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Optical And Numerical Topology Optimization Of Structures

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Abstract

Topology optimization is esoteric. Computer-aided design includes. Design objectives and feasibility are the goals. This study optimizes the crane hook, a common mechanical component with complex geometry, using topology. The crane hook should be light but strong. Photoelasticity allows experimental verification of the design's stress distribution by visualizing and stress patterns in birefringent property materials.

Formulating the topology problem, design space, objective function, and constraints starts the study. The initial design and photoelasticity optics iterations are simulated using finite element analysis. Density method Isotropic Material with Penalization algorithm optimizes by iteratively updating the density distribution to improve the objective function while satisfying constraints. The design is then prototyped using a Photoelastic birefringent material. A known load and boundary conditions under polariscope experimental set-up stress the crane hook prototype. Computational topology and finite element analysis stress distributions are compared to isochromatic fringe principal stress patterns (1–2). Experimental and simulated results validate the design's stress, displacements, and reliability. The study showed

23.45% weight reduction while maintaining crane hook structural integrity. Photoelasticity experimentally verifies stress distribution, boosting confidence in the design. Computational simulations and photoelasticity allow mechanical component validation.

Keywords: Topology, Photo elasticity, Numerical analysis. Stress analysis. Stress optic law.

1. Introduction

Due to the scarcity of natural resources and the rising cost of raw materials, it is feasible for machines and structures to be lightweight, with fewer parts and enhanced performance. Design plays a crucial role in achieving these goals. Utilising numerical analysis and algorithm analysis, the topology method is implemented. Depending on the type of design variables used [1], techniques can be categorised as parameter, shape, or topology. While the objective of parameter is to modify the model's parameters, the objective of shape is to move part boundaries and constraints [2,6]. However, Topology is a technique for modifying the density of material regions in order to form a shape and topology that provides the optimal material distribution of material in a given design domain satisfying a predefined criterion. is iterative finite element analysis (FEM) involving the removal of material at each successive iteration [3]. In addition to permitting size and shape modifications, topology permits voids to appear and disappear in order to achieve an optimal design. The neighbourhood of structures that contribute the least to the overall stress level or stiffness is identified and removed in order to reduce the component's weight and increase its compliance [4][20].

In every field where material reduction is possible, computational topology has become an indispensable tool. It is possible to design mechanical structures conceptually and optimise their density distribution without compromising their strength. The photoelasticity experimental method is one of the recommended optical methods, topology utilising a light source, for achieving the optimal solution. For the design and development of new products, it is essential to find the optimal topology [5][18].

This research explores the contribution of optical method of topology, on evolving the multiple light-in-weight topologies of compliant mechanism, tracing user-defined path the evolutionary algorithm (NSGA-II) is customised to effectively handle the constraint bi-objective, non-linear and discrete problem of compliant mechanisms. The fundamental principle of photoelasticity is based on the birefringent property of certain transparent materials, such as glass and epoxy resin, which, when subjected to mechanical load, exhibit double refraction. When light passes through these stressed materials, its polarisation undergoes a change that can be observed with specialised equipment. By observing the resultant fringe patterns, analysts can infer the distribution of stresses and strains within a material. The research investigates the use of optical stress analysis for optimising topology, exposing the stress distribution through fringes. Examining these fringes reveals the stress distribution and optimises the components.

