Finite Element Model for the Optimization of Steel I-Beam with Variable Depth

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Abstract. The objective of structural design is to select member sizes with the optimal proportioning of the overall structural geometry. Conventional steel I-beam with variable depth have been used widely in various engineering fields. The objective of this study is to develop a three-dimensional finite element model for the total volume of steel I-beam with variable depth. The finite element software package ANSYS was used to determine the optimum total volume for the steel I-beam with variable depth. The purpose of the study is to minimize the total volume of the steel beam. The design variables are the height of the steel beam at support, the flanges width, the thickness of flanges, the height of the steel beam at mid-span, and the web thickness. The constraints considered in this study are the normal stress in steel beam and the mid-span displacement of the steel beam. Optimization results of steel beam indicate that the total volume was reduced approximately by 52 %.

1. Introduction

Developments in production processes and material technology led to an increase in steel strength. From the designer's point of view, the best use of the higher strength in structures is important. Higher strength typically implies higher production costs that need to be taken into account in pursuing economic designs. A common strategy is to assign different grades of steel for the web and the flanges to make the web of weaker steel than the flanges in order to achieve economical solutions on beams. These hybrid cross-sections are another way of finding better solutions for designers. Various approaches to numerical solution in the literature were developed to highlight the structural behavior of various types of beams subject to different boundaries and loads [1-9]. In order to more analyze and understand the behavior and stability of different steel beams, Finite Element (FE) models were proposed in the numerical research [8]. In order to investigate optimal structural design, other researchers have previously established theoretical and numerical models [1, 3-6, 8-9, 11-13]. The use of higher strength steel in welded beams was considered economical by Mela and Heinisuo [3]. In accordance with Eurocode 3 design rules, they optimized the beams separately for weight and cost. This study takes into account bending and shear resistances. The cost function includes the transportation, fabrication and erecting the beam on site. The results show that while high strength steels can achieve a significant weight reduction, cost savings relative to S355 are rather limited. Ozbasaran and Yilmaz [5] studied the shape optimization of doubly-symmetric I-beam flange and/or web tapered and discussed the contribution of web tapering and/or web tapering to the economic design. The optimized method is based on changing the Big Bang-Big Crunch algorithm slightly, and the Deb’s constraint handling procedure is installed. Finite element analysis software was used to validate the final designs and optimizes four beam.
configurations with various loading and restraint conditions. It is shown the location of the inflection point can, under certain conditions, not have a significant effect on the material economy.

In order to replace traditional cellular beams and to understand the mechanisms of the bending and shearing actions, Tsavdaridis et al. [6] focus on the application of structural optimization technology in steel performed I-sections. The results of parametric studies suggest an optimal web opening configuration. Finite element analysis is also used to determine the optimized beam’s performance compared to the conventional cellular type beam. The result shown that the optimized beam over performs in terms of stress intensities, load carrying capacities and deformations. A model for optimization of the steel girder with external prestressing was developed by Abbas et al. [13]. To find the steel girder optimum design, the finite element ANSYS software package was considered. In this study, the strain energy and the total volume minimization are considered as objective functions. The design variables include the top flange width, the top flange thickness, the bottom flange width, the bottom flange thickness, the web thickness, web height and the area of prestressing tendons. Volume minimization results show that the optimal values of area of section for the prestressed girder is smaller than for the non-prestressed girder. This paper developed a three-dimensional model using finite element ANSYS software to investigate the optimal total volume of a steel I-beam with variable depth. In this study, the objective function is to minimize total volume. The depth of beam is considered variable. In ANSYS, the optimization routines use three types of variables describing design optimization, the design variables, objective function, and constraints. In the optimization process, using ANSYS Parametric Design Language (APDL) is an important step.

2. Finite element modelling
ANSYS [15] is used for modelling and analyzing steel I-beam with variable depth. The four-node shell element required for the representation of the steel I-beam with variable depth through the finite element. To this purpose, the steel I-beam with variable depth was modeled using a four node Shell181 element. The Shell181 element has six degrees of freedom at each node, which are the x, y and z-axis rotations and translations. For nonlinear and linear applications, this element is used. It also has plasticity, large deflections and stress stiffening [15]. Material properties have an important role in the FE analysis of the ANSYS program. Precise material property values must be entered in the ANSYS program as inputs. In this study the bilinear stress curves for steel are considered. The yield strengths of the steel (Fy) is 410 MPa, poisson's ratio (ν) is 0.3 and elastic modulus (Es) is 200000 MPa.

3. Optimization of steel I-beam with variable depth
In the literature there have been numerous studies on the optimization of the steel structure. Few studies have been concerned for optimizing the design of steel I-beam with variable depth. Finite element analysis are used in this paper to minimize the total volume of steel I-beam with variable depth subjected to static loading. The study includes the five design variables: the height of the steel beam at support (WH1), flange thickness (FT), flanges Width (FW), the height of the steel beam at midspan (WH2), and Web thickness (WT). Figure 1 show the design variables. The aim of the optimization method is to minimize the total volume of steel I-beam with variable depth while meeting the required serviceability and strength limit states in accordance with the AASHTO specifications [16] and AISC manual [17]. In this study, the objective function is to minimize of the total volume for beam. The limitations of this study are as follows:
- Stress in steel I-beam with variable depth.
- Deflection at midspan of steel I-beam with variable depth.
In this study, the steel I-beam with variable depth are considered as simply supported. Geometry and boundary conditions are illustrated in Figure 2. The loads were applied to the total length of the steel beam as uniform loads. As illustrated in Figure 2, the steel beam total length is $L = 20$ m.

