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Optimisation of Pre-Engineered Buildings

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Abstract

In traditional building practice, a lot of construction material is wasted, because the structures are often grossly over-dimensioned. Inevitably, optimisation is a fundamental aspect of human life as well as a feature of nature. Although numerical optimisation methods have the potential to minimise the usage of structural materials, their application in routine design practice is limited by the absence of tailored algorithms. Structural optimisation based on mathematical computing is one of the approaches for sustainable and effective design in the field of civil engineering. It includes the formulation of the optimisation problem, defining variables, objective functions and constraints followed by a suitable optimisation method with mathematical programming to achieve structural optimisation resulting in reduced overall weight and cost of the structure. The current study includes an overview of prior research on structural optimisation and provides an analysis of the optimisation objectives, optimisation process and different methods and their limitations. The paper includes a numerical study to suggest an optimal design solution for a structural element which is part of a considered pre-engineered building. Topology optimisation of a conventional steel beam (I- section) is performed by numerical analysis along with the finite element method in ABAQUS. The topology optimisation of the beam in terms of decreasing the profile volume reduces the overall material consumed, thereby reducing the cost of the structure. The current numerical analysis helps in arriving at a cost-effective and efficient design solution for a typical pre-engineered building alternative to experimental tests and conventional trials.

Keywords: I-Section, Optimisation, Pre-Engineered Building, Topology Optimisation

1.0 Introduction

Structural engineering aims at providing the best design, which is optimally planned and designed. Traditionally for many years, this has been achieved by repetitive trials, prior experiences, learning from failures, through intuition and from previous design examples. The existing buildings and fine civil structures are excellent products of this method, yet most of them are grossly over-dimensioned. With the advances in computational methods for analysis and with an increasing demand for cost-effective and structurally efficient designs, structural optimisation methods have evolved over the years. These methods help in evaluating numerous available alternative options and arrive at the best possible solution[1].

Unlike the earlier decades, involving heavy engineering constructions, there has been an acute shift towards steel structures and pre-engineered buildings (repetitive structures) in recent years. This is due to the reduced time of construction and the cost-effective and efficient performance of such structures. There is increased investment and ample research and development to improve the quality like durability, strength, corrosion resistance, etc. Along with these, the optimum structural design of such structures would additionally reduce the overall material consumption, weight and cost of the structure.

With the advances in computational and construction techniques, a wide variety of complex civil structures are structurally optimised. A few real-time structures

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include i) CITIC Financial Center in Shenzhen, China – an example of topology optimisation. The structure was provided with an exoskeleton truss layout to improve the material efficiency, ensuring the overall stiffness of the structure. ii) Qatar National Convention Centre, Doha- An iterative 3D extended structure with optimized topology, designed to minimise structural compliance[2,3].

1.1 Optimisation

To optimise means to achieve the optimum result under particular circumstances. Civil structures can be optimised with respect to design, execution, construction, maintenance and operation. Structural optimisation is crucial it seeks to determine the optimal configuration of structures or structural elements to accomplish the best arrangement of structures under predetermined conditions for a particular material[4]. The four main categories used to categorise structural optimisation are as below[5,6]:

1. Dimensional/ Size optimisation: considers the cross-sectional size and area of the structures, as design variables.
2. Geometric /Shape optimisation: considers the nodal coordinates as design variables.
3. Topology optimisation: deals with several elements. Based on the nodes/joints connection, the unnecessary structural elements are excluded to achieve the optimal solution;
4. Multi-objective/layout optimisation: considers two or more objectives involving size, shape and topology.

These optimisation categories are used to serve one of the following purposes: 1) Cost minimisation: by minimising the volume/weight of the structure; 2) Improved Structural performance: Dealing with improved mechanical behaviour, aerodynamic or seismic performance to meet the functional requirement. 3) Reduce Environmental impact: Improve the environmental performance of civil structures by reducing energy consumption and greenhouse gas emissions. Structural Optimisation is carried out in the following steps: a) fixing the iterative modelling technique for discrete optimisation or continuum optimisation; b) Defining the problem using design variables, objective functions and constraints; c) Applying mathematical programming to achieve optimisation; d) Setting up appropriate computing tool and software platform, to run the optimisation codes and conduct the design.