2. The Optical Stress Analysis Theory

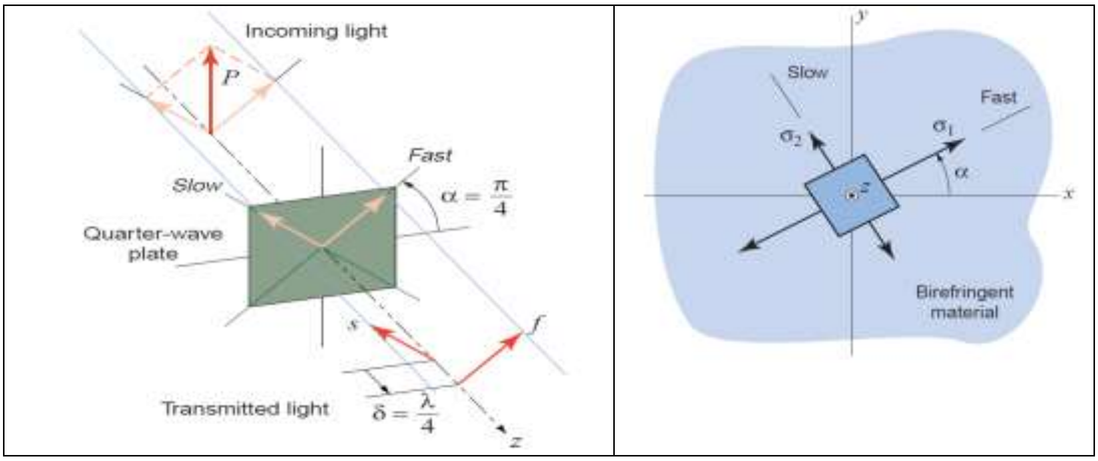
Photoelasticity is a non-destructive, whole-field, graphic stress-analysis technique based on birefringence, an optomechanical property possessed by numerous transparent polymers. In conjunction with other optical elements and when illuminated by an ordinary light source, a loaded Photoelastic specimen (or Photoelastic coating applied to an ordinary specimen) displays fringe patterns that are proportional to the difference between the principal stresses in a plane normal to the light propagation direction. The method is primarily applied to the analysis of two-dimensional plane problems, which is the focus of these notes. Stress freezing is a technique that allows the method to be applied to three-dimensional problems. Photoelastic coatings are utilised to analyse the surface stresses of complexly shaped bodies.

The sensitivity of a Photoelastic material is defined by its fringe constant f, which relates the value N associated with a given fringe to the specimen's thickness h during light-propagation. When a transparent material is subjected to mechanical load, its refractive index changes in different directions, a phenomenon known as birefringence. The term for this phenomenon is birefringence or double refraction. The stress-induced birefringence is proportional to the magnitude of the stress and the Photoelastic constant of the material.

Focus on Optics Law: The stress-birefringence relationship is governed by the Stress Optics Law, also known as the Photoelastic equation. It can be mathematically expressed as,

$$\Delta n = P\,\sigma \qquad (1)$$

where n represents the change in index of refraction, P represents the Photoelastic constant (a material property), and represents the applied stress.



(a) **(b)**

Figure 1: (a) Quarter Wave Plate (b) Birefringence Phenomenon

The circular polariscope (Figure 2) comprises a light source, a polarizer, a quarter-wave plate oriented at 45 degrees with respect to the polarizer, the specimen, a second quarter-wave plate, and an analyzer. The two imperfect quarter-wave plates are typically crossed (as depicted in Figure 2) in order to minimise error. The analyzer is either parallel to or crossed with respect to the polarizer (as depicted in

Figure 2). Again, the direction of polarisation of the polarizer is assumed to be vertical, and the expression (Eqn. 2) is used to represent the polarised light leaving the polarizer.

$$P\ ae^{i\emptyset} = F \qquad (2)$$

Consider now the light emanating from the second quarter-wave plate. As previously stated, the second quarter-wave plate is typically crossed in relation to the first quarter-wave plate. Consequently, this plate has the effect of "derotating" the light that was "rotated" by the first quarter-wave plate.