**Figure 1.** Cross section of steel I-beam with variable depth with design parameters used in the optimizations.

**Figure 2.** Loading conditions and geometry for the proposed steel I-beam with variable depth. The load is applied uniformly on the width of flange in order to prevent numerical problems in the FE analysis. Figures 3 and 4 show the meshing and boundary conditions for the modeling of a steel I-beam with variable depth. Only one-half of the beam was modeled due to symmetry. In the center the beam, the displacement in Z-direction and rotation about X-axis were constrained due to symmetry. In this study, the steel I-beam with variable depth was modeled with 3D solid elements.
3.1. Optimization strategy

The ANSYS program package [15] outlines several optimization procedures: the first order method and the sub-problem method. The sub-problem optimization method may be considered as a zero order approach that does not require derivatives and only variable values. The sub-problem approximation approach is considered in this study.

Optimization of steel I-beam with variable depth is a process that generally requires many iterations until the design is satisfactory. The designer can often choose a structural solution and adjust various parameters.
3.2. Optimization result
In this section, the steel I-beam with variable depth is considered for the optimization using the total volume as objective function. The compression, tension and deflection are constraints.
In order to determine total volume optimization, random design iterations are conducted with the material parameter limits. The initial values for the design variables provide a basis for the above mentioned optimization approaches. The initial data values do not affect the result of the optimization but affect the number of iterations. The evolution of the objective function (optimal overall volume) versus the iterations number for the steel I-beam with variable depth are shown in Figure 5. Figure 6 illustrates the evolution of optimal WH2 versus the number of iterations for the steel I-beam with variable depth.

![Figure 5](image-url)

**Figure 5.** Evolution of optimum total volume versus iterations number for the steel I-beam with variable depth.

The results of the initial and optimal variables for design for steel I-beam volume minimisation are shown in Table 1. Table 1 shows that by total volume minimization processes, the WH1 and the total volume are decreased. In this table it can also be noted that, compared with the initial part, the total volume is reduced by nearly 52 percent.

![Figure 6](image-url)

**Figure 6.** Evolution of optimum WH2 versus iterations number for the steel I-beam with variable depth.
Table 1. Optimum, Limits and initial of constraints and design variables for the total volume minimization.

| Objective function | Minimum | Initial value | Maximum | Optimum |
|--------------------|---------|---------------|---------|---------|
| Total Volume (mm³) | 326252812 | 157044612 |
| FT (mm)            | 10      | 15            | 25      | 10.5    |
| FW (mm)            | 275     | 375           | 475     | 280     |
| WH1 (mm)           | 400     | 850           | 900     | 550     |
| WH2 (mm)           | 800     | 950           | 1200    | 1050    |
| WT (mm)            | 10      | 20            | 30      | 11.5    |
| Max. $f_c$ (MPa)   | -200    | -106          | 0.0     | -194    |
| Max. $f_t$ (MPa)   | 0.0     | 101           | 200     | 153     |
| Max. $U_y$ (mm)    | 0.0     | 22.5          | 75      | 48      |

where:
- $f_c$ is the compressive stress in steel
- $f_t$ is the tension stress in steel
- $U_y$ is the mid-span deflection of the steel beam

A retrofitting steel I-beam is obtained after optimization because of the reduction in total volume. The uniform load vs. midspan deflection curves of the beam a after and before optimization are reported in Figure 7. It is clear that the controlled load of the optimized steel beam is relatively augmented compared to the steel beam before the optimization.

The ultimate uniform load for the controlled steel beam following optimisation was found equal to 52.5 kN/m against 84.8 kN/m for the not optimized steel beam. This reduces in controlled load which is 38 percent compared with the total volume optimization (almost 52 per cent). We conclude from the figure that it is important to optimize the total volume of the steel beam, since this allows us to find an optimal total volume with low costs and appropriate service conditions.

Figure 7. Load versus mid-span deflection before and after optimization.
4. Conclusion
A 3D finite element model using ANSYS is presented for the investigation of the optimal steel I-beam with variable depth design and for the determination of optimal beam size. Optimization approaches by ANSYS involve three types of variables describing the process of design optimization: design variables, constraints and the objective function. In the optimization process, using APDL is an important step. Following conclusions can be drawn from the analysis and optimization of the steel I-beam with variable depth:

1- The total volume was reduced approximately by 52 %. There was also a significant decrease in FT and WT, respectively of about 30 % and 43%.
2- It is evident that the web height at support (WH1) is reduced significantly from 850 mm for the initial state to 650 mm for the converged solution. This decrease (approximately 24 percent of the initial height) is important.
3- The ultimate uniform load for a controlled steel beam was found equal to 52,5 kN/m after optimization against 84,8 kN/m for the non-optimized steel beam. Thus a 38% reduction in the load control compared to the optimization of the total volume (almost 52%). We conclude that it is very important to optimize the total volume of a steel I-beam with variable depth because it makes it possible to find the optimum total volume with suitable conditions for service and low cost.

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