The above objectives can be achieved by using different optimisation methods including metaheuristic algorithms. There is ample study in this field to enhance the performance of these existing metaheuristic techniques and to arrive at a novel optimisation technique. The metaheuristic methods are inspired by nature or human activities like water flow, ant colonies and ensembles of musicians. Various metaheuristic methods evolved in recent days include artificial bee colony, genetic algorithm, particle swarm optimisation, tabu search, cuckoo search, firefly algorithm, harmony search, flower pollination algorithm, teaching-learning-based optimisation differential evolution etc. These techniques are being applied for various types of civil structures and different purposes and researchers have demonstrated the best possible optimal solutions for the problems[6]. For example, to achieve high solution accuracy and less computational power, Mor Tazavi *et al.,*[7] applied a fuzzy-tuned interactive search algorithm to optimise the size and topology of structural elements. Zheng *et al.*,[8] proposed an effective transformable triangular mesh method for structural topology optimisation method. Kociecki *et al.,*[9] applied a two-phase genetic algorithm to optimise the size and topology of framed hollow sections. Mortazavi *et al.,*[10] used an integrated Particle Swam Optimisation (PSO) algorithm on the truss to suggest optimal size by improving structural dynamic characteristics and reducing the weight. A genetic algorithm was used by Alapati[11] to optimise a benchmark structure considering stresses and deflection constraints. Medeiros *et al.*,[12] optimised the RC beams and proposed pre-sizing parameters by considering sectional height as a design variable and serviceability limit, flexural, shear and torsion reinforcements as constraints. Dede, *et al.*,[13] have effectively used teaching–learning–based optimisation for designing trusses and showed that it outperforms other algorithms. Sharafi *et al.*,[14] applied graph theory/ multi-colony ant algorithm for multi-objective size and shape optimisation of open and closed thin-walled steel sections to maximise strength and minimise the mass. This was applicable for optimising the size of the roof sheeting and the shape of the steel sections. Kaveh, *et al.*,[15] applied a combination of Particle Swarm, Harmony Search and Ant Colony to create discrete heuristic particle swarm ant colony optimisation and applied it for trusses.

Compared to classical techniques, it worked better with high convergence and less computational time. Poitras *et al.*,[16] used Particle swarm optimisation to reduce the mass/cost of composite and non-composite steel floors. The size of the girder, beams and concrete thickness was considered as a design variable. Cicconi *et al.*,[17] used a genetic algorithm and SAP 2000 software and optimised the steel frames of the onshore power plant by reducing its weight and overall cost by 5% to 15% for different loading cases. Rozylo[18] demonstrated optimisation of the I- section using the Finite Element Method (FEM).

Since the amount of research pertaining to topology optimisation using the finite element method is limited and the method varies for different structures, there is no established technique for the same. This method of optimisation is also beneficial in the field of materials and mining. Hence it is necessary to conduct research in this field focusing on topology optimisation.

2.0 Optimisation of Steel Beam

The aim of optimisation here, is to the reduce weight, dimensions and thereby cost of the steel beam without compromising its load-carrying capacity and general strength. This is achieved by reducing the volume of the structure. The material properties and overall dimensions of the structure remain the same. The complex computation involving the optimisation is solved with the help of FEM. Topology optimisation gives information related to the location of material for a structure in the workspace such that the structure's geometry is optimal with the applied boundary conditions and load. It determines the maximum or minimum of a function, meeting the specified conditions that limit a given problem. It is achieved by effectively reducing the region which is redundant in terms of excessive volume.

