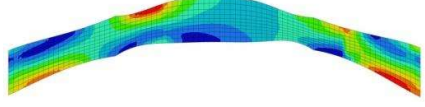
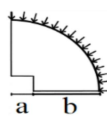
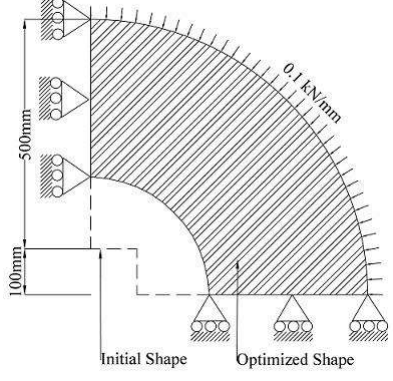
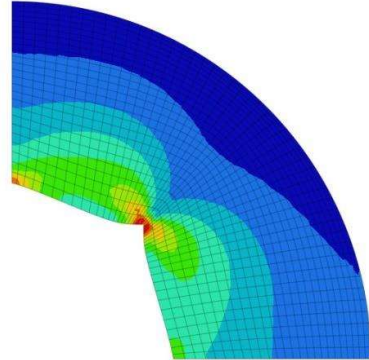
Type of structure	Dimensions (mm)	Loading	σ_t (N/mm ²)	Iterations (Nos.)		Runtime (Sec.)		Weight Reduction (%)		Max. deflection (mm)	
				GSO	OptiStruct	GSO	OptiStruct	GSO	OptiStruct	GSO	OptiStruct
B1 	L = 1000 H = 150 D = 50 a = b = 500	Point Load (60 kN)	40	28	5	07	10	25.58	15.74	0.937	0.839
B2 	Cur. L = 800 H = 100 D = 100 a = 300 b = 150	Two-point load (40 kN and 40 kN)	20	177	5	22	09	20.18	41.27	0.084	0.116
CC 	R = 600 D = 5 a = 100 b = 500	Uniformly distributed load (0.1 kN/mm)	20	69	4	09	10	15.04	18.69	--	--

Table 4.2: Final optimized shape of B1, B2 and CC.

Type of structure	Final optimized shape	
	GSO	OptiStruct
<p>B1</p> 		
<p>B2</p> 		
<p>CC</p> 		

The third structure examined in this study is Beam B3, which is a composite beam consisting of two different materials fixed at the ends and uniformly loaded throughout. The objective of Beam B3 is to compare the effects of different material properties on the optimized shape. To achieve this, five different versions of Beam B3 (B3a, B3b, B3c, B3d, and B3e) are created, with each version having different material properties. The dimensions of all versions of Beam B3 are the same, with a length of 1200 mm, height of 200 mm, and depth of 100 mm. The two materials used are referred to as Material 1 and Material 2, and Material 2's Young's modulus is gradually changed for each version of Beam B3 at the point where the bending moment becomes zero. The

serviceability criteria are not considered in this study, as the main objective is to investigate the maximum change in shape that can be achieved with different material properties for a target maximum shear stress. Table 4.3 shows the number of iterations and system time taken by GSO and OptiStruct to obtain the optimized shape for each version of Beam B3, along with the percentage weight reduction. Table 4.4 provides information on the co-ordinate changes required to achieve the final optimized shape for each version of Beam B3.

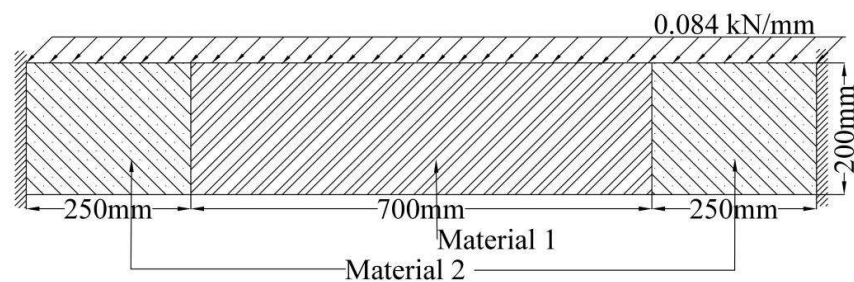








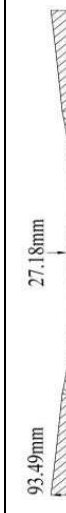



Figure 4.4: Schematic representation of beam B3.

