

Development of Optimal Design Support System for Beam Structure

By

Muhamad Fahmi Bin Azman

16790

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the requirements for the
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Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

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Approved by,

(Dr Dereje Engida Wolde Michael)

Senior Lecturer

Mechanical Engineering Dept.

Universiti Teknologi PETRONAS

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMAD FAHMI BIN AZMAN

Final Year Student

Mechanical Engineering

Universiti Teknologi PETRONAS

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All praises to God the Almighty which always guide me and give me strength to complete my Final Year Project (FYP) in Universiti Teknologi PETRONAS starting from January 2015 to September 2015.

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ABSTRACT

This paper is about the development of a support system to optimize the beam design. Designing is known to be a tedious and lengthy process especially for flexural members and it is time consuming. This project aims to come out with a mathematical model that able to shorten the time of designing the flexural members by utilizing software that already available in the industry.

The approach used by the author is based on optimizing concept which is a skill that human used every day without notice. Optimization helps in determining the best solution either to maximize or minimize. Each problem has different method and formulas to approach, including the limitation and constraints. It can be said that the optimized result of one case is distinctive to another.

This project comprises of 2 phases. The phases are distinguished by the software that the author used. In the first phase, the author used Microsoft Excel application that is already available and can be accessed anywhere. While for the second phase, the project will be conducted by incorporating MatLab software. The benchmark of this project is OptDesX, an optimization software that is already available and used in the industry.

Afterwards, errors debugging is conducted before this support system can be tested on external user. In a nut shell, the development of the support system to optimize flexural member is successful and the objectives set are met.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Beams have been used since ancient times to support loads whereby thick columns as the pillar supporting them. The Egyptians developed buildings that comprises of many pillars due to Greek influence. In the old days, beams are originally made from timber due to abundance of it and easy to carve. The word beam came from German word, 'Baum' and some said originated from the Dutch which is 'boom'. (Ayto, 2009).

Throughout the centuries, beams are designed by empirical methods, applicable only to specific cases and no generalization formula was obtained. Galileo, an Italian physicist, engineer, mathematician and astronomers also studied beams. He did not get it right but he showed how the subject should be approached. The theory of beams was only finalized in the late 17th century with the introduction of elasticity which are very complex and it is impossible to obtain an accurate result. (Calbert, 2003)

After the calculus and differential equations introduced, the beam problems were tackled in different approach that turn out the calculations are very close to the truth. Approximation method which depend on the use of the statics, superposition and simplifying assumptions are sufficient for the engineering work.

As engineering comprises of many activities such as analysis, design, fabricate, and research, design is considered the most important step as it solves 50 percent of the problem. To relate this with beam, there are various design solutions in choosing the best beam for specific case which can be time consuming and costly. (Arora, 2012)

1.1 PROBLEM STATEMENT

Designing the flexural members require optimization of the size of cross-section are in which lesser weight is favoured. By manipulating the dimension of the area either width, breadth, thickness, radius or some of them, relatively lighter beam could be obtained which indirectly lessen the material used to fabricate it. Weight reduction benefits include enhanced fuel economy in transportation of items, reduced shipping cost, and reducing overall system weight. (Vanek, F., 2014)

Nowadays resources depletion is an alarming issue as the consumption of them is faster than replenishment. As the beams are made from steel as main component, it is important to take note that demand for resources from the industry rises but finding and digging out new sources of supply is becoming more and more challenging as well as expensive. (Ehrlich, P.R, 2008)

As an example, oil companies have to search further and drill deeper to find new reserves of oil which double up the cost of an average well has in the past ten year (Bhardwaj, A., 2014). This is just a simple example of resources depletion problem. The author felt this project incorporating the utilization of resources properly by minimizing the weight by optimizing cross section area of the beam. In doing so, the amount of steel used will be lesser without sacrificing the strength and durability.

Another importance of this project is the need to ease the job of the engineers or technical personnel in determining the best shape of beam. There are various shape of them which have their own advantages and disadvantages to one another. Each case has different loading configuration whether the load is situated at the end, middle or axial position.

Some beams are cantilevered, simply-supported, and other mechanism supports such as both ends of the beams may be clamped to the wall. Another type is one end may be bolted and the other end is free to rotate, or the beam may be clamped at one end but overhang a support placed at some point along its length. (Mulimani, R., 2011)

For the offshore structures, the beam design may vary from each other. Locally, the American Petroleum Institute (API) standard has been used extensively in conjunction with the American Institute of Steel Construction (AISC) standards.

There is a trend now to optimize the design further due to increasing costs and the need to support decreasing oil reservoirs. A group of technical personnel addressed the issue and produced a local design standard for the offshore structures where beams are made up of tubular members to reduce significant drag effects of the wave. The design code comply with the American Petroleum Institute, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms - Working Stress Design also known as API-RP-2A-WSD. (Liew, M.S., 2011)

The above example shows there are several conditions that the engineers need to consider each and every design solutions. Several iterations are required to obtain the optimum dimension of the cross section area for different case. A handy support system must be created to find the best optimum design for beam structure.

1.3 OBJECTIVE

1. To develop optimal design support system to design flexural member of beam structures.
2. To validate the system with industrial case studies.

1.4 SCOPE OF STUDY

The scope of the project covers from deciding the optimum dimension or size. By manipulating the dimensions of the beam, the value of the cross section area will vary and directly affect the volume of the material. With lesser material used, lesser weight of the beam can be obtained. This study also uses several governing equations of statics and solid mechanics of beam structure.

CHAPTER 2

LITERATURE REVIEW & THEORY

2.1 OPTIMIZATION CONCEPT

As mentioned before, optimization is necessary in which the performance is optimized while all other requirements are satisfied. Optimization can be defined as finding an alternative with the most cost effective or highest achievable performance under given constraints, by maximizing desired factors and minimizing undesired one. Basically maximizing means trying to obtain highest or maximum result or outcome without regard to cost or expense. (Arora, J.S. 2012)

An example of optimization is the determination of best ratio for engine combustion. The ratio is one to seventeen in which one is the fuel while oxygen is the latter. Human practices optimization frequently in their daily life without them notice as they always preferred the best option while at the same time they need to compromise in several aspects.

From a descriptive statement or problem, it must be translated into a mathematical statement for optimization. Generally, proper definition and formulation solve 50 percent of the problem by eliminating unnecessary workload. A well-defined procedure for formulation is crucial.

By including critical constraint in formulation of the beam, the optimize solution wont violate it. If too many constraints added with inconsistency, no solution can be obtained. After proper formulation is attained, a system or a software can be utilized to deal with the rest work. Basically there are 5 steps of formulation:

1. **Project/problem description:** For a beam, basic parameters of the cross section area are decided which are the width range, thickness range, deflection without load and the width to thickness ratio should be known.
2. **Data and information gathering:** The data that need to be collected are comprise of material properties, performance requirements, resource limits, and cost of the raw material if required. The analysis tools must present e.g. Finite Element Method (FEM)

for structure analysis. Several assumptions are made. Several expression (bending moment, shear stress, axial stress, moment of inertia, axial strain and shear force)

3. **Definition of design variables:** A set of variables that describe the system is identified. These variables are the optimization variables. They should be independent to each other as far as possible. Minimum number of design variables to formulate properly. Some of the variables can be assumed to a specific value.

4. **Optimization criteria:** The criteria need to be set to determine one design is better than another. To compare the design, criterion must be determined which is a scalar function in numerical value. This function also called objective function can be maximized or minimized function. Maximize if aiming for profit and quality while for minimization it's aiming for cost reduction, weight or energy for example.

It can be multi objectives where 2 or more objectives are set. Must be influenced by variables of the design problem. Some of the problems do not have obvious objective function. So divide the problems into several sub problems. Each one is formulated as an optimized problem separately to be more manageable.

5. **Formulation of constraints:** Constraints are the restrictions placed on the design. The constraints expressions need to be developed for them. These constraints must depend on design variables. Examples of constraints are not fail under normal operating load, the natural frequency of the beam must be different with the operating frequency under load to avoid resonance, and the members must fit to available space.

Optimization methods are iterative where a trivial design is analysed and evaluated before a new trial design is generated. These steps are repeated till optimum solution is obtained and satisfying. (Arora, 2012)

2.2 BEAM CONCEPT

A beam is a structure loaded by forces acting transversely (sideways) to its length and this makes the beam bend. Beams may be supported across a span in various ways as shown below:

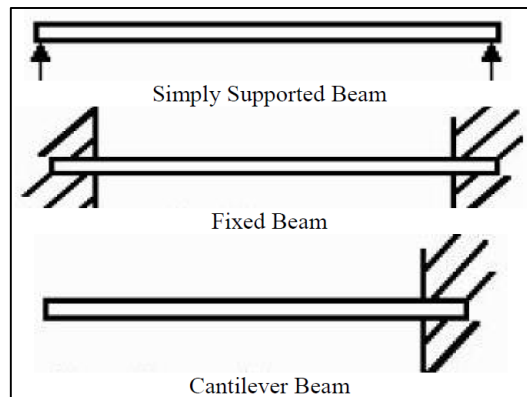


Figure 4: Beam Types (Pamnani, et. al 2014)

Beam basically functions to safely support the design loads after put in use. Generally the load can be in x, y and z direction depends on situation which can result in bending, fatigues, shear, deflection and others. It is the combination of tension and compression that occurs along the beam when it is loaded.

Shear force acts perpendicular to the axis of the beam, causing the internal particles to slide against each other. The amount of movement of a structural member under loading is called deflection. It is typically measured in inches or millimetres and the maximum deflection is based on what the beam will support. (Fisette, 2003)

Load may come from multiple direction. Angled direction usually resolved into components to ease the calculation work. When the beam under the load, deflection occur in line with the direction of the load impedes. Deflection factor must be considered to avoid the load acted upon the beam does not exceed the elasticity region.

Codes and design standards limit the deflection of structural members. Excessive deflection, although not normally a safety issue, can badly affect the performance of the machine or building. Too much movement can cause cracks in walls and ceilings, misalignment of systems, and incorrect operation of equipment. In addition, excessive deflection can give people an uncomfortable feeling, or can simply make them feel uncomfortable about the potential safety of the building.

In the elastic theory, the maximum load that a structure could support is assumed to be equal the load that caused a stress somewhere in the structure is the yield stress, F_y of the material. The members are designed to avoid the computed bending stress for service load did not exceed the yield stress divided a safety factor. (Assakkaf, 2002)

For ductile members like steel, it does not fail until a great deal of yielding occurs after yield stress is first reached. There is a greater margin of safety against collapse. The elastic modulus for a rectangular section breadth time depth ($b \times d$) can be worked out using the flexural formula.

For materials, cost is generally directly related to the amount of material used. The more material (in other words, the more weight), the higher the cost. Designers typically attempt to reduce the weight of the construction materials to reduce cost.

Structural design is an iterative process. The first step in beam design is determining design loads before analyse the beam for maximum shear and bending moment. Next is the selection process of a preliminary member that is expected to provide adequate bending and shear strength with the least cost. (Arora, 2012)

This preliminary member must be assessed to guarantee that it will provide a safe and workable design. Sometimes the chosen member does not provide enough shear strength or enough stiffness to adequately resist deflection. So choice revision is a must by always keeping cost in mind. This will change the section properties used and may affect the loading calculations which require recalculation, reanalysis, and redesign. This process is repeated until a cost effective member is found that will be both safe and working.

When a beam is loaded, the internal fibres of the member must carry and transfer the resulting internal shear and bending moment to the beam supports. These internal forces result in internal stress in the member. Stress is a measure of the magnitude of the internal forces acting between particles of the member resulting from external forces which expressed as the average force per unit area. (Hibbeler, 2011)

Axial stress happens when a force acts along the length of the member. Tension and compression occurs while the force is acted upon the member due to axial forces or axial stresses. Tension stress and compression stress are represented by the Greek letter sigma.

Strain is the change in size or shape of a material caused by the external forces. It is also mentioned as deformation. Axial strain is represented by the Greek letter epsilon whereby it is dimensionless. In many materials, stress is directly related to strain up to a certain point.

The graph below shows the typical relationship between tensile stress and strain for steel. As the tensile stress increases, strain increases. The relationship is linear until the material reaches its yield stress. At this point, the material begins to elongate much more quickly with respect to an increase in stress.

The maximum stress that a material can carry is called the ultimate stress of the material. If a member is loaded beyond the ultimate stress, the material will begin to stretch very quickly (called necking) and eventually break at the fracture point.

