Multi-Criteria Driven Integrated Zero-Order Shape Optimization of Structural Elements

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by

“ISHAN JHA”

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005

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CHAPTER 8

Conclusions and future scope of study

8.1 Introduction

The primary research studies conducted in this thesis are outlined as follows:

1. Suggested a new fuzzy-based multi-criteria driven integrated zero-order method for shape optimization of structural elements.
2. Suggested a novel approach towards shape optimization of SCS sandwich beams by optimizing the thickness of face plates and core at their interface.
3. Suggested a new method of optimizing the concrete shape and cable layout simultaneously in a synergistic manner for pre-stressed beams.

In this chapter, a succinct overview of the objectives and conclusions of each study is presented. Additionally, a brief description of the new software developed to achieve these objectives is provided. The chapter concludes with a section on recommendations for further research, highlighting areas that have yet to be explored and suggesting potential avenues for future study.

8.2 Integrated zero-order fuzzy-controlled shape optimization.

This chapter of the thesis presents a new fuzzy-controlled integrated zero-order method for optimizing the shape of structures. Concepts of design elements and design nodes have been used to control the geometry of the structure. The nodal movement and convergence are governed using the fuzzy membership function. The whole method is coded in FORTRAN to work with software labelled GSO. GSO utilizes the "fully stressed design" criteria to find the optimal shape for the structure under different constraints. The results of the method show that the obtained stress value (σ) is very close to the selected target stress value (σ_t).

The use of minimal design elements and proper design nodes in the method allows for faster convergence without compromising the quality of the results. The capabilities of GSO are effectively demonstrated through various examples such as initial imperfections, composite beams, and flat tops under different sets of initial conditions. The results of these examples highlight the effectiveness of the suggested approach.

The suggested method has been found to be successful in obtaining optimized shapes for different structures with varying geometrical and material parameters and the software can be used in the field of structural optimization to obtain the optimized shape of structural elements.

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

The study conducts a comparison of the capabilities of GSO, a fuzzy-based integrated zero-order method for shape optimization of structures, with OptiStruct, one of the most widely used industrial software for the same purpose. The approach used in GSO has been embodied as a software program, which was written in FORTRAN, and is able to effectively interact with the given constraints and changes in structure while maintaining the serviceability criteria.

One of the most crucial tasks in GSO is to accurately define the design elements and select the proper design nodes in order to achieve the desired optimized shape with faster convergence without compromising the quality of results. The overall runtime of the program is also minimal and does not require any high-end computing capabilities from a computer.

From the results obtained in the mesh convergence study, it is found that GSO converges to give validated results at a much coarse mesh size than that of the OptiStruct. This is due to the use of 9 noded elements in GSO which is not present in the OptiStruct. The overall average time per iteration as obtained in the present study for GSO is 0.23 seconds whereas for OptiStruct it is 3.64 seconds. The final optimized shapes obtained by GSO are found to have fewer stress concentration areas and fewer sharp corners, making them more practical and adaptable for use in the industry than those obtained by OptiStruct.

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

The study presents a successful application of a fuzzy-based integrated zero-order method for the shape optimization of Steel-Concrete-Steel (SCS) structures. The method focuses on a new idea of optimizing the shape at the interface between the core and the faceplate of the structure, in order to decrease the amount of steel and increase the amount of concrete while maintaining the overall cross-section of the beam for a certain load imposed on the beam. This results in a reduction of the overall weight of the structure while still fulfilling the criteria of structural integrity and serviceability. The study also finds that the method produces values of σ_{max} that are very close to the σ_t taken and that σ_i at no point exceeds the value of σ_t taken.

Using the GSO a few SCS beams under different loading conditions and constraints have been optimized at the interface and in each case, the software was able to successfully optimize the thickness of face plates and core across the section according to the stress coming at that section. In doing so the change in deflection before optimization and after optimization is also very less of the order 10^{-4}. Each iteration done by the GSO software on average takes a runtime of approximately $1.406\text{x}10^{-1}$ seconds. The study concludes that the suggested approach is successful in shaping the optimization of SCS sandwich beams and can be used for industrial applications.

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

The presented work suggests a novel methodology for achieving an optimally designed cable layout and concrete shape for PSC beams in a synergistic manner. The approach is encapsulated in another software program, labelled SSCO, which is again written in the FORTRAN programming language. The methodology involves modifying the shape of the concrete from its edges without creating any additional cavities, and subsequently adjusting the cable profile to ensure that the top and bottom sections of the beam are under compression (<0.5 N/mm^2) at all the nodes.

To demonstrate the effectiveness of the proposed approach, three distinct PSC beams with varying spans, cross-sections, lengths, applied loads, and pre-stressing forces were successfully optimized to obtain an optimal concrete shape and cable layout. The results of these optimizations exhibit that the optimized PSC beams show material savings of 12-24% compared to their initial state without experiencing any unusually high deflection. The impact of frictional loss on the overall optimal concrete shape and cable layout was also successfully demonstrated. The obtained results showed variation in the final optimized cable layout and concrete shape. This variation, stemming due to the ignorance and consideration of friction loss accounts that the SSCO is sensitive to the loss in pre-stressing force along the span of the beam and modifies both the cable layout and concrete shape as per the actual pre-stressing force at that section. The overall runtime of SSCO for all the demonstrated examples is found to be less than 1 second.