2.1 Numerical Study

A typical pre-engineered industrial building is considered and two structural elements of the Pre Engineered Building (PEB), i.e. steel beams of 3m and 5m are evaluated for topology optimisation in Abaqus/CAE 2018. A conventional hot rolled steel of I section resembling ISMB 400 is considered. The numerical model of the beam is shown in Figure 1. The lower edges of the boundary were fixed and a load of 100KN (3m), 170kN and 210kN (5m) was centrally applied in terms of pressure on the upper surface of the beam for 500 and 600mm. The static analysis of the beam is carried out determining the stresses and displacement in the beam followed by structure topology optimisation based on the finite element method. The material properties of steel and the geometric properties of the beam/model are shown in Table 1. The standard elastic and plastic properties of steel of grade E-350 were adopted. The optimisation is carried out in combination with the finite element method in Abaqus software. The overall volume of the beam is reduced by a certain percentage, simultaneously maintaining similar stresses for the corresponding load in the structure before and after optimisation.

Two beams type –I and type –II of lengths 3000mm and 5000mm respectively are considered with different loading conditions. Type- I beam is subjected to 100kN load, while type –II beam is subjected to 170kN and 210kN respectively as shown in Figures 2 and 3. The beam was meshed using linear brick element C3D8R with an overall mesh size of 50mm. Finite element

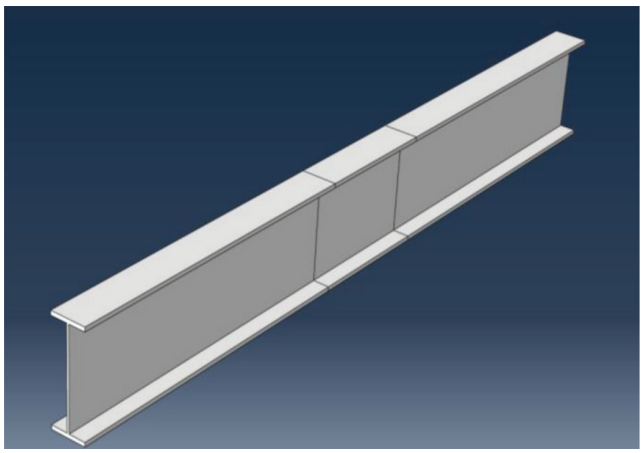


Figure 1. Numerical model of I-section beam in Abaqus.

Table 1. Material and geometric properties of the steel beam

Parameter	Value
Density of steel	7850 kg/m^3
Young's modulus	2.1x10^5 N/mm^2
Poissons ratio	0.3
Width of flange	140mm
Thickness of flange	16mm
Thickness of web	8.9mm
Depth of beam	400mm

analysis of respective beams was performed and the corresponding stresses and deflection were noted. In the optimisation module of Abaqus, the necessary optimisation properties were defined. Condition-based optimisation of the beams is done considering strain energy and volume as design variables and to minimise the same with the target of 40 per cent and 30 per cent volume reduction for type I and type II respectively. The aim was to reduce the volume of the beam maintaining the stresses in a similar range as that of the obtained stresses before optimisation and to have stress distribution throughout the beam. This can be done by having a constraint criteria of constant deformation energy during optimisation. The maximum reduction of 40 and 30 per cent by volume was allowed for type-I and type-II beams. The pre-optimisation and post-optimisation stresses were expected to resemble and vary in a small range. The goal of optimisation was to maintain equal strength values for the profile while considerably reducing the volume of the profile in areas that are not actively involved in the activity and operation of the structure.

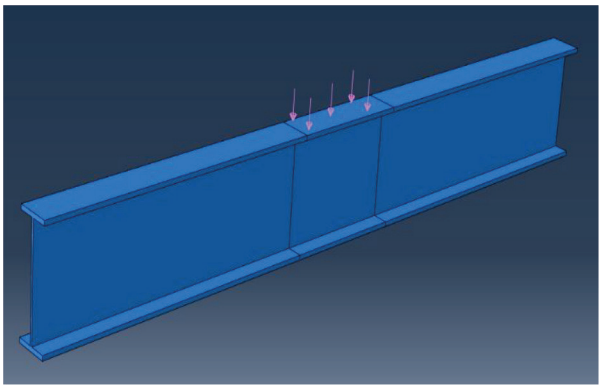


Figure 2. Type-I beam with centrally applied load.