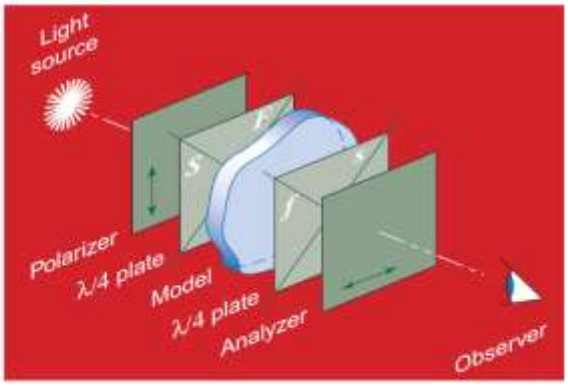


Figure 2: Circular Polariscope Arrangement

The results of a circular polariscope are isochromatic but not isoclinic. Often, the absence of isoclinic is desired, as the dark isoclinic in a plane polariscope obscures large portions of the model. Because of this, the majority of Photoelastic patterns published in the scientific literature are obtained using a circular polariscope. Now, the intensity of light leaving the analyzer can be calculated using

$$I = |A|^2 = a^2 \sin^2 \frac{\Delta}{2} \qquad (3)$$

Examining Equation (3) reveals that the entire field is dark when there is no model or when the model is unstressed, i.e., = 0 everywhere. The configuration of the circular polariscope that was just studied is therefore known as the dark field configuration. Analyse the isochromatic pattern. Using equation 4, the difference in principal stress is calculated.

$$\sigma_1 - \sigma_2 = \frac{N\, f\sigma}{h} \qquad (4)$$

The materials must have the birefringent property, which serves two purposes: 1. Photoelasticity separates incoming light into two components, one parallel to 1 and the other parallel to 2, and 2. It retards one of the components, M2, relative to the other, M1, by an amount proportional to the principal stress difference, 1-2.

3. **Numerical Analysis**

Utilizing the density distribution method, the numerical analysis determines the optimal layout for a linear elastic structure. In this context, "layout" refers to the topology, shape, and dimensions of the structure as well as its material distribution. Optistruct employs the Solid Isotropic Material with Penalty method. In the SIMP method, the design variable is a pseudo material density; consequently, it is also known as the density method. The density of the material varies continuously between 0 and 1, with 0 representing the void state and 1 representing the solid state. The crane hook asunder by design and non-design space as shown in Figure 3, the design space which analysis carried out, the non-design space remains unaltered.

The optical Topology method is established in order to achieve the optimal component layout. The 3D tetrahedron element used for meshing, topology constraints, and the problem statement have been set to achieve the optimal solution, density values and compliance by 25 iterations, the first optimal solution discovered at the 20th iteration, and the second optimal solution discovered at the 25th iteration. Figure 4 depicts the optimal solution for the crane hook's 20th iteration. Prior to component, displacement and stress distribution are examined using FEM analysis.

The software has had a significant impact on the practical application of topology design methods. Attained convergence criteria for an optimal solution. The component's density converges on the 20th iteration with a convergence value of 0.00483, and the second convergence occurs on the 25th iteration with a value of 0.0068. Convergence will be the determining factor for the component’s design.

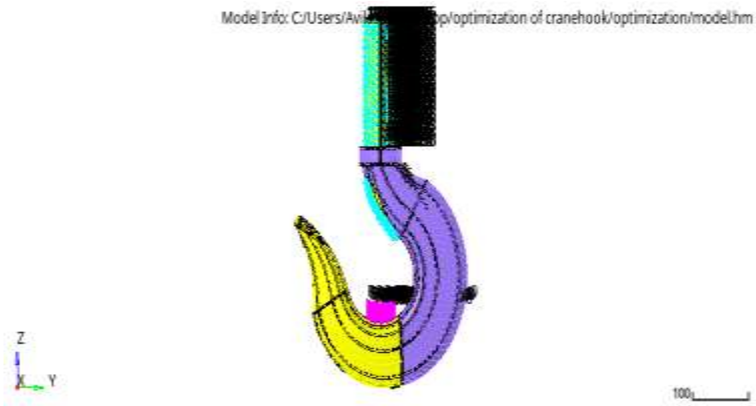
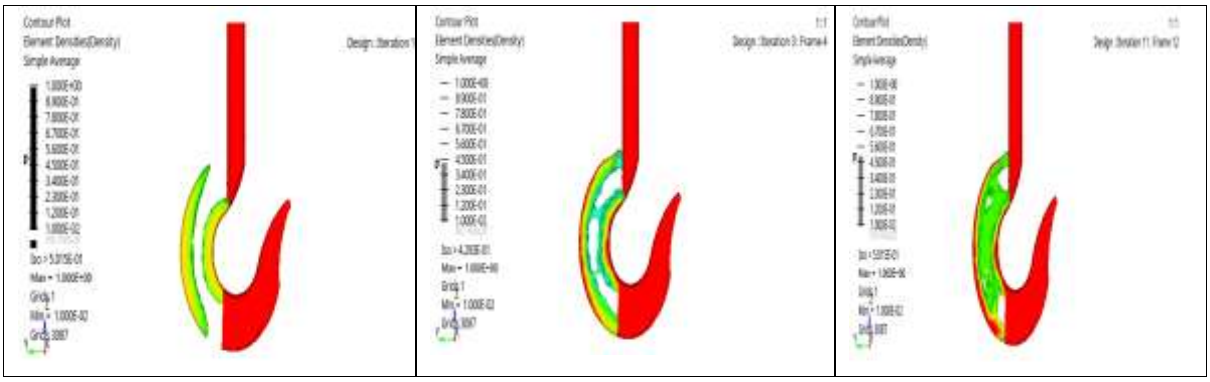