The slope of the linear portion of the graph is called the modulus of elasticity, or Young's modulus, and is represented by a capital E. Each material has a unique modulus of elasticity. For steel, E is between 190 to 210 GPa. (Hibbeler, 2011)

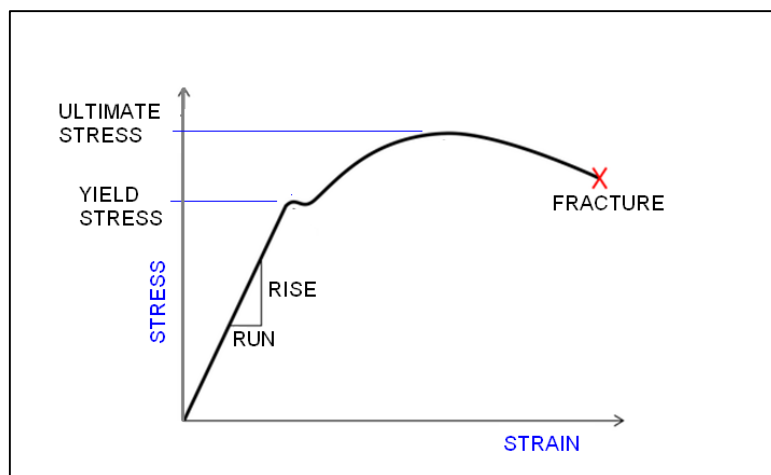


Figure 5: Stress-Strain Diagram

2.3 Beam Shapes

There are a large variety of cross sectional shapes where some might be solid or hollow. Solid beams are heavier than hollow beams. The major ones include I-beams (W and S types), channels, tubes, angles, pipes, and tees. The I-beam is generally the most efficient, but may not fit the space or needs of a particular structure. Many times, structural shapes are combined, such as two angles, to give new shapes.

One point to note is that there are two I-beam types, W and S shapes. The S or Standard beam is narrower than the W or Wide-flange beam and was the first standardized I-beam sections. With the increased quality of steel and manufacturing techniques, the W beams have largely displaced the S beams. (Gramoll, K., 1998)

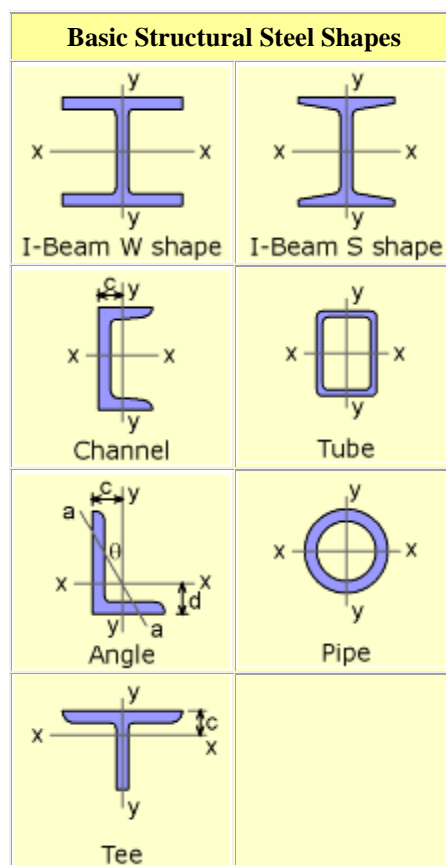


Figure 3: Shapes of Beam (Gramoll, K., 1998)

The geometric cross section is critical in beam design. For instance, a solid rectangular cross section will support considerably less load than an efficient I-beam. The reason for this can be assumed by manipulating the bending stress equation, $\sigma = My/I$. As moment of inertia, I becomes larger, the stress decreases. Therefore, it is beneficial to have most of the cross-sectional area away from the x-axis which increases I . (Gramoll, 1998)

As the central part of a beam remains almost unstressed, the cross sectional shape of a beam can be designed with much of the central part removed. This keeps the strength in the edges of a beam where it is needed while reducing the weight. A good example of this is an I-beam. However, too much of a good thing is bad for instance an I-beam, if the web section is too thin, the shear stress will cause failure. This is why the other shapes are not favoured in general applications. (Avison, 1989)

2.4 Beam Material

Usually cost is commonly considered in choosing the ideal structural material. Other considerations such as weight, strength, constructability, availability, sustainability, and fire resistance will be taken into account before a final decision is made.

The cost of the materials will depend entirely on the geographical location and the availability of the materials. Just as the price of gasoline goes up and down, so do the prices of steel. Some of the characteristics that a beam material should have is by having high strength, stiffness, toughness and ductile properties. That material also should be able developed into nearly any shapes and easy to fabricate. (Koji, 2012)

A common material for steel is ASTM A36 low-carbon structural steel, which replaced the ASTM A7 structural steel in the 1970's. A36 steel is similar to an SAE 1015 steel, with less than 0.2% carbon. The usual working stress in bending is taken as $0.66F_y$, or 24,000 psi. This gives a factor of safety of 2.5 against the ultimate strength, while ensuring that service deflections will remain in the elastic region. Steel is particularly valuable as a material for building vehicle, building, and machine because it is strongest when stretched. (John, 1989)

Steel beams used for building construction in United States use standard alloys identified and specified by ASTM International. These steels have an alloy identification beginning with 'A' and then two, three, or four numbers. The standard commonly used structural steels are carbon steels:

- A36 - structural shapes and plate
- A53 - structural pipe and tubing
- A500 - structural pipe and tubing
- A501 - structural pipe and tubing
- A529 - structural shapes and plate

The four-number AISI steel grades commonly used for mechanical engineering, machines, and vehicles are a completely different specification series. Carbon steels and alloy steels are designated by a four digit number, where the first digit indicates the main alloying element, the second digit indicates the secondary alloying element, and the last two digits indicate the amount of carbon, in hundredths of a percent by weight. (De Garmo., 2011)

For example, a 1060 steel is a plain-carbon steel containing 0.60 wt% of carbon. Major classifications of steel designated by Society of Automotive Engineers (SAE) International are:

- 1xxx - Carbon steels
- 2xxx - Nickel steels
- 3xxx - Nickel-chromium steels
- 4xxx - Molybdenum steels
- 5xxx - Chromium steels
- 6xxx - Chromium-vanadium steels
- 7xxx - Tungsten steels
- 8xxx - Nickel-chromium-molybdenum steels
- 9xxx - Silicon-manganese steels

2.5 BEAM LAYOUT AND LOADING CONFIGURATIONS

In engineering, beams come with several types (American Architect and Architecture, Vol 23):

1. Simply supported - a beam supported on the ends which are free to rotate and have no moment resistance.
2. Fixed - a beam supported on both ends and restrained from rotation.
3. Over hanging - a simple beam extending beyond its support on one end.
4. Double overhanging - a simple beam with both ends extending beyond its supports on both ends.
5. Continuous - a beam extending over more than two supports.
6. Cantilever - a projecting beam fixed only at one end.
7. Trussed - a beam strengthened by adding a cable or rod to form a truss.

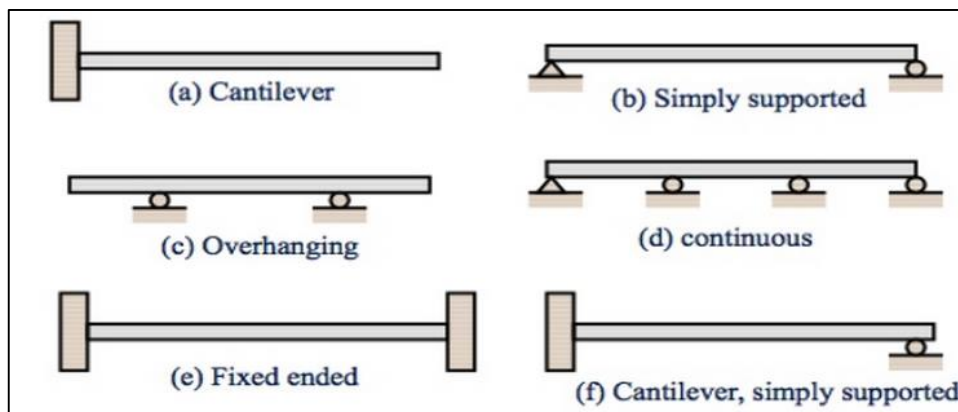


Figure 4: Beam Types

Each of this beam may experience different loading configurations: (Gere, 2011)

1. Concentrated force.
2. Uniform load distribution.
3. Uniform load triangle distribution.
4. Varying point load.
5. End moment.

2.6 STANDARDS

The following standards define the shape and tolerances of I-beam steel sections:

1. Euronorms

- EN 10024, Hot rolled taper flange I sections – Tolerances on shape and dimensions.
- EN 10034, Structural steel I and H sections – Tolerances on shape and dimensions.
- EN 10162, Cold rolled steel sections – Technical delivery conditions – Dimensional and cross-sectional tolerances

2. Other

- DIN 1025-5 – Defines the dimensions, masses and sectional properties.
- ASTM A6, American Standard Beams
- BS 4-1
- IS 808 – Dimensions hot rolled steel beam, column, channel and angle sections.

There are also several tables of the structural shapes for steel, aluminium ASTM, ISO and others:

- AISC Ultimate Structural Shapes Properties Viewer
- AISC,ASTM Channel Steel
- AISC,ASTM Wide Flange #1 Steel
- AISC,ASTM Wide Flange #2 Steel
- AISC,ASTM S Narrow Flange I-Beam Steel
- AISC,ASTM Angle Steel #1
- AISC,ASTM Angle Steel #2
- AISC,ASTM S Flange (Steel)
- Steel Section Properties Chart Narrow I-Beam BS 4-1 | EN 1993-1-1

2.7 TOOLS REQUIRED

This project mostly done using computer modelling software such as Microsoft Excel, MatLab, Visual Basic, or C++ programme depends on the time frame given. Below are the comparison of them:

1. Microsoft Excel

This application build great charts. Data is inserted into individual cells in rows or columns, allowing it to be sorted and filtered, and then displayed in a visual presentation. Help identify trends. When presenting data in the form of charts or graphs, it can be helpful to include average lines, which explicitly detail the key trends emerging from the information.

It can also bring data together. Excel can be used to bring information from various files and documents together, so that it exists in a single location. As well as raw data and information from other spreadsheets, it is possible to import text and images. It is extremely susceptible to petty human errors for example missed negative signs and misaligned rows may produce convincing results even though it is wrong.

2. MatLab

MATLAB (MATrixLABoratory) is an interactive system for matrix-based computation, designed for scientific and engineering use. MATLAB is a high performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notations.

Typically uses include: Math and computation Algorithm development modelling, simulation, and prototyping Data analysing, exploration and visualization Scientific and engineering graphics Application development including graphical user interface building MATLAB is a software package for high-performance numerical computation and visualization. It provides an interactive environment with hundreds of built-in functions for technical computation, graphics, and animation.

It also provides easy extensibility with its own high-level programming language. MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows solving many technical computing problems especially those with matrix and vectoring foundation.

MATLAB has several operators for our use:

- i. + addition – subtraction
- ii. * matrix multiplication
- iii. / division
- iv. ^ exponentiation
- v. .* term-by-term multiplication
- vi. ./ term-by term division
- vii. . term-by term exponentiation

3. Visual Basic

The structure of the Basic programming language is very simple, particularly as to the executable code. It provides a comprehensive interactive and context-sensitive online help system. However visual basic is an exclusive programming language written by Microsoft, so programs written in Visual basic cannot easily be transported to other operating systems. Moreover, it is difficult to troubleshoot or pinpoint the location of error and it takes ages to trace the logic of formulas from one related cell to another.

4. C++

This program is very efficient in which it can compile into highly optimized CPU-specific machine code with little or no runtime overhead. However the complexity makes the learning curve steep and takes a long time to master.

From the evaluation of the softwares/applications above, the author has decided to omit the C++ and Visual Basic options and proceed with Microsoft Excel and MatLab to complete the project as both them are accessible in the university and easy to learn.

2.8 BENCHMARK

The benchmark for this study is a design optimization software called OptDesX. It provides a design environment for optimization of engineering problems. This software supports interactive variable and function selection, design space graphics, tolerance analysis, optimization with continuous and discrete algorithms. The software is available on Unix platform only.

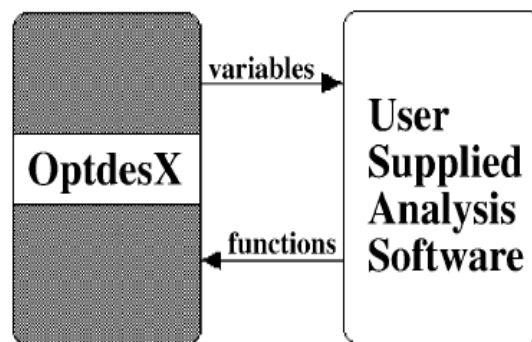


Figure 5: Relationship between OptdesX and analysis software (A.R. Parkinson and R.J. Balling)

From the author observation, this application is very extensive in designing by playing around with several parameters and constraints set. It provides an interactive design environment for exploration and optimization of an engineering model. It also has the ability to determine robust optimum for instance determination on how much we must back off the optimum design in order to take into account tolerances on variables.