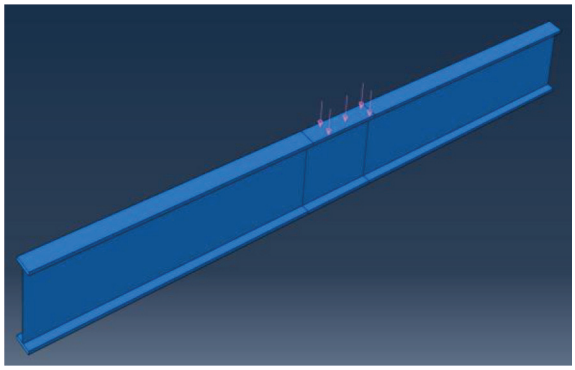


Figure 3. Type-II beam with centrally applied load.

3.0 Result and Discussion

The stress distribution and deflection in the beam before optimisation and post-optimisation were extracted from the numerical analysis. In general, for all the beams, before optimisation, the symmetrical bending of the beam enabled the determination of the areas of the beam where the stress was insignificant and that particular area was excluded during optimisation. The observations and results are listed below.

1) For a 3m beam (type-I) subjected to 100 kN load, it is observed that the stress distribution for a corresponding displacement of 1.3mm in the middle of the beam is 86.7MPa and 95.6MPa before and after optimization respectively. The stresses in the beam increased by 8.9MPa after optimisation accounting for a 9.3 % increase in stress. The stress distribution in the beam before optimisation and post optimisation are shown in Figure 4 and Figure 5 respectively. The optimised shape of the beam is shown in Figure 6, which depicts a 40 per cent reduced volume of the I-beam forming an arch kind of shape in the front view.
2) For a 5m beam (type-II) subjected to 170 kN load, it is observed that the maximum stress distribution in the beam is 243.7MPa and 261.4MPa before and after optimisation respectively. The stresses in the beam increased by 17.7 MPa after optimisation accounting for a 6.7 % increase in stress. The stress distribution in the beam before optimisation and post-optimisation are shown in Figure 7 and Figure 8 respectively. The optimised shape of the beam is shown in Figure 9, corresponding to a 40 per cent reduction in the volume of the beam by removing the region of less stress concentration.
3) For a 5m beam (type-II) subjected to 210 kN load, it is observed that the maximum stress distribution in the beam is 300MPa and 344.4MPa before and after optimisation respectively. The stresses in the beam increased by 44.4MPa after optimisation accounting for a 12.89% increase in stress. The stress distribution in the beam before optimisation and post optimisation are shown in Figure 10 and Figure 11 respectively. The optimised shape of the beam is shown in Figure 12, corresponding to a 30 per cent reduction in the volume of the beam by removing the region of less stress concentration.

For all the above beams the highest stress was observed at the ends of the beam which are defined by

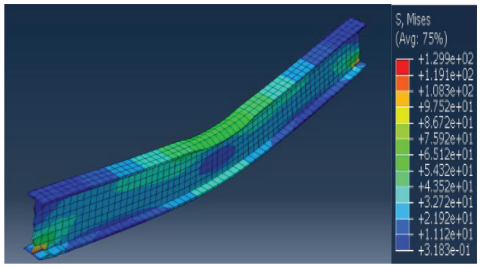


Figure 4. Stress distribution in type –I beam prior to optimization.

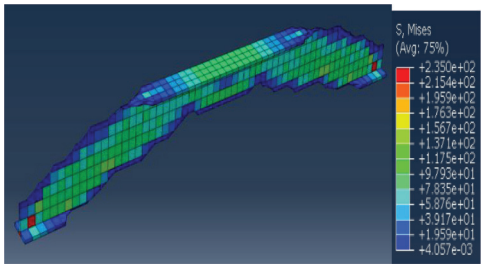
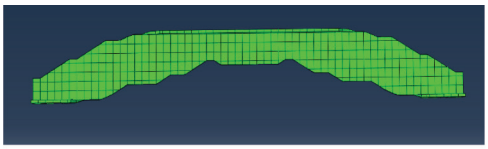
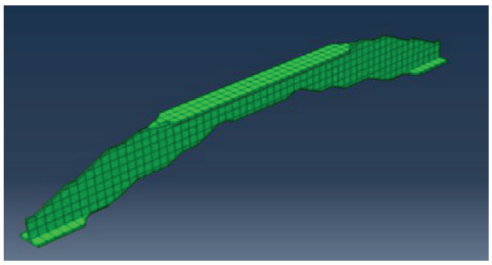