Figure 3: Design, Non-Design space and Boundary Conditions

It consists of determining the optimal distribution of density based on the level of stress in the component; to achieve this, the positioning of material in the structure is crucial for its optimality; therefore, the iterations that reached optimal convergence are displayed. The material removed from the area of the crane hook's design space where stress is low. The study has considered the third iteration. Each iteration displays the densities of the crane hook, with values ranging from 1 to 0. A value of 1 indicates that the material was retained, while values of less than 1 and 0 indicate that the material was removed. As depicted in Figure 4, the outcomes of Optisruct. The values for strain and displacement are tabulated.



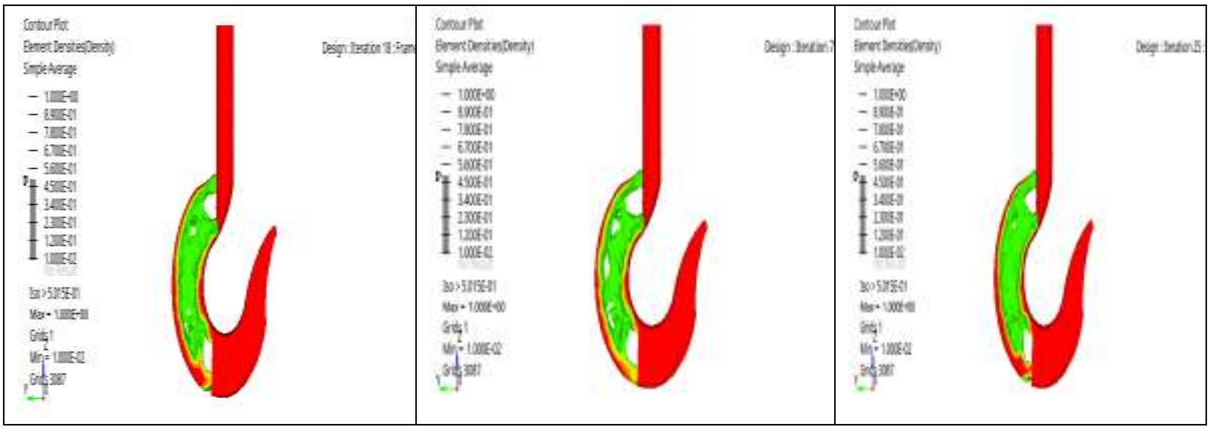


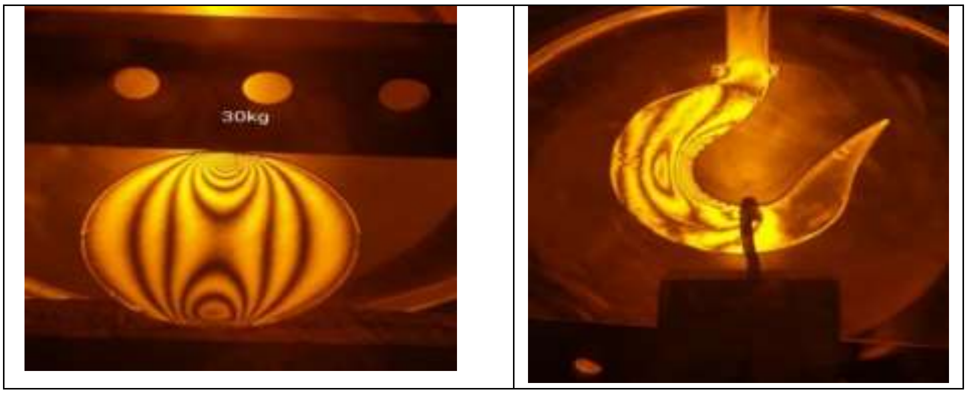
Figure 4. results from Optisruct.

The optimal solution convergence criteria. Convergence of the crane hook is attained after is attained. Therefore, the history of convergence for each iteration is examined to find the optimal solution.

4. Optical Photoelasticity Approach

The photo-elasticity method was applied to an epoxy resin circular disc model in order to calibrate the material and determine the material fringe constant. The specimen's diameter is 53 mm, its thickness is 5 mm, it is subjected to a diametric compression load, and it is observed using a photo-elastic, circular polariscope arrangement. Figure 2, depicts the experimental arrangement. The Photoelastic material has a fringe constant of 9.6 N/mm/fringe.