The author does not has the opportunity to test out this software but from the manual obtained, this software is the correct datum to be used for this study. Below are the figures of the software user interface:

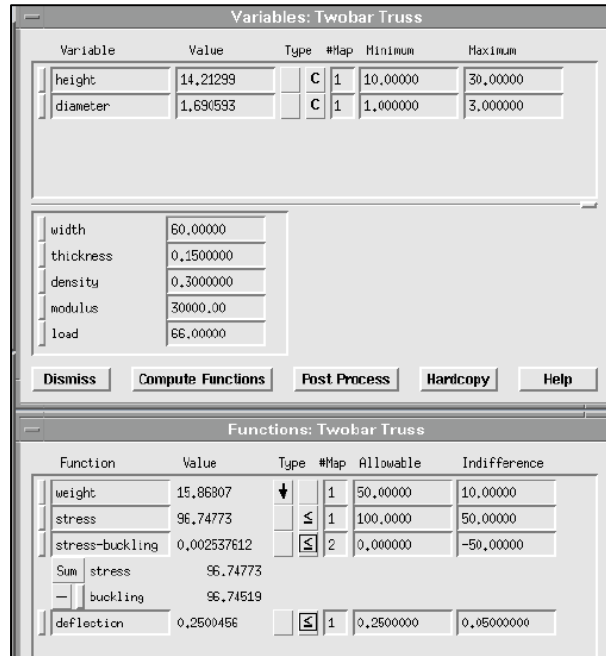


Figure 6: The OptDesX user interface (UI). (A.R. Parkinson and R.J. Balling)

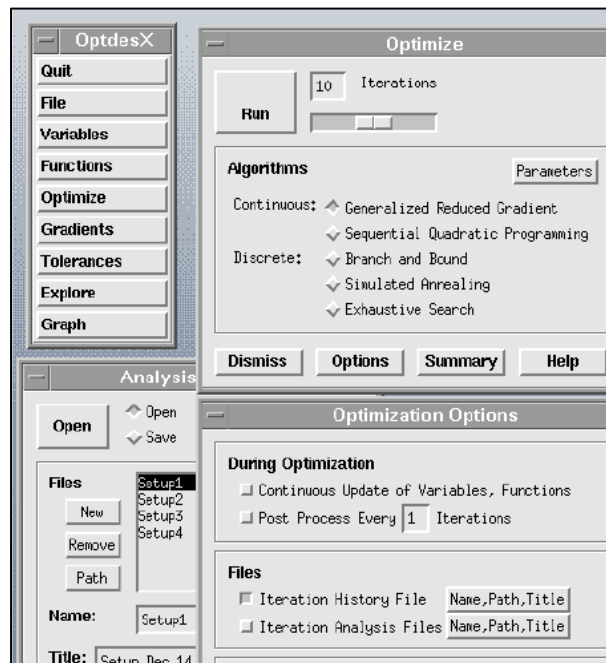


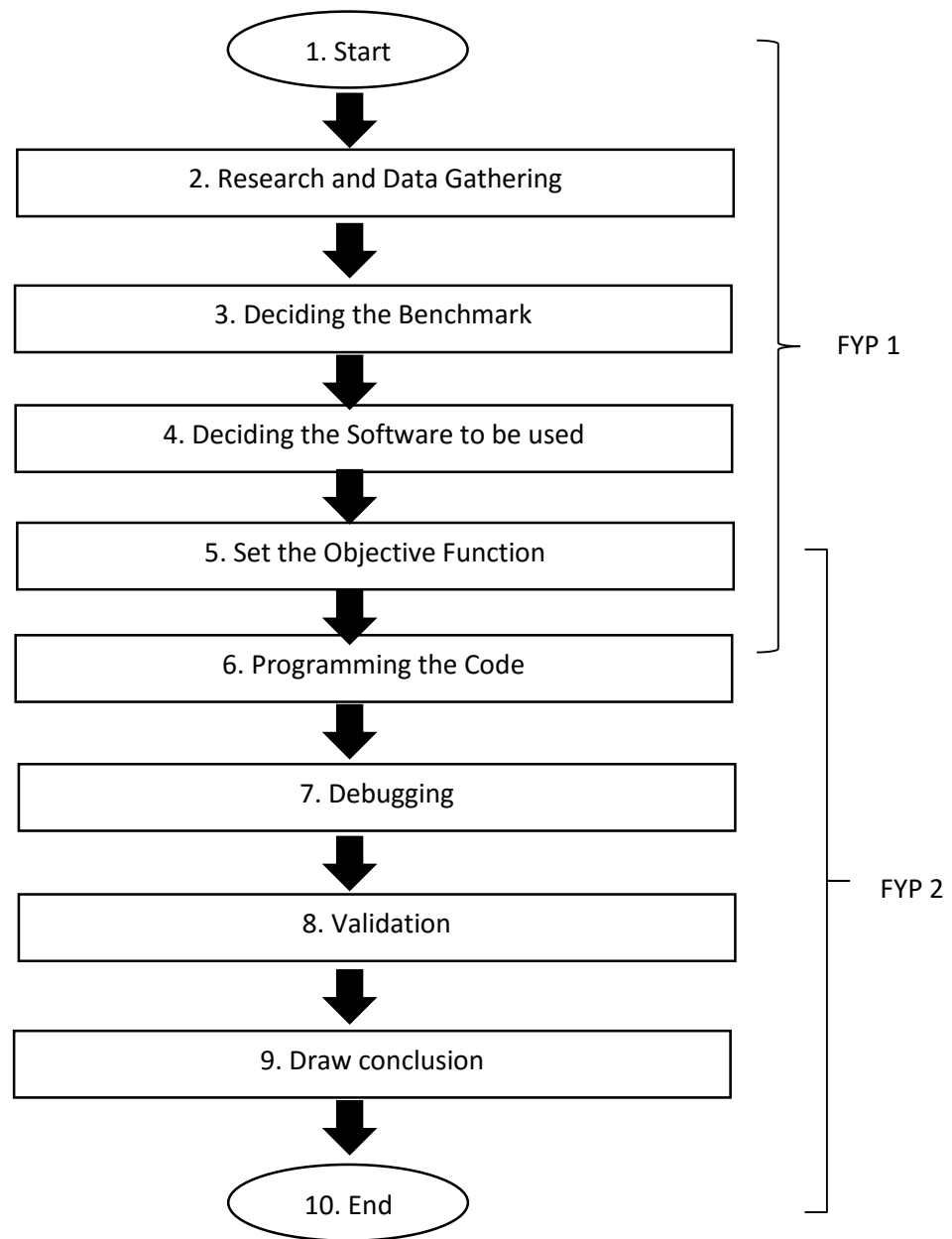
Figure 7: Another UI of OptDesX (A.R. Parkinson and R.J. Balling)

CHAPTER 3

METHODOLOGY

3.1 FLOWCHART OF THE PROJECT

Below is the flow chart of the author's approach on the project which start from the FYP1 (first semester) to FYP2 (second semester).