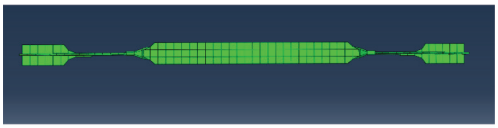
Figure 5. Stress distribution in type –I beam after topology optimization.



a) Front view



b) Side view



c) Top view

Figure 6. Optimized shape of the 3 m beam.

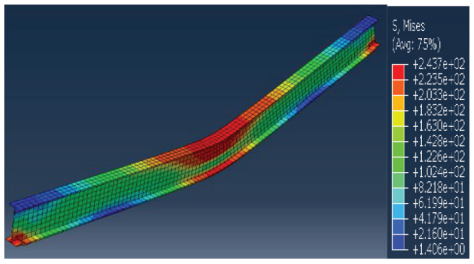


Figure 7. Stress distribution in type –II beam at 170 kN load prior optimization.

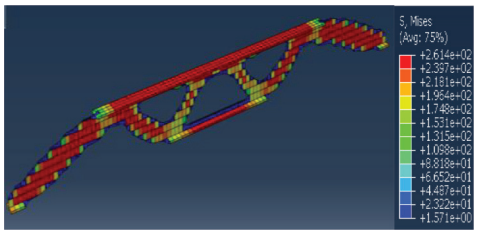
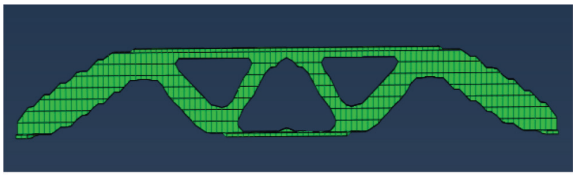
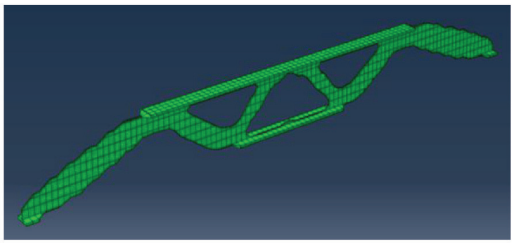


Figure 8. Stress distribution in type II beam at 170 kN load after topology optimization.



a) Front view



b) Side view



c) Top view

Figure 9. Optimized shape of the type- II beam at 170 kN load.

fixed boundary conditions at the bottom. The maximum displacement was observed in the region where the load was applied. Hence for all the cases, the topology optimisation was performed by freezing the areas where boundary conditions and load are applied. Hence the corresponding optimised shapes are extracted where the planes which are subjected to loading and the region where boundary condition is applied is retained as it is and is not subjected to the optimisation process. The target of the current optimisation was to reduce the

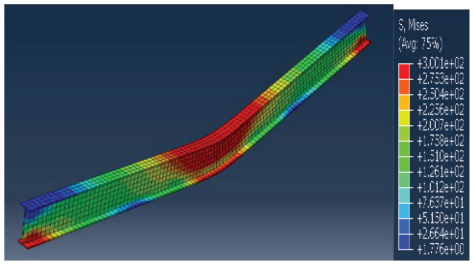


Figure 10. Stress distribution in type –II beam at 210N load prior optimization.