Experiments are conducted using a Photoelastic model of a crane hook with the same dimensions as the model used for numerical analysis. As shown in Figure 5, the hook is fixed at its upper end to the loading frame and is subjected to tensile loading. The experiment is conducted on a crane hook while loading conditions and attachments are considered. The optimal solution obtained after a specified number of iterations.



(a) (b)

Figure 5: (a) Calibration of photo Elastic Material. (b). Isochromatic Fringes

As shown in Figures 6(b) and (c), after observing the model with a polariscope, more material is removed by introducing additional slots. Figures 6(d), (e), and (f) depict the enlargement of these slots while ensuring that the stress level at the critical point is within the permissible range. The fringe patterns are observed from the inner circumference to the outer layer of the crane hook, the order of the fringes N is identified to achieve the , the lower order fringes are the location where the difference in principal stress is minimal, and the concept of is applied to these regions.

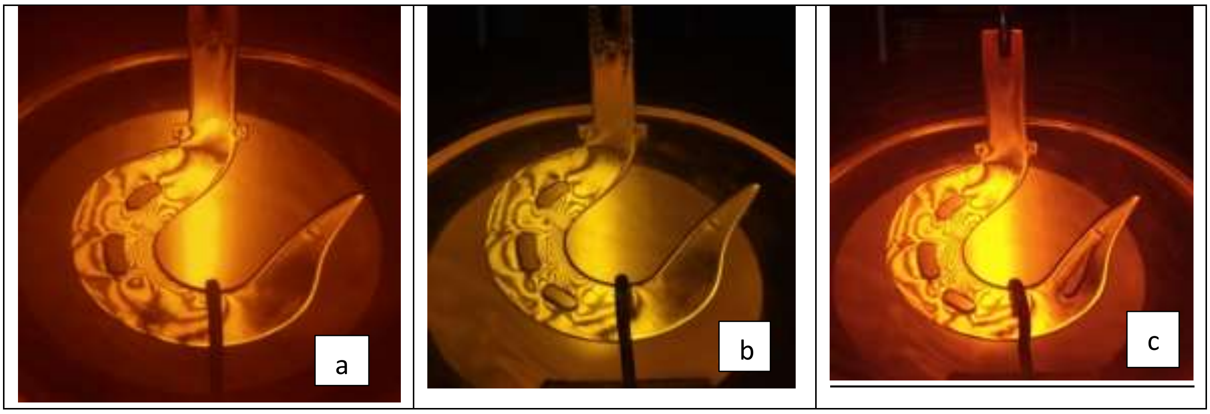


Figure 6; (a): 1st iteration - 2 slots are made; (b): 3 slots are made; (c): The material has been removed from the tip of the crane hook; (d): the upper slot dimension enlarged towards the fixed end; (e): the upper slot dimension enlarged towards the diametral surfaces; (f): The upper and middle slots dimension enlarged.

