ABSTRACT

In today's cost-effective engineering era, optimizing structural shapes is vital. This thesis focuses on minimizing construction costs while maintaining structural integrity. Conventional methods, like gradient-based approaches, can be computationally costly due to sensitivity calculations. Thus, a new multi-criteria-driven zero-order optimization method is suggested.

The work proposes an integrated zero-order fuzzy-controlled shape optimization technique. It optimizes structural components iteratively, automating mesh generation and refinement to maintain a smooth profile. Using design elements and fuzzy set theory, this method facilitates nodal movement, ensuring convergence towards a target maximum shear stress. The software created for this purpose, GSO (Gradientless Shape Optimization), undergoes testing with various structural configurations. Comparative analysis between the proposed zero-order approach and the widely adopted gradient descent method using commercial software reveals the proposed method's superiority in generating industry-ready designs, emphasizing its practical significance.

Expanding its scope, GSO optimizes steel-concrete-steel (SCS) sandwich beams by reshaping faceplates and core interfaces, enhancing structural performance and reducing steel usage. The optimized beam displays minimal deflection changes, around 10^{-4}, demonstrating the method's effectiveness.

Expanding on GSO, another innovative approach is introduced through the software "Simultaneous Shape and Cable Optimization" (SSCO). This technique optimizes both concrete shapes and cable layouts for pre-stressed concrete beams simultaneously, eliminating tensile stress and ensuring minimal concrete cover. Notably, SSCO boasts remarkable computational efficiency, with an overall runtime of less than 1 second for all demonstrated cases. The study also considers frictional losses

during post-tensioning, offering practical solutions for industry applications. Further, the research explores the impact of varying the number of spans in PSC beams on the optimized cable layout and concrete shape, emphasizing material savings. SSCO adeptly identifies the optimal number of spans, achieving a balance between material efficiency and the required supports.

Through these contributions, this thesis advances the field of structural shape optimization by offering cost-effective, efficient, and practical solutions to real-world engineering challenges.

PREFACE

During the current time, where there is a desire to achieve maximum returns while minimizing costs, it is crucial in the field of engineering to ensure that construction costs are minimized without sacrificing the durability and functionality of the structures. Taking this in mind, shape optimization is one of the best ways to achieve the aforementioned criteria. Shape optimization focuses on the way to improve the overall shape of the structure within the sense that it satisfies the given constraints imposed on it. Structural shape optimization is generally solved using either gradient-based methods or zero-order (non-gradient) methods. In gradient-based methods, sensitivity calculations are done, which mostly involve a large number of design variables making it computationally expensive. On the other hand, zero-order methods are much simpler and computationally less expensive. The current work is inspired by the previous research on zero-order methods in the area of shape optimization for structures, and aims to suggest a multi-criteria-driven zero-order procedure for the shape optimization of structural elements. The thesis addresses the following objectives in the field of structural shape optimization.

1. **Integrated zero-order fuzzy-controlled shape optimization.**

   An integrated zero-order technique is suggested, which focuses on automatic mesh generation and mesh refinement after every iteration to acquire a smooth profile and avoid any sharp corners causing erroneous shapes. To acquire a smooth profile, the notion of design elements is practised. In view of avoiding manual mesh refinement after each iteration, an automatic mesh generator has been created. The fuzzy set theory is utilized to manage the nodal movement of the design nodes and ensure final convergence. The shape modifications are made based on the chosen target maximum shear stress (σ_t) with the objective of achieving a result that is as close as possible to the target value at all points. This approach works on the zero-order shape optimization concept. The current approach has been developed as a software program called GSO (Gradientless shape optimization), which is written in the FORTRAN programming language. A few examples have been worked upon to show the working of the approach using different constraints like initial imperfections, fixed beams with different materials, beams with different types of loadings, and beams with flat tops. The approach seems to work in all conditions properly and gives a successfully optimized shape of different beams and plates considered.

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

Gradient-based techniques have gained much wider acceptance worldwide, and nearly all optimization software utilizes gradient-based methods, while largely overlooking zero-order methods and the research carried out on them. The study compares the results obtained by one of the widely used commercial shape optimization software against the results generated using the proposed approach. To demonstrate the effectiveness of the present method, several structural shapes were optimized under various constraints and the results were compared with those obtained using OptiStruct (a part of the software suite HyperWorks from Altair engineering), which works on gradient descent method. The proposed approach was found to be successful and yielded results that are more suitable for industrial fabrication compared to those obtained by the gradient descent method in OptiStruct. To explain the efficacy of the current approach, a few structural shapes have been optimized under various constraints, and the results of the same are compared to those obtained using OptiStruct, which works on gradient descent method. The proposed approach works well and produces more industry-fabricable results than what is produced by the gradient descent method in OptiStruct.

3. GSO-assisted shape optimization of steel–concrete–steel sandwich beams.

The GSO shape optimization method is employed to optimize steel-concrete-steel (SCS) sandwich beams. The method utilizes a unique approach of modifying the shape of the faceplates and core at the interface without altering the overall shape of the SCS sandwich beam. This is achieved by implementing a technique that involves perpendicular growth and shrinkage in the design boundary at the faceplate-core interface to obtain an optimized shape. The method involves selecting a target maximum shear stress value (σ_t) and modifying the shape in such a way that the maximum shear stress (σ) at any point is less than or equal to the value of σ_t. The method has been found to be effective in determining the optimized shape of the faceplates and core. To demonstrate the effectiveness of GSO, several examples with varying boundary conditions and shapes of the SCS sandwich beam have been analyzed.

4. Synergetic concrete shape and cable layout optimization of pre-stressed concrete (PSC) beams.

A new technique intended towards synergetic optimization of concrete shape and cable layout of pre-stressed concrete (PSC) beams is proposed. Another in-house software labelled "Simultaneous Shape and Cable Optimization" (SSCO) which is an extension of the GSO, is developed. In SSCO, along with shape optimization of concrete, the cable layout is also modified simultaneously. The pre-stressing cable is modelled as a curvilinear three-noded bar element tracing a B-spline profile, while the concrete is modelled as a discretized continuum using nine-noded lagrangian elements. The concrete is modified from its initial shape using the proposed integrated zero-order technique, whilst the cable is modified employing a coherent algorithm designed towards the modification of ordinates of knot vector. The entire modification process is iterative in nature and is directed towards the removal of tensile stress (< 0.5 N/mm^2) from the beam while maintaining a minimum concrete cover of 40 mm, giving an overall optimized concrete shape and cable layout. Frictional loss encountered during post-tensioning of cables is also contemplated in the present study. Its effect on the overall optimized concrete shape and cable layout is distinguishably demonstrated. Using SSCO, a few PSC beams having different span lengths, cross-sections, span numbers, imposed loading, and pre-stressing force are efficiently optimized for certain applied constraints. The optimized PSC beam acquired is easy to fabricate and can be used by industries. Further, the study has been extended to investigate the changes occurring in the optimized shape and cable layout of PSC beams due to changes in span length and to find out the optimum number of spans which will strike a perfect balance between the amount of material saved due to optimized shape and the number of spans needed to be given.