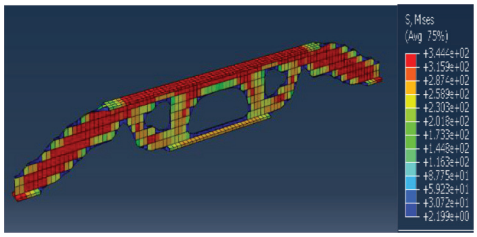
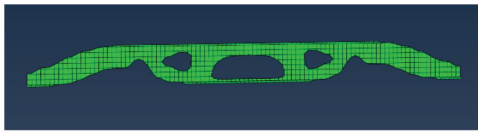
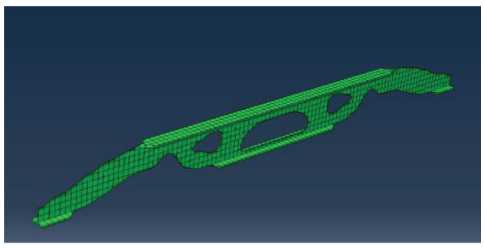


Figure 11. Stress distribution in type II beam at 210 kN load after topology optimization.



a) Front view



b) Side view



c) Top view

Figure 12. Optimized shape of the II beam at 210 kN load.

volume and thereby weight of the beam in the region which is less susceptible to bending stresses. The topology optimisation criteria were used to slim down the structure without smoothing the shape. Hence the images shown in optimised results of Figures 6, 9 and 12 show the numerical results right after optimisation which are to be smoothened and checked further for the maximum stress limits as per the design and serviceability requirement and only then can be approved to be used in practice.

Hence, the optimisation tool in Abaqus proves to be a promising method where, by reducing the volume of the beam by 30 to 40 per cent, the overall structure weight and production cost can be reduced. Increased stresses after optimisation lie in the range of 6 to 12 per cent which could be acceptable, despite such a high reduction in volume of the conventional I profile. The current study focuses on the benefits and application of numerical analysis and topology optimisation to suggest the optimal design which can reduce the production cost of the PEB. The results obtained in the current problem definition are described for particular constraints only and hence are not final and cannot be applied to define technological processes.

4.0 Conclusion

This current paper presented a review of different types of optimisation- size, shape and topology and various methods involved in optimisation. The advanced techniques of optimisation involving mathematical algorithms evolved in recent years were reviewed. A numerical study of typical steel I-section beams that are a part of a pre-engineered building was considered and an attempt was made to reduce the volume of the conventional steel beam and to arrive at the optimum design solution, to reduce the material cost and overall production cost of PEB. The static analysis of the beam was performed using a finite element method in Abaqus. Based on the stress distribution over the beam, the region of lower stresses was eliminated and an optimum topology was created using a topology optimisation tool in the Abaqus environment. The area was minimised by reducing the volume by 30 to 40 percent, without disturbing the loading and support region and the maximum stresses were distributed throughout the beam. The solution of optimisation gives an idea about the possible topology that can be used for the beam to maximise its function. Such numerical analysis and trials prove to be cost-effective and the best alternative in arriving at the optimal solution, as the experimental tests involved in determining the best design, are time-consuming and expensive.

The following observations were drawn from the numerical analysis of steel beams: The topology optimisation using FEM provides the optimum design solution based on the constraints and preset parameters and it generates the approximate shape of the particular

structure with improved mechanical properties. Though the reduced material and volume after optimisation results in slightly higher stresses in the beam, it is acceptable if it is in the range of allowable stresses. In the current study, after optimisation, thinner profiles were obtained for all 3 cases of loading and the volume was reduced by 30 to 40 per cent with increased stress in the range of 6.9 to 12.89 per cent. There was less volume reduction for a beam with more load and vice versa. Hence an approximate optimum shape suitable for a PEB as a replacement of heavy conventional I – I-section beams is suggested that helps in reducing the overall production cost of PEB.

5.0 Scope of Future Work

The current study only focused on the topology optimisation of the conventional I – I-profile and the different possible shapes using Abaqus. Based on the standard norms and requirements, the maximum stress in the structure can be limited to a certain value and the corresponding percentage of volume optimisation can be decided. While the study is carried out on materials and mining, this method of optimisation is beneficial and can be adopted for carrying out research. The optimised shape has to be redesigned and evaluated for the corresponding constraints. Along with the topology, the number of structural elements and their size can be optimised using advanced metaheuristic algorithms and a complete optimum design can be suggested for a typical plan of PEB.

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