The proposed methodology offers a comprehensive tool that can be utilized by industries to achieve an optimized cable layout and concrete shape for PSC beams that are easy to fabricate, saving material and reducing deflection. The use of a holistic approach, and the ability to consider the impact of frictional loss, makes it a powerful tool for designing PSC beams that are both efficient and cost-effective.

8.6 Effect of span length on the synergistically optimized pre-stressed concrete beams.

The study presented in this work successfully compares the impact of varying the number of spans in pre-stressed concrete (PSC) beams on the overall optimized cable layout and concrete shape obtained using the software SSCO. The study was conducted by analyzing different scenarios of PSC beams with different numbers of spans, while keeping the other factors such as the length, imposed loading, and pre-stressing force constant.

The results of the study indicate that for a given length of the pre-stressed beam, increasing the number of spans does not necessarily lead to higher material savings. Instead, there is an optimal number of spans that strikes a balance between material savings and the number of supports required. This optimal number of spans can be effectively determined using the SSCO software, which also provides the optimized cable layout and concrete shape for that number of spans.

8.7 Sources of error

In any engineering study, especially one involving optimization and numerical analysis, there are several potential sources of error that a user should be aware of and account for. Here are some common sources of error that could affect the study described in the thesis:

a) Mesh Discretization: The initial mesh must be discretized with great care, maintaining adequate mesh size and an approximate aspect ratio of 1:1. Failure to do so may result in mesh distortion errors, potentially leading to the abrupt termination of the program. Proper mesh quality is pivotal for precise finite element analysis.

b) Spline Point Definition in SSCO: Accurate definition of the initial spline points in the Simultaneous Shape and Cable Optimization (SSCO) software is imperative. Misalignment in defining these points can introduce deviations from the intended optimized cable shape, impacting the overall structural performance.

c) Load Application: Precise load application to the correct nodes is paramount for accurate structural analysis. Incorrect positioning of loads can yield erroneous optimization results, as the shape optimization process responds to the imposed loads.

d) Input Data and Material Properties: Thorough attention to input data and material properties is essential for achieving a correct stress analysis of the structure. Inaccurate or imprecise input values can propagate through the analysis, leading to unreliable results and suboptimal designs.

e) Target Stress Selection: The choice of the target stress directly influences the optimization objective. Careful consideration must be given to selecting an appropriate target stress value to ensure that the optimization aligns with the desired structural performance criteria.

f) Tolerance Limits: The establishment of appropriate tolerance limits is vital to prevent suboptimal solutions and maintain control over the convergence of the optimization process. Failure to set suitable tolerance values can result in premature convergence or inability to reach optimal designs.

g) Nodal Movement Control: Controlling the nodal movement value is crucial to avoid suboptimal solutions during the optimization process. Improper control of nodal movement can lead to convergence difficulties, hindering the attainment of the desired optimized shape.

h) Convergence Criteria: The selection of convergence criteria demands careful consideration, tailored to the specific problem being addressed. Inappropriate convergence criteria can hinder the optimization process, potentially leading to non-convergent or suboptimal outcomes.

8.8 Software developed

In order to achieve the various objectives outlined in sections 8.1 to 8.6, two software programs have been developed using the FORTRAN programming language. These programs have been tested and run successfully on an AMD Ryzen 5 processor using Microsoft PowerStation. The softwares developed are:

1. GSO (Gradientless Shape Optimization)
2. SSCO (Simultaneous Shape and Cable Optimization)

However, the one practical limitation of the shape obtained using these softwares is that it would be difficult to make formwork for the shapes procured after optimization as they are unconventional. But, as the research work progresses, it is hoped that the issue of having different formworks for different unorthodox shapes will be possible in the near future.

8.9 Future works

The knowledge base developed in this thesis have the potential to be applied to a variety of loading, material, and geometrical conditions, making it an interesting subject for further research. Based on the insights gained from this study, the following recommendations are made for future studies:

1. The work can be extended to incorporate shape optimization of structural elements under dynamic loading. Shape optimization of dynamic problems using mathematical programming methods is a challenging task due to the complexity of the sensitivity calculations involved. Hence, the use of non-gradient methods can be a useful tool in this case. This will help in achieving an optimized shape in case of earthquake, impact and blast loading.

2. The work can also be extended to incorporate the non-linear behaviour of materials so as to incorporate large strains caused due to larger stresses. For problems involving large deformation, it is important to account for geometrical nonlinearities in the shape optimization process as they can have a significant impact on the results.
3. The work can also be extended to incorporate the effects of creep and shrinkage in pre-stressed beams. Also, optimization of pre-stressing forces can also be added to the methodology along with shape and cable.