It is observed that the principal stress difference (1-2=0) when isochromatic fringes are observed, and 'N' is '0'. This is possible under two circumstances: 1) when both principal stresses are zero, and 2) when the principal stresses have the same magnitude and sign. Whether the point under consideration has '0' stress, a material can be removed based on the result of finite element analysis. Thus, a zero-stress point can be identified. Material is removed from these low stress regions, and the model with altered geometry is viewed through a polariscope. Iterations are performed until convergence is reached and a satisfactory design is achieved. For the experimental model's stress analysis, Altair Hyperwork solver is used to conduct the FEM analysis.

The boundary conditions and loads are implemented as if they were identical to the experimental photoelasticity method. Each iteration's principal stresses are determined to validate the experimentally determined principal stresses 1 and 2 and to determine the stress induced in each iteration after material removal. The stress induced in the crane hook before and after should be identical, as the present work focuses on without compromising the component's strength. Each iteration compares the stress results, and the results are appealing. FEM stress analysis identifies low stress regions,

Figure 7: FEM analysis before .

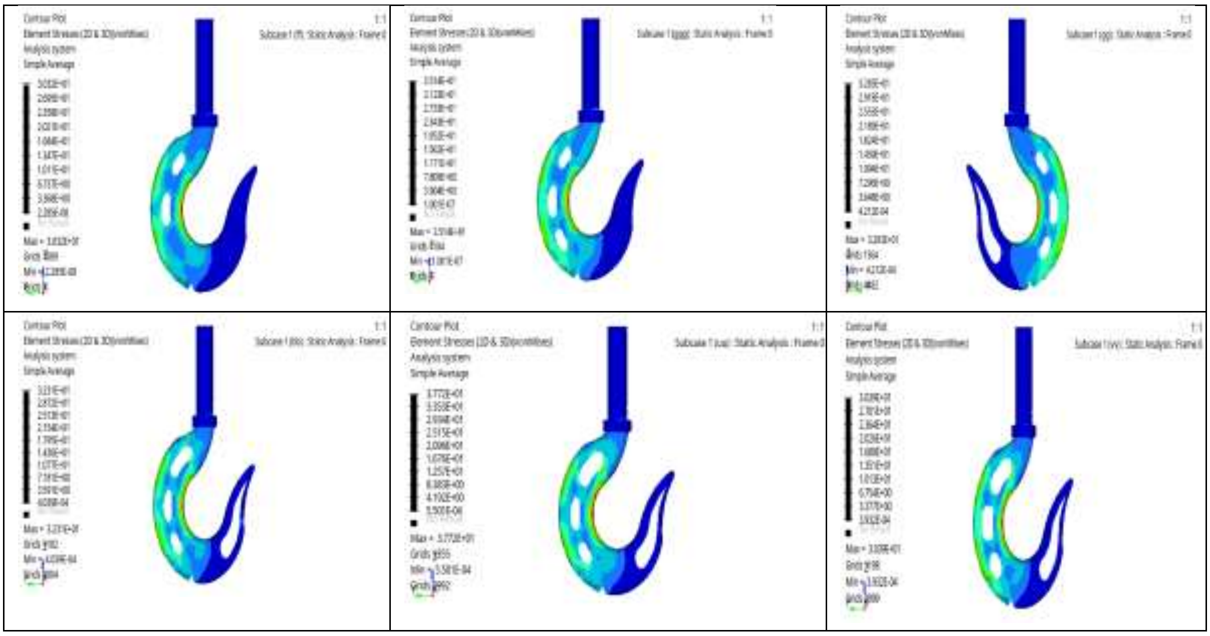


Figure 8: FEM analysis of iterations

5. Results And Discussions

This study demonstrates the viability of optimizing topology with the photoelasticity optical method. For density minimization, the pattern of isochromatic fringes in the initial geometry of the model and the corresponding 1 distribution are studied. A region of low stress is identified and material is removed from it. Figure 6 illustrates the experimental outcomes. The same procedure is repeated for the subsequent iteration. After the second cycle. The analysis reveals that the critical points are observed on the lower hole at the horizontal diameter's boundary points. It is evident from the observation of isochromatic fringes in this iteration that the stress level has not increased significantly despite the removal of material in successive iterations. The experimental, FEM analysis, and Optisruct results are compared and tabulated in Tables 1, 2.

The objective of this study is to demonstrate the viability of using the photoelasticity experimental method for topology. Therefore, the Optisruct, photoelasticity, and FEM analyses are compared to determine the optimal solution with the best performance. The principal stress (1-2) value after of the photoelasticity method is 11.43 Mpa, by the Optisruct method it is 10.89 Mpa, and by the FEM method it is 11.86 Mpa, while the stress before is 9.83 Mpa, 9.53 Mpa, and 9.53 Mpa (Figure 8). The optimal solution was found without compromising the crane hook's strength.