3.2 Gantt Chart

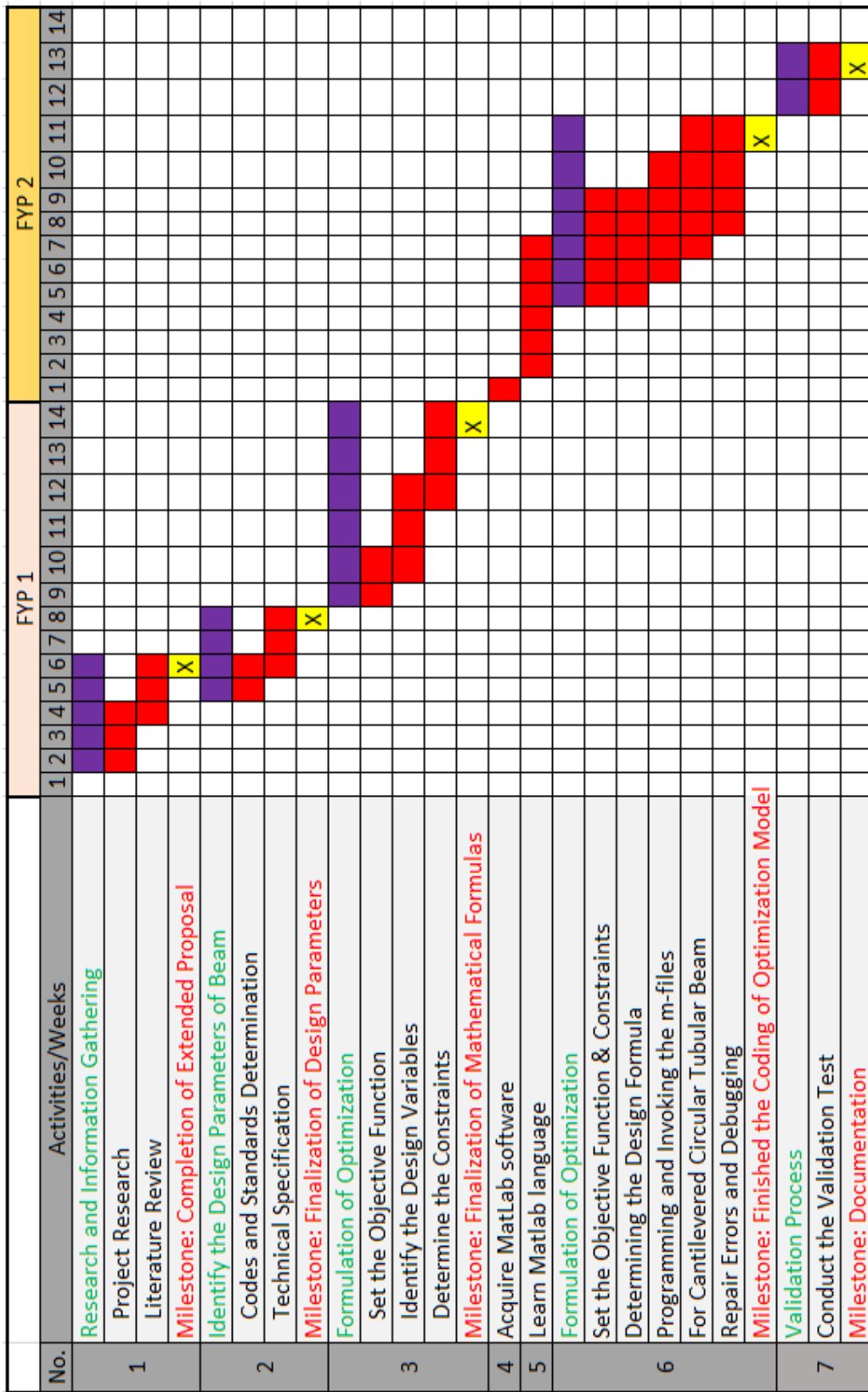


Figure 8: Gantt chart for the Project

3.3 Key Milestones

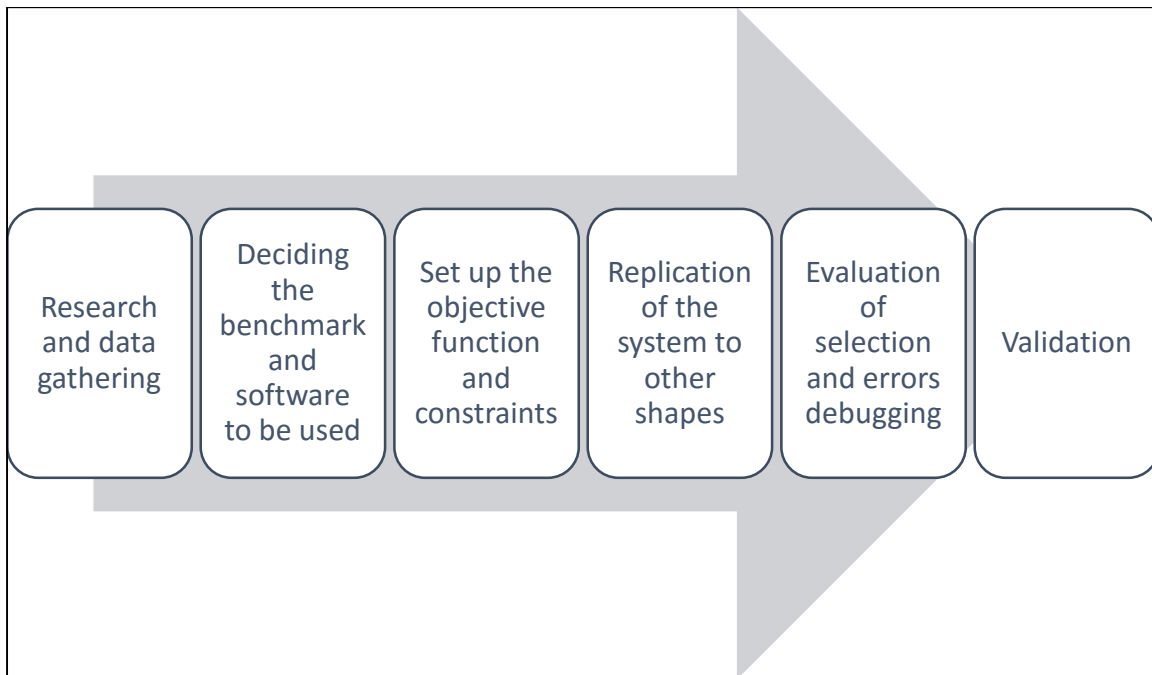
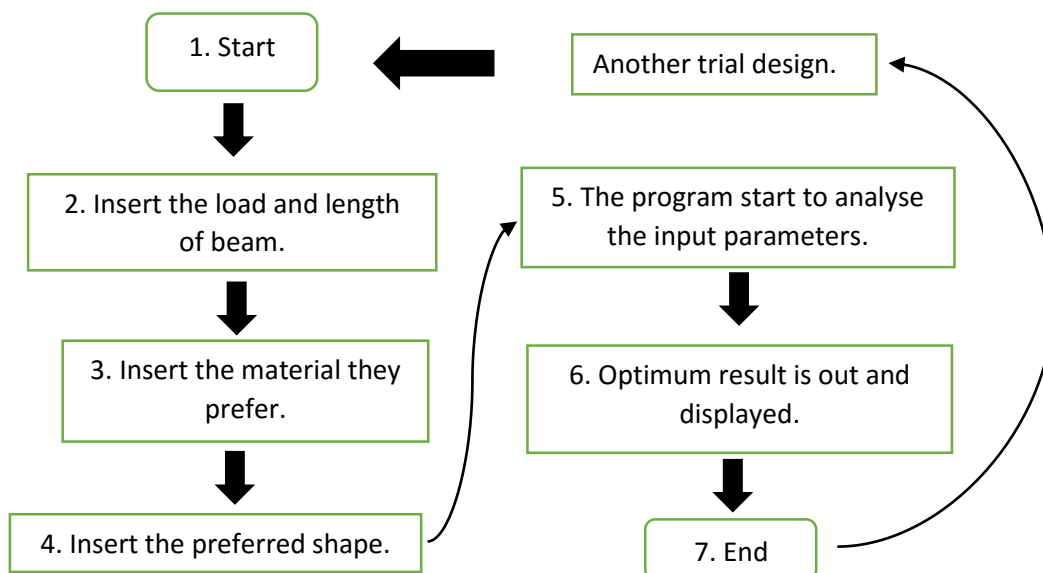


Figure 9: Project Milestone

The flow of the mathematical/analysis model is proposed as below from the Start to End. The end user will experience all of the things as shown in chart below.



Under step number 5 of programming the code, there is a number of steps in it. Below is the concept lies in the 5th step:

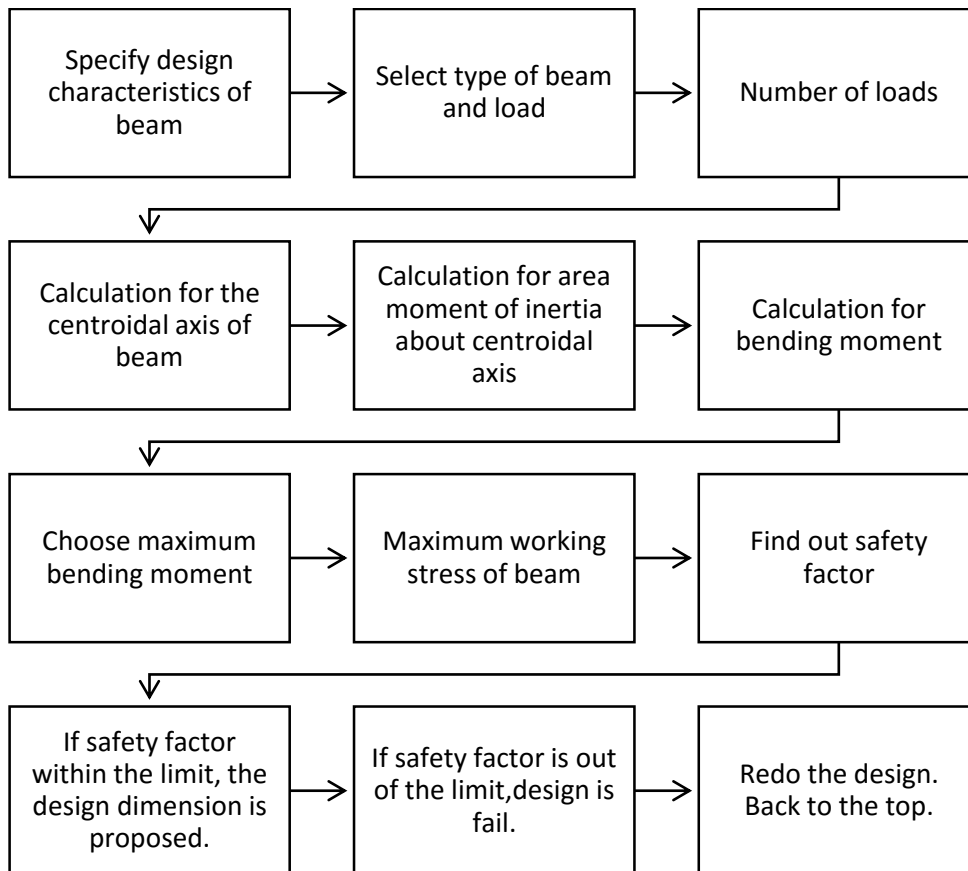


Figure 10: Process flow which determine how the code will be written in step 5

3.4 Steps/Procedures for Microsoft Excel

Data and information is collected before starting the project. One beam shape is decided to be studied upon. The software to be used is determined which Microsoft Excel and MatLab. Microsoft Excel software is opened and a spreadsheet is made. Table of the design variables is made for the user to key-in the parameters. Upper limit and lower limit are set so that the model will manipulate the parameters within the range.

Table 1: Design Variable

Design Variable	Lower Range	Symbol	Value	Upper Range	Unit
web height	0.1	h	0.1	0.65	m
flange width	0.1	b	0.3	0.3	m
flange thickness	0.08	tf	0.22107954	0.4	m
web thickness	0.05	tw	0.05	0.21	m

Define Name is assigned to the dimensions of h, b, tf, tw and the parameters below. The *Define Name* can be found under *Formulas* tab. The properties of the beam, the dependent variables and the other data are determined:

- a) Cross-sectional area, A
- b) Moment of Inertia, M
- c) Uniform load for the beam, w
- d) Bending moment, M
- e) Bending stress, σ
- f) Flange buckling stress limit, σ_f
- g) Web crippling stress limit, σ_w
- h) Shear force, V
- i) Deflection, d
- j) Average shear stress, τ
- k) Live load impact factor, LLIF

Table 2: Design Parameters

Parameter/Properties	Symbol	Value	Unit
Length	L	20	m
Elastic Modulus	E	210	Gpa
Yield strength	YS	262	Mpa
Allowed Fatigue stress	Fa	255	Mpa
Concentrated load for moment	Pm	104	kN
Concentrated load for shear	Ps	155	kN
Live load impact factor	LLIF	1.344827586	none

Table 3: Dependent Variables

Dependent Variables	Symbol	Equation	Units
Cross-sectional area	A	0.005	m ²
Moment of Inertia	I	0.007539466	m ⁴
Uniform Load	w	19	kN/m
Bending moment	M	1470	kN/m
Bending stress	sigma	52.85346998	Mpa
Shear force	V	267.5	kN
Deflection	d	0.025000719	m
Average shear stress	taw	53.5	MPa

The constraints of the analysis model are determined based on the beam properties and safety factor is included in the constraints.

Table 4: Constraints are set with boundaries

Constraint	Value	Equalities (</>/=)	Limit Value	Name
Bending stress	52.85347	<	144.1	Allowed bending stress
Bending stress	52.85347	<	39559.8231	Flange buckling limit
Bending stress	52.85347	<	912069	Web crippling limit
Shear stress	53.5	<	86.46	Allowed shear stress
Deflection	0.02500072	<	0.025	Allowed deflection
Bending stress	52.85347	<	127.5	Allowed Fatigue Stress

The objective function is set which is volume as it is the product of area, A and length of the beam, L. By using Solver add-in of the software, optimization can be done from the data keyed-in above. The Solver need to be set up whereby the Set Objective is set to Volume cell as it is the objective function which need to be minimized. The Changing Variable Cells is assigned to dimensions of the beam that are going to be manipulated and optimized. The constraints are inserted to the analysis model by clicking the Add button whereby another window will pop-up in order to specify the constraints cell and their range.

Table 5: Objective Function

Objective Function	Symbol	Equation	Unit
Volume	Vol	0.1	m3

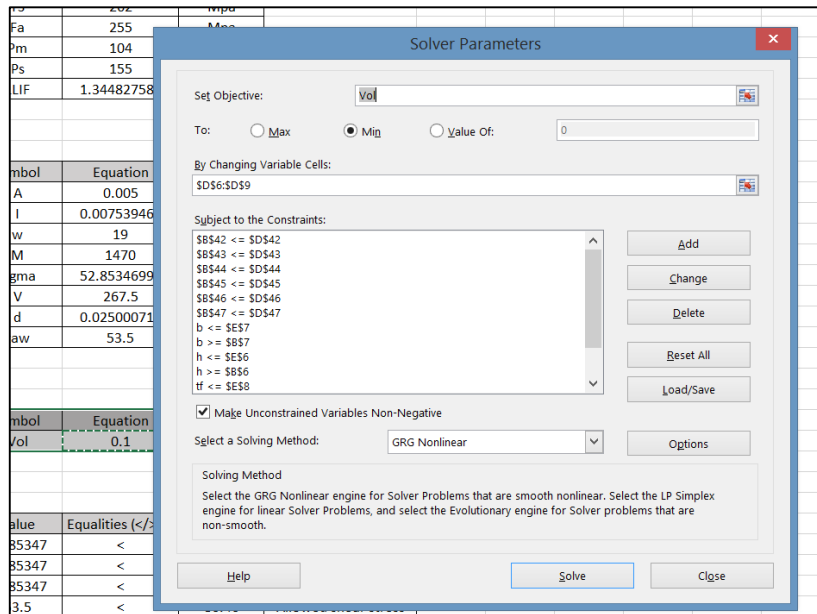


Figure11: Solver Add-in Set-up

The Solve button is clicked where by 3 types of reports are obtained which are the Sensitivity, Answer and Limits Report. After the model is analysed by the system and no error to be found, OK button is clicked to proceed with the optimization process.

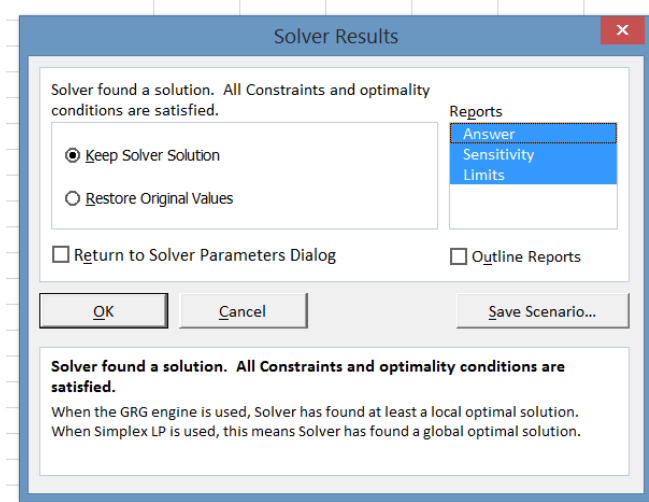


Figure 12: Solver Results Pop-up

The calculations of another shapes are replicated in separate sheet as the governing equations of shapes are different to each other and the Step 5 to Step 12 are repeated. Some tests and simulations are conducted on students or technical personnel to validate the system efficiency. Compare the result of time used by the tester to get the end result using conventional method or software with the newly developed support system. The above steps are repeated for error checking.

3.5 Steps/Procedures for MatLab

3.5.1 Single Script

To initiate the coding of the MatLab programme, first an objective function is determined. For this project, the aim is to get minimum value of cross-sectional area. Therefore, the objective function is the governing equation of area. A function is made with syntax of $f = objfun(x)$. Under this function, several parameters are clarified by asking the user several questions. Below are some of them:

```
prompt='How many number of element?'
NE=input(prompt);

prompt='How long is the beam in m?'
Length=input(prompt);

prompt='What is the design load?'
Load=input(prompt);

prompt='What is the material of the beam? (Aluminium[1],Brass[2],Bronze[3],CastIron[4],Co
y4=input(prompt);
```

Figure 13: Questions for the end user.

After that, on top of the first prompt, the material properties are clarified which comprised of Young's Modulus and density. This material properties are assigned to array namely *material*. This array consists of 1 row and 3 columns. Each row is assigned to different material in which a set of numbers are assigned to them from 1 to 9. While the column represent the properties for instance: [1 70 2710; ...].