Table 4.3: Parameters for B3a, B3b, B3c, B3d and B3e with iterations, runtime and percentage weight reduction to reach the optimized shape.

Type of B3 beams	σ_t (N/mm ²)	Iterations (Nos.)		Runtime (Sec.)		Weight Reduction (%)	
		GSO	OptiStruct	GSO	OptiStruct	GSO	OptiStruct
B3a	50	35	6	08	24	75.32	62.01
B3b	50	43	4	17	28	75.40	63.53
B3c	50	106	5	38	20	78.08	66.71
B3d	50	159	6	40	24	78.11	66.40
B3e	50	79	4	28	17	79.32	63.54

Table 4.4: Final optimized shape of B3a, B3b, B3c, B3d and B3e

Type of B3 beams	Material description (Young's Modulus)	GSO	OptiStruct
B3a	Material 1 : 2.1×10^5 N/mm ² Material 2: 0.2×10^5 N/mm ²		
B3b	Material 1 : 2.1×10^5 N/mm ² Material 2: 0.5×10^5 N/mm ²		
B3c	Material 1 : 2.1×10^5 N/mm ² Material 2: 1.0×10^5 N/mm ²		
B3d	Material 1 : 2.1×10^5 N/mm ² Material 2: 1.5×10^5 N/mm ²		
B3e	Material 1 : 2.1×10^5 N/mm ² Material 2: 2.0×10^5 N/mm ²		

Based on the validation and mesh convergence study conducted in section 4.4, it can be observed that GSO achieves convergence at an average element size of 50, which is larger than what OptiStruct requires to converge at an average element size of 10. Therefore, it can be concluded that the non-gradient method proposed in this study (GSO) needs a sparser mesh and fewer computations to achieve accuracy compared to the gradient descent method (OptiStruct).

Based on the results presented in Table 4.1, we can observe that while OptiStruct requires fewer iterations to reach the optimized shape compared to GSO, the time required per iteration in GSO is much less than that in OptiStruct. The average time per iteration in GSO is 0.23 seconds, while in OptiStruct it is 3.64 seconds. Both methods result in comparable weight reduction under the given target maximum shear stress. However, there are notable differences in the final optimized shape obtained by the two methods. The optimized shape obtained by OptiStruct has more sharp corners, which can lead to more points of stress concentration in structures B1, B2, B3, and CC. On the other hand, the optimized shape obtained by GSO has a smoother transition and more symmetry, even under asymmetrical loading as seen in B2. This feature makes the GSO method more suitable for fabrication and industry applications compared to OptiStruct.

The data in Table 4.3 and Table 4.4 show that GSO is more sensitive to changes in material properties than OptiStruct. The final shape obtained in OptiStruct is almost unchanged with different material properties, while the final shape obtained under GSO has changed significantly. As the Young's modulus increases from $0.2 \times 10^5 \text{ N/mm}^2$ to $2.0 \times 10^5 \text{ N/mm}^2$, the weight reduction for the same target maximum shear stress of 50 N/mm^2 has gradually increased from 75.32% to 79.32% in GSO. However, in

OptiStruct, there is no clear pattern of change in weight reduction with changing material properties..

4.5 Concluding remarks

This study effectively compared the capabilities of GSO with OptiStruct, which is a popular industrial software for shape optimization. The GSO was able to interact with the given constraints and changes in the structure while maintaining serviceability criteria. To achieve a desired optimized shape with faster convergence without compromising the quality of results, the correct design elements and selection of proper design nodes need to be defined. Furthermore, the program has a short overall runtime and does not require high-end computing capabilities. The final optimized shapes obtained by GSO show fewer stress concentration areas and sharp corners, making them more practical and adaptable for industry than those obtained by OptiStruct.