The numerical analysis using Optisruct enables the user to define the design and non-design space in order to achieve the optimal solution. However, the analysis is performed only in the design space, the non-design space remains unchanged despite the possibility of material removal, and the photoelasticity experimental method can be used to circumvent this issue. The experimental method permits the user to analyze the stress distribution as a model as a whole. Even in the non-design space, the density may be modified. As research concentrates on fringe order, which is a crucial parameter for topology, fringe order has become a focal point. The results indicate that the photoelasticity method reduces weight by 19.23% and Optisruct by 23.21%. This research enables the photoelasticity method for optimizing topology.

Table-1: The Comparison Results for FEM and Photoelasticity Experiment.

Iteration	Photoelasticity Experiment				FEM	
	Deformation mm	Stress Mpa	Load Kg	Weight Gram	Deformation mm	Stress Mpa
1	1	17.17		20.848	2.3	13.2
2	1	17.17		20.028	2.4	15.1
3	2	17.17		19.716	2.5	15.22

4	2	17.22	10	19.28	2.6	15.33
5	2.2	17.36		17.697	2.8	16.1
6	2.2	17.86		17.26	3	16.12
7	2.2	17.86		16.855	3.1	16.12

The above results demonstrate conclusively that the weight reduction method and computation method have converged and reached the optimal solution. The photoelasticity method can be used to optimise topology.

Table-2; Comparison results for Before and After.

Parameter	Photoelasticity experiment		Optisruct Results	
	Before	**After**	**Before**	**After**
Weight	20.848 gram	16.855 gram	17 kg	13 kg
Displacement mm	1	2.2	0.26	0.32
Stress MPa	17.176	17.95	15.65	16.1
% Reduction weight	19.15		23.82	

Conclusion

The photoelasticity method for topology provides a potent method for designing efficient and high-performance structures. By combining the visual insights gained from Photoelastic models with algorithms, engineers can optimize material distribution, thereby enhancing structural performance. Despite the challenges associated with scale, material limitations, and cost, the advantages of this method make it a valuable engineering tool for a variety of applications. Component weight can be decreased through topology. Limitations of quantitative method 1. Because they are computationally intensive, the entire domain must be separated into design and non-design domains. The design domain is for topology, while the non-design domain is left unchanged, even though stress levels in that region may be low. Using the experimental photoelasticity approach, these shortcomings can be eliminated. The photoelasticity method provides engineers with a visual representation of stress and strain patterns, enabling them to comprehend the structural behavior more thoroughly. Present research findings concluding that the photoelasticity optical method can be utilized as a topology tool for predicting the optimal component solution. The photoelasticity method is a useful tool for validating and refining the results of topology. It provides experimental insights into stress and strain patterns, enabling engineers to improve the precision and dependability of their computational models.