The bracket shown means a material classed to number 1 has Young's Modulus of 70 GPa and density of 2710 kg/m³. From the figure above, in the fourth question, each material is assigned to their respective numbers for easiness of array calling. The *if* and *elseif* concept is used afterwards to cope with the material scenario that the user choose.

Then, another question is asked whereby the shapes had to be determined. Another prompt is set to appear again to ask the user for desired shape. For this project several shapes are chosen which are the *I* shape, cylindrical, tubular cylindrical, rectangular and tubular rectangular.

They are also assigned to their respective numbers from 1 to 5 due to implementation of *if* and *elseif* syntax. Under the chosen shape, several factors are considered. Governing equations of flexural structures are applied to process the input given by the user. Below is the brief flow chart of the beam analysis.

Before the code is finished, another criteria need to be typed which is the constraints of the analysis. The constraints might be linear or non-linear. For *I*-beam, the ratio of width to thickness need to be set beforehand to avoid lowest boundary value being constantly chosen as the optimum result. Maximum combined stress also being considered as each material has their own capacity to cater the bend. This constraints are made into another function called 'nonfun(x)'. Below is the example constraints of I beam:

```
function [g,geq]=nonfun(x)
g(1) = ((Load*Length^3)/(3*Modulus*pi*x(1)^3*x(2)^2) + (Load*Length^3)/(8*Modulus*pi*x(1)^3*x(2)))/def
g(2) = (2*x(1)/x(2))/60-1; % must be less than 60
g(3) = (Load*Length*2*x(1)/(2*pi*x(1)^3*x(2)))/165-1; % in kPa unit, must be less than 165 MPa
g(4) = (Load/(12*pi*x(1)^3*x(2)))*(12*x(1)^2+x(2)^2)/186-1; % in kPa unit, must be less than 186 MPa
geq=[];
end
```

Figure 14: Non-linear constraints function

The first constraint namely $g(1)$ is the deflection constraint to limit the amount of vertical expansion of beam end under the load. The second constraint, $g(2)$ is the ratio of width to thickness to ensure the thickness is reasonably suggested and available for fabrication. The third one, $g(3)$ is the maximum bending allowed for the beam before failure. The final constraint, $g(4)$ is the shear stress allowed for the flexural member.

3.5.2 Multiple Script Method

A solver is chosen according to the most appropriate one same goes with the algorithm. The design variables are declared to avoid any variables to hang around without assignment. Objective function is written in separate m-file. As the aim of this project to minimize the weight, the function is defined to minimize. A function file is a text file containing MatLab commands with the extension .m. A new function file is created in any text editor or from the built-in MatLab Editor. The file is save after the function is written.

Constraints are assigned to provide bounds, linear constraints, and nonlinear constraints. Constraint functions must be formulated so that they are in the form $c(x) \leq 0$ or $ceq(x) = 0$. The constraints are written in separate m-file to minimize randomness of files in a single script. Optimization Toolbox software is used after the objective function has been defined. By typing ‘optimtool’ at the command line the app can be started.

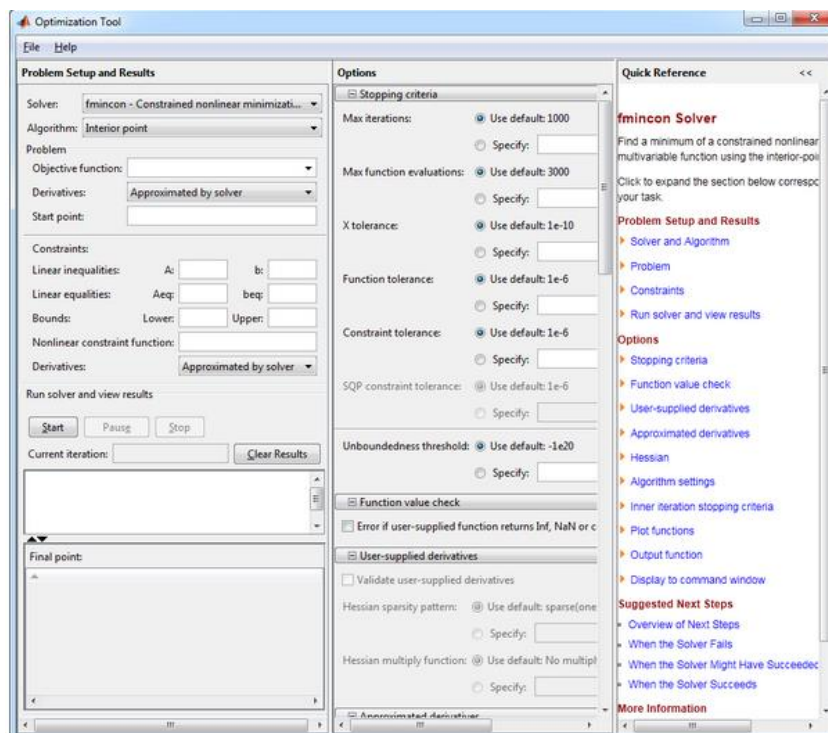


Figure 15: Optimization Tool inside MatLab

The default Solver 'fmincon' - Constrained nonlinear minimization is selected. This solver is appropriate for this problem, since the function created is nonlinear, and the problem has constraints. It is also chosen parallel to the objective function to minimization. The algorithm pop-up menu is set to 'Interior point' which is the default. The objective function problem box is inserted with the name of objective function and add alias symbol before it.

For the start point, [0 0] is entered as the initial point where 'fmincon' begins its search for a minimum. For the Nonlinear constraint function, the empty box is inserted with the name of constraint function by adding alias symbol before it. 'Iterative' is selected in the Level of display pop-up menu in the Options pane at the centre bottom part of window. This enable the display of progress of 'fmincon' in the command window. 'Start' button is clicked which is located under 'Run solver and view results'.

CHAPTER 4

RESULTS & DISCUSSIONS

This chapter will exhibit the result of the optimization for both platform which are the Microsoft Excel and MatLab.

4.1 Microsoft Excel Results

4.1.1 Simply Supported I-Beam Flexural Member

For this case, several parameters had been set and made as constants:

Table 6: Constraints

Parameter/Properties	Symbol	Value	Unit
Length	L1	20	m
Elastic Modulus	E1	210	Gpa
Yield strength	YS1	262	Mpa
Allowed Fatigue stress	Fa1	255	Mpa
Concentrated load for moment	Pm1	104	kN
Concentrated load for shear	Ps1	155	kN
Live load impact factor	LLIF1	1.344827586	none
Parameter/Properties	Symbol	Value	Unit
Length	L1	20	m
Elastic Modulus	E1	210	Gpa
Yield strength	YS1	262	Mpa
Allowed Fatigue stress	Fa1	255	Mpa
Concentrated load for moment	Pm1	104	kN
Concentrated load for shear	Ps1	155	kN
Live load impact factor	LLIF1	1.344827586	none

Figure below shows the dimension variables before the optimization start as an initial value shall be suggested for the optimization to start. The web height and thickness values, and flange width and thickness values are put randomly into the table under the 'Value' column.

Design Variable	Lower Range	Symbol	Value	Upper Range	Unit
web height	0.1	h1		0.65	m
flange width	0.1	b1		0.3	m
flange thickness	0.08	tf1		0.4	m
web thickness	0.05	tw1		0.21	m

Figure 16: Design Variables Table

From the result obtained, the analysis model came out with 3 reports which are Answer Report, Sensitivity Report and Limits Report. The Answer Report below shows the optimization took 4 iterations which completed in split seconds. The initial value of the Volume has changed from random number, 4.25 m^3 to 1.1 m^3 . This is due to the fact that the model play around with the h, b, tf and tw within the range set beforehand. The variable design values are the suggested dimension for the I-beam structure which are the optimum cross-sectional area that has minimum weight.

Variable Cells				
Cell	Name	Original Value	Final Value	Integer
\$D\$6	h1_	0.1	0.1	Contin
\$D\$7	b1_	0.3	0.1	Contin
\$D\$8	tf1_	0.346079539	0.260408345	Contin
\$D\$9	tw1_	0.05	0.05	Contin

Figure 17: Optimized Variables

4.1.2 Simply Supported Tubular Cylinder Beam Structure

For this case, several parameters had been set and made as constants similar to previous one:

Parameter/Properties	Symbol	Value	Unit
Length	L	20	m
Load	P	50000	N
Elastic Modulus	E	210000	Mpa
Yield strength	YS	262	Mpa
	b	33	
	Q	5304.75	
Shear force	V	50000	N
Shear stress	τ_{aw}	319.8019638	MPa
Axial stress	σ	805.8478131	Mpa

Figure 18: Parameters / Constants of the Problem

Figure below shows the look of the dimension variables before the optimization start. Later on, the web height and thickness values, and flange width and thickness values are put randomly into the table under the 'Value' column.

Design Variable	Lower Range	Symbol	Value	Upper Range	Unit
outer diameter	4.00E+01	do		4.00E+02	mm
thickness	1.00E+00	t		1.00E+01	mm
internal diameter	3.00E+01	di		3.50E+02	mm
ratio d/t	1.00E+00	d over t		6.00E+01	

Figure 19: Variables Table

Figure 17 above shows the variables that are dependent on the dimension of the beam. Any instant changes done on the variables dimension will affect these dependent variables.

Objective Cell (Min)			
Cell	Name	Original Value	Final Value
\$C\$37	Vol	856.32	1240.929098

Figure 20: Volume as the Objective of Optimization

Variable Cells				
Cell	Name	Original Value	Final Value	Integer
\$D\$6	do	5.00E+00	4.00E+01	Contin
\$D\$7	t	6.00E+00	1.00E+00	Contin
\$D\$8	di	7.00E+00	7.00E+00	Contin
\$D\$9	d_over_t	8.00E+00	8.00E+00	Contin

Figure 21: Optimized Variables

4.1.3 Cantilevered Circular Tubular Beam

Similar to the previous case, the design variables are determined and the constraints of them are made known.

Design Variable	Lower Range	Symbol	Value	Upper Range	Unit
outer diameter	6.00E+01	do	7.14E+01	6.00E+02	mm
thickness	1.00E+00	t	1.00E+00	2.00E+01	mm
internal diameter	3.00E+01	di	4.00E+00	5.50E+02	mm
ratio d/t	1.00E+00	d over t	6.00E+00	6.00E+01	
outer radius		ro	3.57E+01		mm
internal radius		ri	2.00E+00		mm

The objective cell is determined whereby the aim is to minimize the weight:

Objective Function	Symbol	Equation	Unit
Volume	Vol	2226.288523	mm ³

Objective Cell (Min)				
Cell	Name	Original Value	Final Value	
\$C\$39	Vol	1869.247629	2226.288523	

Variable Cells				
Cell	Name	Original Value	Final Value	Integer
\$D\$6	do	6.00E+01	7.14E+01	Contin
\$D\$7	t	1.00E+00	1.00E+00	Contin
\$D\$8	di	4.00E+00	4.00E+00	Contin
\$D\$9	d_over_t	6.00E+00	6.00E+00	Contin

Figure 22: Optimization Results

4.1.4 Cantilevered Square Tubular Beam

Below is the table of design variables for square tubular beam:

Design Variable	Lower Range	Symbol	Value	Upper Range	Unit
width	80	w4	80	650	mm
thickness	10	t4	10	40	mm
ratio w/t	2	w4/t4	8	8	

Figure 23: Design Variables Table

The aim of the optimization is to minimize the volume:

Objective Function	Symbol	Equation	Unit
Volume	Vol4	8400	mm ³

Figure 24: Objective Cell

Figure above shows the summary of the optimization process which is successful without error. While the figure below show the objective cell of the optimization and the cells that are manipulated throughout the process:

Objective Cell (Min)				
Cell	Name	Original Value	Final Value	
\$C\$33	Vol4_	10428	8400	


Variable Cells				
Cell	Name	Original Value	Final Value	Integer
\$D\$6	w4_	90	80	Contin
\$D\$7	t4_	11	10	Contin
\$D\$8	w4_t4	8.181818182	8	Contin

Figure 25: Optimization Result

4.2 MatLab Results

4.2.1 Single Script

The result of optimization is depend on what the user input in. For this project, the file is called as 'Beamtesting.m'. As mentioned in previous section, several questions are asked in term of prompt to get the brief detail of what the user desire. Below is an optimization process which start with asking the number of element. This is asked to obtain the node-by-node deflection and slope. The beam is divided into several elements to get the bending moment value experienced by each element as they are different on each element.



```
Command Window
>> Beamtesting

prompt =
How many number of element?
How many number of element?10

prompt =
How long is the beam in m?
How long is the beam in m?5

prompt =
What is the design load?
What is the design load?3000

prompt =
What is the material of the beam? (Aluminium[1],Brass[2],Bronze[3],CastIron[4],Concrete[5],Steel[6],Titanium[7],Wood[8],WroughtIron[9])
What is the material of the beam? (Aluminium[1],Brass[2],Bronze[3],CastIron[4],Concrete[5],Steel[6],Titanium[7],Wood[8],WroughtIron[9])3
```

Figure 26: The user interface of the system

The next question is the length whereby the user input a value of 5 metre. Next, the user had to assign the design load which is used a lot later on in process analysis. Afterwards, the user had to choose the materials for the beam from what is given.

```
Command Window
prompt =
What is the shape of the beam? (Ishape[1]/Cylinder[2]/CylinderTubular[3]/RectangularSolid[4]/RectangularTubular[5])
What is the shape of the beam? (Ishape[1]/Cylinder[2]/CylinderTubular[3]/RectangularSolid[4]/RectangularTubular[5])3
prompt =
What is the design outer diameter of the tube in in mm?
What is the design outer diameter of the tube in in mm?300
prompt =
What is the design thickness of the tube in mm?
What is the design thickness of the tube in mm?50
```

Figure 27: Another prompts

Then several questions are asked from the shape and design area. Each shape has distinct governing equation to calculate the area moment of inertia, I . This I play big role in the analysis. It is known that the further the neutral axis of a beam to the outer most part, the stronger it will be in handling bending. Next is the design area. To obtain this value, the system will ask the user on imaginary dimension of their design. From this dimensions input, a design area can be estimated so that the optimization can suggest optimum dimension by playing around within the design area suggested. Below is the results of optimization for this particular problem:

```
Following results are Diameter (mm):
Thickness of tube (mm):
650.7413
48.0408
```

From the results obtained, for this particular case, the diameter of the tubular beam is approximately 651 mm and the thickness of it is around 48 mm to obey the constraints and parameters given.

4.2.2 Multiple Script

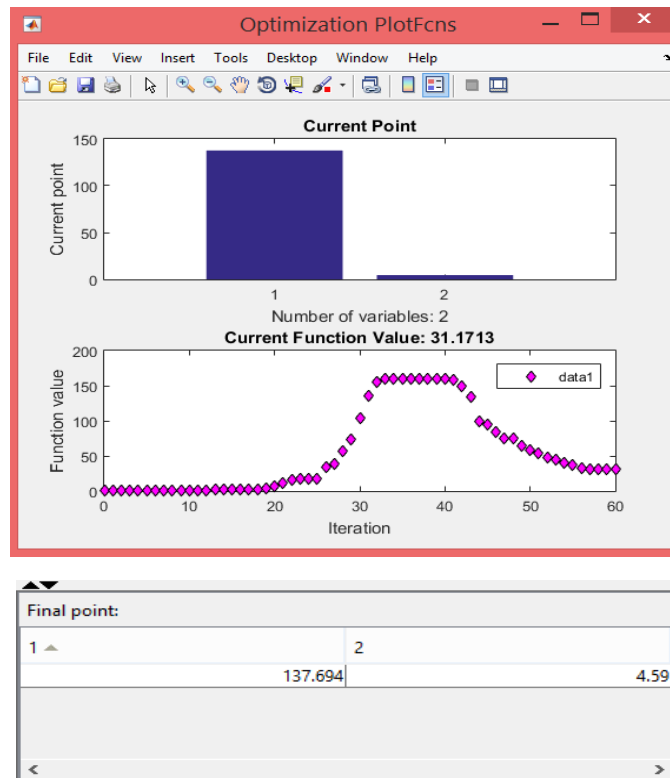


Figure 28: Optimization Result

From the figure shown above, in the optimization process, two variables are set. For this figure, an example result of tubular beam is used. The two variables are the radius and thickness which are assigned to be x_1 and x_2 respectively. The top plot shows the result of 61 times of iterations to produce the minimum value of objective function, which is the area as mentioned before. In the bottom plot, the product of x_1 and x_2 is the area are plotted within the boundaries set beforehand before converging to the most minimum value.

From the optimization conducted for tubular cylinder, the local minimum is found and satisfies the constraints. As mentioned before, the optimization is completed because the objective function is non-decreasing in feasible directions, to within the default value of the function tolerance. Cross-sectional area equation is considered as it is directly proportional to the volume and mass of the flexural member. Therefore, the optimum radius suggested is 137.694 mm while the optimum thickness is 4.59 mm. The value of 31.17 represents the mass of the beam by multiplying the area with the determined length.

4.3 Validation

The validation refers to checking that the support system created meets the specifications and fulfils its intended purpose. Simply put it roles to ensure the codes are built right. From the testing perspective, there are 3 main things:

- Fault – wrong or missing function in the code
- Failure – the manifestation of a fault during execution
- Malfunction – according to its specification the system does not meet its specified function.

There are 2 ways to validate either with manual calculation or using the features available in the applications. However with the accuracy of the MS Excel in mathematical execution, the manual calculation is not needed. For MatLab programme, to check a paragraph of code is simply right click the code and choose the ‘Evaluate Selection’. The command window will show some error reminder under the command window with red font. The red reminder usually explain briefly the mistake and specify the line which the error occurs. However, a simple test was conducted on 2 students who are decent in the course. The test was conducted on 3 separate occasion to see the median of solving time. Both of them took around 35 to 50 minutes in average to solve a beam problem related to elemental stiffness. Table below shows the recorded data of their performance.

Table 7: Time performance of both students.

Student	t1 (minute)	t2 (minute)	t3 (minute)	t ave (minute)
A	48	42	31	40
B	37	33	26	32

Compared to the supported system made that able to solve within seconds, the manual calculations are far behind in term of time performance. This somehow proves the automation of steps in designing the beam saves a lot of time, resources and manpower.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

As conclusion, this project is succeed in developing a support system that able to find optimum design for flexural members. It is known that lesser cross-sectional area means lesser the volume is lead to less material used to fabricate it. The life-cycle cost of the beam is related to its total mass. A quick and efficient way of optimizing the beam design is developed through MatLab code which can be used to solve beam design problems quicker and errorless. The author would like to highlight several main point of the article. They are:

- MatLab is a very good and fast application for optimization same goes with Excel.
- There are many approaches for optimization in MatLab. The first approach used by the author is by using function syntax and fmincon in a single script. The other one is by using Optimization Tool, an add-in inside the Matlab whereby separate script files are made and called.
- Excel can be used for the validation of the MatLab code rather than by hand calculations which is tedious and lengthy.
- This support system is able to help the designers and engineers to design and play around with beam dimensions to see the suitability with the load, material and length. In business point of view, if this support system is refined and improved further, it can be sold and used by the engineering community.

5.1 Future Works/Recommendations

1. The author would like to improve this study by adding GUI-Graphical User Interface. The plan is to give the user friendly features rather than facing paragraphs of coding. By doing this, the interaction between the user and interface can go smoother.
2. The author would like to suggest to UTP to include Matlab as one of the core Mechanical subject. The author experienced difficulties in grasping and applying the concept of Matlab in a short period as learning without guru is a bad practice.

6.0 References

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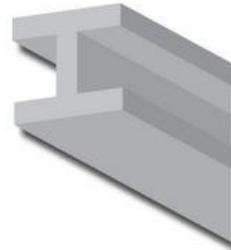
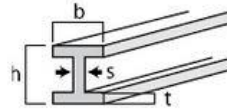
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7.0 Appendices

Metric Wide Flange Beams - Light Weight

CARBON STEEL

IPB-1 Range Sections, DIN 1025-3, EN 10034, Euronorm (HEA), St37-2, St52-3, S235JrG2C, S355J2G3C, Stock Length 6 Meters

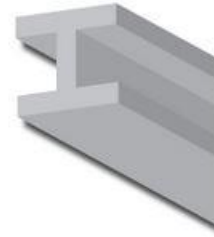
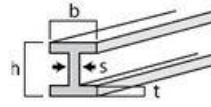


IPB-1 SECTION NUMBER	DEPTH h mm	WIDTH b mm	THICK t mm	WEB s mm	kg/m	lb/ft
100	96	100	8	5	16.7	11.24
120	114	120	8	5	19.9	13.39
140	133	140	8.5	5.5	24.7	16.62
160	152	160	9	6	30.4	20.46
180	171	180	9.5	6	35.5	23.89
200	190	200	10	6.5	42.3	28.47
220	210	220	11	7	50.5	33.99
240	230	240	12	7.5	60.3	40.58
260	250	260	12.5	7.5	68.2	45.9
280	270	280	13	8	76.4	51.42
300	290	300	14	8.5	88.3	59.43
320	310	300	15.5	9	97.6	65.7
340	330	300	16.5	9.5	105	70.66
360	350	300	17.5	10	112	75.38
400	390	300	19	11	125	84.13
450	440	300	21	11.5	140	94.22
500	490	300	23	12	155	104.31
550	540	300	24	12.5	166	111.72
600	590	300	25	13	178	119.79
650	640	300	26	13.5	190	127.87

Metric Wide Flange Beams - Medium Weight

CARBON STEEL

IPB Range Sections, DIN 1025-2, EN 10034, Euronorm (HEB), S137-2, S152-3, S235JrG2C, S355J2G3C,
Stock Length 6 Meters

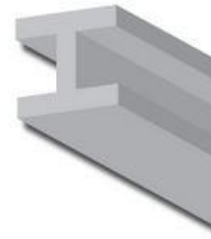
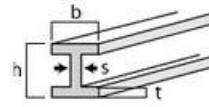


IPB SECTION NUMBER	FLANGE			WEIGHT		
	DEPTH h mm	WIDTH b mm	THICK t mm	WEB s mm	kg/m	lb/ft
100	100	100	10	6	20.4	13.73
120	120	120	11	6.5	26.7	17.97
140	140	140	12	7	33.7	22.68
160	160	160	13	8	42.6	28.67
180	180	180	14	8.5	51.2	34.46
200	200	200	15	9	61.3	41.25
220	220	220	16	9.5	71.5	48.12
240	240	240	17	10	83.2	55.99
260	260	260	17.5	10	93	62.59
280	280	280	18	10.5	103	69.32
300	300	300	19	11	117	78.74
320	320	300	20.5	11.5	127	85.47
340	340	300	21.5	12	134	90.18
360	360	300	22.5	12.5	142	95.56
400	400	300	24	13.5	155	104.31
450	450	300	26	14	171	115.08
500	500	300	28	14.5	187	125.85
550	550	300	29	15	199	133.92
600	600	300	30	15.5	212	142.67
650	650	300	31	16	225	151.43

Metric Wide Flange Beams - Heavy Weight

CARBON STEEL

IPBv Range Sections, DIN 1025-4, EN 10277-2, EN 10034, Euronorm (HEM), St37-2, St52-3, S235JrG2C, S355J2G3C, Stock Length 6 Meters



IPBv SECTION	DEPTH h mm	FLANGE		WEB s mm	WEIGHT	
		WIDTH b mm	THICK t mm		kg/m	lb/ft
100	120	106	20	12	41.8	28.13
120	140	126	21	12.5	52.1	35.06
140	160	146	22	13	63.2	42.53
160	180	166	23	14	76.2	51.28
180	200	186	24	14.5	88.9	59.83
200	220	206	25	15	103	69.32
220	240	226	26	15.5	117	78.74
240	270	248	32	18	157	105.66
260	290	268	32.5	18	172	115.76
280	310	288	33	18.5	189	127.2
300	340	310	39	21	238	160.17
320/305	320	305	29	16	177	119.12
320	359	309	40	21	245	164.89
340	377	309	40	21	248	166.9
360	395	308	40	21	250	168.25
400	432	307	40	21	256	172.3
450	478	307	40	21	263	176.9
500	524	306	40	21	270	181.7
550	572	306	40	21	278	187.1
600	620	305	40	21	285	191.8

Simply Supported I-Beam Report Appendices

Microsoft Excel 15.0 Answer Report

Worksheet: [analysis model_rev1.xlsx]Solver I-beam Simply Supp

Report Created: 20/04/2015 17:10:20

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: GRG Nonlinear

Solution Time: 0.141 Seconds.