References

[1] Bendsøe MP, Kikuchi N (1988) Generating optimal topologies in structural design using a homogenization method. Compute Methods Appl Mech Eng 71:197–224.

[2] M.P. Bendsoe. of Structural Topology, Shape, and Material. Springer Verlag, Heidelberg, 1995.

[3] Bendsøe MP (1999), Variable-topology: Status and challenges, In: Wunderlich W. (ed): Proc European Conf on Computational Mechanics—ECCM '99, Aug 31–Sept 3, 1999, Munich, Germany, CD-Rom, Tech Univ of Munich, Germany, 21 pp

[4] Bendsøe MP and Diaz A (1998), A method for treating damage related criteria in optimal topology design of continuum structures, Struct. Optim. 16 (2/3), 108–115.

[5] zheng-dong ma, noboru kikuchi, multidomain topology for structural and material designs. July 2006, vol. 73 **/** 565.

[6] parís, navarrina, colominas, casteleiro, topology of continuum structures with local and global stress constraints. (2009) 39:419–437.

[7] Erik Holmberg · Bo Torstenfelt · Anders Klarbring. Stress constrained topology. (48), 1, 33-47.

[8] k.t. cheng and n. olhoff, regularized formulation for optimal design of axisymmetric plates, internat. j. solids and structures 18(2) (1982) 153-170.

[9] V. Tvergaard, On the optimum shape of a fillet in a flat bar with restrictions, in: A. Sawczuk and Z. Mroz, eds., in Structural Design (Springer, New York, 1975) 181-195; also, in: Proceedings IUTAM Symposium on in Structural Design (Springer, Berlin, 1973).

[10] Bendsøe MP (1989) Optimal shape design as a material distribution problem. Struct Optima 1:193–202.

[11] Duysinx P, Bendsøe MP (1998) Topology of continuum structures with local stress constraints. Int J Numerical Methods Eng 43:1453–1478.

[12] Liang QQ et al (1999) Optimal selection of topologies for the minimum-weight design of continuum structures with stress constraints. Proc Inst Mech Eng, C, J Mech Eng Sci (UK) 213(8):755–762.

[13] Navarrina F et al (2004) Topology of structures: a minimum weight approach with stress constraints. Adv Eng Softw 36:599–606.

[14] Hughes TJR (1987) The finite element method: linear static and dynamic finite element analysis. Prentice-Hall, Englewood Cliffs.

[15] Duysinx P (1995), topologies: Du milieu a la structure elastique, PhD Thesis, Faculty of Applied Sciences, Univ of Liege, Belgium.

[16] Ramesh, K., et al. "A simple approach to photo elastic calibration of glass using digital photoelasticity." Journal of Non-Crystalline Solids 378 (2013): 7-14.

[17] Ramesh, K., and Vivek Ramakrishnan. "Digital photoelasticity of glass: A comprehensive review." Optics and Lasers in Engineering 87 (2016): 59-74

[18] Sampson, Robert C. "A stress-optic law for photo elastic analysis of orthotropic composites." Experimental Mechanics 10.5 (1970): 210-215.

[19] Flores-Johnson, E. A., et al. "Photo elastic evaluation of fibre surface-treatments on the interfacial performance of a polyester fibre/epoxy model composite." Composites Part A: Applied Science and Manufacturing 42.8 (2011): 1017-1024.

[20] Bhima Raju, H. S. "Design & Analysis of Static Stresses for Leaf Springs using Photoelasticity & Numerical Methods", International Journal of Engineering Technology & Computer Research. 3(4), (2015): PP 225-236.

[23] Jadhav Mahesh, V., Zoman Digambar, B., & YR, K. "Performance Analysis of Two Mono Leaf Spring Used for Maruti 800", In Vehicle, 'International Journal of Innovative Technology and Exploring Engineering (2012, December)