Iterations: 6 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Central

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Objective Cell (Min)

Cell	Name	Original Value	Final Value
\$C\$37	Vol1_	4.252954474	1.141633378

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
\$B\$42	Bending stress Value	41.67753699	\$B\$42<=\$D\$42	Not Binding	102.422463
\$B\$45	Shear stress Value	62.29057701	\$B\$45<=\$D\$45	Not Binding	24.16942299
\$B\$46	Deflection Value	0.025000611	\$B\$46<=\$D\$46	Binding	0
\$B\$44	Bending stress Value	41.67753699	\$B\$44<=\$D\$44	Not Binding	912027.3225
\$B\$47	Bending stress Value	41.67753699	\$B\$47<=\$D\$47	Not Binding	85.82246301
\$B\$43	Bending stress Value	41.67753699	\$B\$43<=\$D\$43	Not Binding	493938.5217
\$D\$9	tw1_	0.05	\$D\$9<=\$E\$9	Not Binding	0.16
\$D\$6	h1_	0.1	\$D\$6>=\$B\$6	Binding	0
\$D\$8	tf1_	0.260408345	\$D\$8<=\$E\$8	Not Binding	0.139591655
\$D\$8	tf1_	0.260408345	\$D\$8>=\$B\$8	Not Binding	0.180408345
\$D\$9	tw1_	0.05	\$D\$9>=\$B\$9	Binding	0
\$D\$7	b1_	0.1	\$D\$7<=\$E\$7	Not Binding	0.2
\$D\$6	h1_	0.1	\$D\$6<=\$E\$6	Not Binding	0.55
\$D\$7	b1_	0.1	\$D\$7>=\$B\$7	Binding	0

Microsoft Excel 15.0 Sensitivity Report
Worksheet: [analysis model_rev1.xlsx]Solver I-beam Simply Supp
Report Created: 20/04/2015 17:10:20

Variable Cells

Cell	Name	Final Value	Reduced Gradient
\$D\$6	h1_	0.1	0.76386711
\$D\$7	b1_	0.1	10.64795753
\$D\$8	tf1_	0.260408345	0
\$D\$9	tw1_	0.05	2.087918916

Constraints

Cell	Name	Final Value	Lagrange Multiplier
\$B\$42	Bending stress Value	41.67753699	0
\$B\$45	Shear stress Value	62.29057701	0
\$B\$46	Deflection Value	0.025000611	-14.89082737
\$B\$44	Bending stress Value	41.67753699	0
\$B\$47	Bending stress Value	41.67753699	0
\$B\$43	Bending stress Value	41.67753699	0

Microsoft Excel 15.0 Limits Report
Worksheet: [analysis model_rev1.xlsx]Solver I-beam Simply Supp
Report Created: 20/04/2015 17:10:20

Objective

Cell	Name	Value
\$C\$37	Vol1_	1.141633378

Cell	Variable Name	Value	Lower Limit	Objective Result	Upper Limit	Objective Result
\$D\$6	h1_	0.1	0.1	1.141633378	0.65	1.691633378
\$D\$7	b1_	0.1	0.1	1.141633378	0.1	1.141633378
\$D\$8	tf1_	0.260408345	0.260408345	1.141633378	0.4	1.7
\$D\$9	tw1_	0.05	0.05	1.141633378	0.05	1.141633378

Simply Supported Circular Tubular Beam Appendices

Microsoft Excel 15.0 Answer Report

Worksheet: [analysis model_rev1.xlsx]Solver Tubular

Report Created: 20/04/2015 16:25:31

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: GRG Nonlinear

Solution Time: 0.046 Seconds.

Iterations: 2 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001

Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Central

Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Dependent Variables	Symbol	Equation	Units
Cross-sectional area	A	62.04645491	mm ²
Moment of Inertia	I	25132.74123	mm ⁴
Uniform Load	w	2500	N/m
Bending moment	M	125000	N/m
Bending stress	sigma	99.47183943	Mpa
Deflection	d	0.000986824	mm

Microsoft Excel 15.0 Sensitivity Report

Worksheet: [analysis model_rev1.xlsx]Solver Tubular

Report Created: 20/04/2015 16:25:31

Variable Cells

Cell	Name	Final Value	Reduced Gradient
\$D\$6	do	40	31.41592598
\$D\$7	t	1	1225.221069
\$D\$8	di	7	0
\$D\$9	d_over_t	8	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
\$C\$31	sigma	99.47183943	0
\$B\$45	Area Value	62.04645491	0
\$B\$44	Deflection Value	0.000986824	0

Microsoft Excel 15.0 Limits Report
Worksheet: [analysis model_rev1.xlsx]Solver Tubular
Report Created: 20/04/2015 16:25:31

Objective		
Cell	Name	Value
\$C\$37	Vol	1240.929098

Variable			Lower	Objective	Upper	Objective
Cell	Name	Value	Limit	Result	Limit	Result
\$D\$6	do	4.00E+01	4.00E+01	1.24E+03	4.00E+02	1.26E+04
\$D\$7	t	1.00E+00	1.00E+00	1.24E+03	1.00E+01	1.10E+04
\$D\$8	di	7.00E+00	0.00E+00	1.24E+03	#N/A	#N/A
\$D\$9	d_over_t	8.00E+00	1.00E+00	1.24E+03	6.00E+01	1.24E+03

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
\$C\$31	sigma	99.47183943	\$C\$31<=250	Not Binding	150.5281606
\$B\$45	Area Value	62.04645491	\$B\$45>=0	Not Binding	62.04645491
\$B\$44	Deflection Value	0.000986824	\$B\$44<=\$D\$44	Not Binding	0.019013176
\$D\$6	do	4.00E+01	\$D\$6<=\$E\$6	Not Binding	360
\$D\$7	t	1.00E+00	\$D\$7>=\$B\$7	Binding	0.00E+00
\$D\$7	t	1.00E+00	\$D\$7<=\$E\$7	Not Binding	9
\$D\$6	do	4.00E+01	\$D\$6>=\$B\$6	Binding	0.00E+00
\$D\$9	d_over_t	8.00E+00	\$D\$9<=\$E\$9	Not Binding	52
\$D\$9	d_over_t	8.00E+00	\$D\$9>=\$B\$9	Not Binding	7.00E+00

Cantilevered Circular Tubular Beam Appendices

Microsoft Excel 15.0 Answer Report
Worksheet: [analysis model_rev1.xlsx]Solver Circular Cantilevered
Report Created: 20/04/2015 16:43:27
Result: Solver found a solution. All Constraints and optimality conditions are satisfied.
Solver Engine
Engine: GRG Nonlinear
Solution Time: 0.188 Seconds.
Iterations: 9 Subproblems: 0
Solver Options
Max Time Unlimited, Iterations Unlimited, Precision 0.000001
Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Central
Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

For this case, several parameters had been set and made as constants:

Parameter/Properties	Symbol	Value	Unit
Length	L	20	m
Load	P	50000	N
Elastic Modulus	E	210000	Mpa
Yield strength	YS	262	Mpa
	b	67.36496465	
	Q	30282.89837	mm3
Shear force	V	50000	N
Shear stress	taw	17.65336598	MPa
Axial stress	sigma	449.178078	Mpa

Below are dependent variables of the optimization process:

Dependent Variables	Symbol	Equation	Units
Cross-sectional area	A	111.3144262	mm2
Moment of Inertia	I	142729.9293	mm4
Uniform Load	w	2500	N/m
Bending moment	M	125000	N/m
Bending stress	sigma	250	Mpa
Deflection	d	0.000173766	m

Constraints					
Cell	Name	Cell Value	Formula	Status	Slack
\$C\$33	sigma	250	\$C\$33<=250	Binding	0
\$B\$47	Area Value	111.3144262	\$B\$47>=0	Not Binding	111.3144262
\$B\$46	Deflection Value	0.000173766	\$B\$46<=\$D\$46	Not Binding	0.019826234
\$D\$7	t	1.00E+00	\$D\$7<=\$E\$7	Not Binding	19
\$D\$6	do	7.14E+01	\$D\$6>=\$B\$6	Not Binding	1.14E+01
\$D\$6	do	7.14E+01	\$D\$6<=\$E\$6	Not Binding	528.6350353
\$D\$7	t	1.00E+00	\$D\$7>=\$B\$7	Binding	0.00E+00
\$D\$9	d_over_t	6.00E+00	\$D\$9<=\$E\$9	Not Binding	54
\$D\$9	d_over_t	6.00E+00	\$D\$9>=\$B\$9	Not Binding	5.00E+00

Constraint	Value	Equalities (</>/=)	Limit Value	Name
Bending stress	250	<	144.1	Allowed bending stress
Shear stress	17.653366	<	86.46	Allowed shear stress
Deflection	0.00017377	<	0.02	Allowed deflection
Area	111.314426	>	1	Minimum area

Microsoft Excel 15.0 Sensitivity Report
Worksheet: [analysis model_rev1.xlsx]Solver Circular Cantilevered
Report Created: 20/04/2015 16:43:27

Variable Cells

Cell	Name	Final Value	Reduced Gradient
\$D\$6	do	71.36496465	0
\$D\$7	t	1	1089.584588
\$D\$8	di	4	0
\$D\$9	d_over_t	6	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
\$C\$33	sigma	250	-4.483992947
\$B\$47	Area Value	111.3144262	0
\$B\$46	Deflection Value	0.000173766	0

Microsoft Excel 15.0 Limits Report
Worksheet: [analysis model_rev1.xlsx]Solver Circular Cantilevered
Report Created: 20/04/2015 16:43:27

Objective

Cell	Name	Value
\$C\$39	Vol	2226.288523

Variable

Cell	Name	Value	Lower Limit	Objective Result	Upper Limit	Objective Result
\$D\$6	do	7.14E+01	7.14E+01	2.23E+03	6.00E+02	1.88E+04
\$D\$7	t	1.00E+00	1.00E+00	2.23E+03	2.00E+01	3.86E+04
\$D\$8	di	4.00E+00	0.00E+00	2.23E+03	#N/A	#N/A
\$D\$9	d_over_t	6.00E+00	1.00E+00	2.23E+03	6.00E+01	2.23E+03

Cantilevered Square Tubular Beam Appendices

Result: Solver found a solution. All Constraints and optimality conditions are satisfied.

Solver Engine

Engine: GRG Nonlinear
 Solution Time: 0.078 Seconds.
 Iterations: 3 Subproblems: 0

Solver Options

Max Time Unlimited, Iterations Unlimited, Precision 0.000001
 Convergence 0.0001, Population Size 100, Random Seed 0, Derivatives Central
 Max Subproblems Unlimited, Max Integer Sols Unlimited, Integer Tolerance 1%, Assume NonNegative

Several properties of the beam are set constant:

Parameter/Properties	Symbol	Value	Unit
Length	L4	3	m
Load	P4	25000	N
Elastic Modulus	E4	210000	Mpa
Yield strength	YS4	262	MPa
	Q4	37000	mm3
Shear force	V4	25000	N
Shear stress	taw4	19.82142857	Nmm-2

The optimization shall obey the constraints set below:

Constraint	Value	Equalities (</>/=)	Limit Value	Name
Bending stress	1.285714286	<	1.5	Allowed bending stress
Shear stress	19.82142857	<	25	Allowed shear stress
Deflection	4.59184E-07	<	10	Allowed deflection

The variables of the dependent parameters are checked and made sure to be linked with the design variables as well as constants above:

Dependent Variables	Symbol	Equation	Units
Cross-sectional area	A4	2800	mm2
Moment of Inertia	I4	2333333.333	mm4
Bending moment	M4	75000	Nmm
Bending stress	sigma4	1.285714286	Nmm-2
Deflection	d4	4.59184E-07	mm

Constraints					
Cell	Name	Cell Value	Formula	Status	Slack
\$B\$38	Bending stress Value	1.285714286	\$B\$38<=\$D\$38	Not Binding	0.214285714
\$B\$39	Shear stress Value	19.82142857	\$B\$39<=\$D\$39	Not Binding	5.178571429
\$B\$40	Deflection Value	4.59184E-07	\$B\$40<=\$D\$40	Not Binding	9.999999541
\$D\$7	t4_	10	\$D\$7<=\$E\$7	Not Binding	30
\$D\$7	t4_	10	\$D\$7>=\$B\$7	Binding	0
\$D\$6	w4_	80	\$D\$6<=\$E\$6	Not Binding	570
\$D\$6	w4_	80	\$D\$6>=\$B\$6	Binding	0
\$D\$8	w4_t4	8	\$D\$8<=\$E\$8	Binding	0
\$D\$8	w4_t4	8	\$D\$8>=\$B\$8	Not Binding	6

Microsoft Excel 15.0 Sensitivity Report
Worksheet: [analysis model_rev1.xlsx]Solver Square Tubular Cantilever
Report Created: 20/04/2015 17:50:47

Variable Cells

Cell	Name	Final Value	Reduced Gradient
\$D\$6	w4_	80	120
\$D\$7	t4_	10	719.9998779
\$D\$8	w4_t4	8	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
\$B\$38	Bending stress Value	1.285714286	0
\$B\$39	Shear stress Value	19.82142857	0
\$B\$40	Deflection Value	4.59184E-07	0

Microsoft Excel 15.0 Limits Report
Worksheet: [analysis model_rev1.xlsx]Solver Square Tubular Cantilever
Report Created: 20/04/2015 17:50:47

Objective

Cell	Name	Value
\$C\$33	Vol4_	8400

Variable

Variable			Lower Objective		Upper Objective	
Cell	Name	Value	Limit	Result	Limit	Result
\$D\$6	w4_	80	80	8400	650	76800
\$D\$7	t4_	10	10	8400	40	19200
\$D\$8	w4_t4	8	2	8400	8	8400

Matlab Single Script Code

```
function f=Beamtesting(x)

clear all

%clc
A=[-1 0 ;0 -1 ;0 0;2 0];
b=[0; 0; 240; 0];
Lb=[1,1];
Ub=[1000,1000/60];
x0=Lb+(Ub-Lb).*rand(size(Lb));

options=optimset('Algorithm','active-set','Display','iter','TolFun',1e-08);

[x,fval]=fmincon(@objfun,x0,A,b,[],[],Lb,Ub,@nonfun,options);

end

function f=objfun(x)

material=[1 70 2710;2 100 8600;3 120 8800;4 170 7400;5 31 2400;6 210 7850;7
110 4500;8 12 720;9 190 7800];

prompt='How many number of element?'
NE=input(prompt);

prompt='How long is the beam in m?'
Length=input(prompt);

prompt='What is the design load?'
Load=input(prompt);

prompt='What is the material of the beam?
(Aluminium[1],Brass[2],Bronze[3],CastIron[4],Concrete[5],Steel[6],Titanium[
7],Wood[8],WroughtIron[9]) '
y4=input(prompt);
if (y4==1);
    Modulus = material(1,2);
    Rho = material(1,3);
elseif (y4==2);
    Modulus = material(2,2);
    Rho =material(2,3);
elseif (y4==3);
    Modulus =material(3,2);
    Rho=material(3,3);
elseif (y4==4);
    Modulus =material(4,2);
    Rho=material(4,3);
elseif (y4==5);
    Modulus =material(5,2);
    Rho=material(5,3);
elseif (y4==6);
    Modulus = material(6,2);
    Rho=material(6,3);
elseif (y4==7);
    Modulus =material(7,2);
```

```

        Rho=material(7,3);
elseif (y4==8);
    Modulus =material(8,2);
    Rho=material(8,3);
elseif (y4==9);
    Modulus =material(9,2);
    Rho=material(9,3);
else
    'Choose from the options given.\n';
end
prompt='What is the shape of the beam?
(Ishape[1]/Cylinder[2]/CylinderTubular[3]/RectangularSolid[4]/RectangularTu
bular[5])';
y5=input(prompt);

if (y5==1);

prompt='What is the design breadth of both flange in mm?'
x_1=input(prompt);

prompt='What is the design thickness of both flange in mm?'
x_2=input(prompt);

prompt='What is the design thickness of the web in mm?'
x_3=input(prompt);

prompt='What is the design height of the web in mm?'
x_4=input(prompt);

A1=x_1*x_2; %area of top flange in mm2
y1=x_4+x_2+x_2/2; %centroid of top flange in mm
A2=x_4*x_3; %area of web in mm2
y2=x_4+x_4/2; %centroid of web in mm
A3=x_4*x_3; %area of bottom flange in mm2
y3=x_4/2; %centroid of bottom flange
centroid_y=(y1*A1+y2*A2+y3*A3)/(A1+A2+A3); %overall centroid

%moment of inertia of part 1
I1=1/12*x_1*x_2^3; % in unit mm4
d1=(x_2+x_4+x_4)-centroid_y; %in unit mm

%moment of inertia of part 2
I2=1/12*x_3*x_4^3; % mm4
d2=(x_3+x_4/2)-centroid_y; % mm

%moment of inertia of part 3
I3=1/12*x_3*x_4^3; %mm4
d3= x_4/2-centroid_y; %mm

Area=(A1+A2+A3)*10^-6; %in m
Imoment=(I1+I2+I3)*10^-12; % in m
x(1)=x_1;x(2)=x_2;x(3)=x_3;x(4)=x_4;

f=(x(1)*x(2)+x(4)*x(3)+x(4)*x(3))*10^-6;
Le=Length/NE;
%Element stiffness matrix of each element

```

```

Ke=Modulus*Imoment*[12,6*Le,-12,6*Le; 6*Le,4*Le*Le,-6*Le,2*Le*Le; -12,-
6*Le,12,-6*Le; 6*Le,2*Le*Le,-6*Le,4*Le*Le]/Le/Le/Le;

%Global stiffness and mass matrix assembly
KGlobal=zeros(2*(NE+1),2*(NE+1));

for ii=1:NE
    KGlobal(2*ii-1:2*(ii+1),2*ii-1:2*(ii+1))= KGlobal(2*ii-1:2*(ii+1),2*ii-
1:2*(ii+1))+Ke;
end

KGlobal(1:2,:)=[];
KGlobal(:,1:2)=[];

FGlobal=zeros(2*NE,1); %This is the empty force vector
FGlobal(2*NE-1)=1*3*(Modulus*Imoment);

deflectionANDslope=inv(KGlobal)*FGlobal %displacement in m,slope results in
rad

Moment=deflectionANDslope(2*NE-1,1)*KGlobal(1:2,:);

Moment1=Moment(1,1);
disp('Max bending moment is :' )
disp(Moment1)

elseif (y5==2);

    prompt='What is the design diameter in mm?'
    diameter=input(prompt);

    Area=10^-6*pi*diameter*diameter/4;

    Imoment=1/64*pi*diameter^4*10^-12;
    Le=Length/NE;

%Element stiffness matrix of each element
Ke=Modulus*Imoment*[12,6*Le,-12,6*Le; 6*Le,4*Le*Le,-6*Le,2*Le*Le; -12,-
6*Le,12,-6*Le; 6*Le,2*Le*Le,-6*Le,4*Le*Le]/Le/Le/Le;

%Global stiffness and mass matrix assembly
KGlobal=zeros(2*(NE+1),2*(NE+1));

for ii=1:NE
    KGlobal(2*ii-1:2*(ii+1),2*ii-1:2*(ii+1))= KGlobal(2*ii-1:2*(ii+1),2*ii-
1:2*(ii+1))+Ke;
end

KGlobal(1:2,:)=[];
KGlobal(:,1:2)=[];

FGlobal=zeros(2*NE,1); %This is the empty force vector
FGlobal(2*NE-1)=1*3*(Modulus*Imoment);

```

```

deflectionANDslope=inv(KGlobal)*FGlobal %displacement in m,slope results in
rad

Moment=deflectionANDslope(2*NE-1,1)*KGlobal(1:2,:);

Moment1=Moment(1,1);
disp('Max bending moment is :')
disp(Moment1)
f=Area;
elseif (y5==3);
prompt='What is the design outer diameter of the tube in in mm?'
diameter_outer=input(prompt);

prompt='What is the design thickness of the tube in mm?'
thickness=input(prompt);

diameter_inner=diameter_outer-thickness;

Area=pi/4*(diameter_outer^2-diameter_inner^2)*10^-6;

Imoment=pi/64*(diameter_outer^4-diameter_inner^4)*10^-12;
Le=Length/NE;

%Element stiffness matrix of each element
Ke=Modulus*Imoment*[12,6*Le,-12,6*Le; 6*Le,4*Le*Le,-6*Le,2*Le*Le; -12,-
6*Le,12,-6*Le; 6*Le,2*Le*Le,-6*Le,4*Le*Le]/Le/Le/Le;

%Global stiffness and mass matrix assembly
KGlobal=zeros(2*(NE+1),2*(NE+1));

for ii=1:NE
    KGlobal(2*ii-1:2*(ii+1),2*ii-1:2*(ii+1))= KGlobal(2*ii-1:2*(ii+1),2*ii-
1:2*(ii+1))+Ke;
end

KGlobal(1:2,:)=[];
KGlobal(:,1:2)=[];

FGlobal=zeros(2*NE,1); %This is the empty force factor
FGlobal(2*NE-1)=1*3*(Modulus*Imoment);

deflectionANDslope=inv(KGlobal)*FGlobal %displacement in m,slope results in
rad

Moment=deflectionANDslope(2*NE-1,1)*KGlobal(1:2,:);

Moment1=Moment(1,1);
disp('Max bending moment is :')
disp(Moment1)

f=Area;

elseif (y5==4);

```



```

prompt= 'What is the design width?'
Width=input(prompt);
prompt='What is the design height?'
Height=input(prompt);
Area=Width*Height*10^-6;
Imoment=Width*Height*Height*Height/12*10^-12;
Le=Length/NE;

%Element stiffness matrix of each element
Ke=Modulus*Imoment*[12,6*Le,-12,6*Le; 6*Le,4*Le*Le,-6*Le,2*Le*Le; -12,-
6*Le,12,-6*Le; 6*Le,2*Le*Le,-6*Le,4*Le*Le]/Le/Le/Le;

%Global stiffness and mass matrix assembly
KGlobal=zeros(2*(NE+1),2*(NE+1));

for ii=1:NE
    KGlobal(2*ii-1:2*(ii+1),2*ii-1:2*(ii+1))= KGlobal(2*ii-1:2*(ii+1),2*ii-
1:2*(ii+1))+Ke;
end

KGlobal(1:2,:)=[];
KGlobal(:,1:2)=[];

FGlobal=zeros(2*NE,1); %This is the empty force factor
FGlobal(2*NE-1)=1*3*(Modulus*Imoment);

deflectionANDslope=inv(KGlobal)*FGlobal %displacement in m,slope results in
rad

Moment=deflectionANDslope(2*NE-1,1)*KGlobal(1:2,:);

Moment1=Moment(1,1);
disp('Max bending moment is :')
disp(Moment1)
    f=Area;
elseif (y5==5);
    prompt='What is the design width of the beam in mm?'
    Width_outer=input(prompt);

    prompt='What is the design height of the beam in mm?'
    Height_outer=input(prompt);

    prompt='What is the thickness of the tube beam in mm?'
    Width_inner=Width_outer-input(prompt);
    Height_inner=Height_outer-input(prompt);

    Area=(Width_outer*Height_outer-Width_inner*Height_inner)*10^-6;
    Imoment=(Width_outer*Height_outer^3-Width_inner*Height_inner^3)/12*10^-
12;
    Le=Length/NE;

%Element stiffness matrix of each element
Ke=Modulus*Imoment*[12,6*Le,-12,6*Le; 6*Le,4*Le*Le,-6*Le,2*Le*Le; -12,-
6*Le,12,-6*Le; 6*Le,2*Le*Le,-6*Le,4*Le*Le]/Le/Le/Le;

```

```

%Global stiffness and mass matrix assembly
KGlobal=zeros(2*(NE+1),2*(NE+1));

for ii=1:NE
    KGlobal(2*ii-1:2*(ii+1),2*ii-1:2*(ii+1))= KGlobal(2*ii-1:2*(ii+1),2*ii-
1:2*(ii+1))+Ke;
end

KGlobal(1:2,:)=[];
KGlobal(:,1:2)=[];

FGlobal=zeros(2*NE,1); %This is the empty force vector
FGlobal(2*NE-1)=1*3*(Modulus*Imoment);

deflectionANDslope=inv(KGlobal)*FGlobal %displacement in m,slope results in
rad

Moment=deflectionANDslope(2*NE-1,1)*KGlobal(1:2,:);

Moment1=Moment(1,1);
disp('Max bending moment is :')
disp(Moment1)
f=Area;
else
    disp('Choose from the options given')
end

end

function [g,geq]=nonfun(x)
g(1) = ((Load*Length^3)/(3*Modulus*pi*x(1)^3*x(2)^2) +
((Load*Length^3)/(8*Modulus*pi*x(1)^3*x(2)))/deflectionANDslope(2*NE-1,1) -1
;% must be less than 0.1mm
g(2) = (2*x(1)/x(2))/60-1; % must be less than 60
g(3) = (Load*Length*2*x(1)/(2*pi*x(1)^3*x(2)))/165-1; % in kPa unit, must
be less than 165 MPa
g(4) = (Load/(12*pi*x(1)^3*x(2)))*(12*x(1)^2+x(2)^2)/186-1; % in kPa unit,
must be less than 186 MPa
geq=[];

end

```

Matlab Multiple Script Code

```
1st script
% File name = tubularbeam_objf.m
% Tubular beam design
function f = tubularbeam_objf(x)
% Rename design variables
x1 = x(1);x2=x(2);
% Set input parameters
L=10; % Length of column (m)
rho = 0.000785 ; % density (kg/m3)
f = rho*L*2*pi*x1*x2; %mass of tubular beam

2nd script
% File name = tubularbeam_conf.m
% Tubular beam design
function [g,h] = tubularbeam_conf (x)
x1=x(1);x2=x(2);
% Set input parameters
P = 4000; % loading(N)
E = 210e3; % Youngs Modulus (Pa)
L =1000; %length of tubular beam (mm)
delta = 0.1; % allowed deflection (mm)
Sb = 165; %#ok<NASGU> % allowed bending stress (MPa)
tau = 186; % allowed shear stress (MPa)

% Inequality constraints
g(1) = [(P*L^3)/(3*E*pi*x1^3*x2^2) + (P*L^3)/(8*E*pi*x1^3*x2)]/delta -1 ;%
must be less than 0.1mm
g(2) = [2*x1/x2]/60-1; % must be less than 60
g(3) = [P*L*2*x1/(2*pi*x1^3*x2)]/165-1; % in kPa unit, must be less than
165 MPa
g(4) = [P/(12*pi*x1^3*x2)*(12*x1^2+x2^2)]/186-1; % in kPa unit, must be
less than 186 MPa

% Equality constraint
h = 0;
```

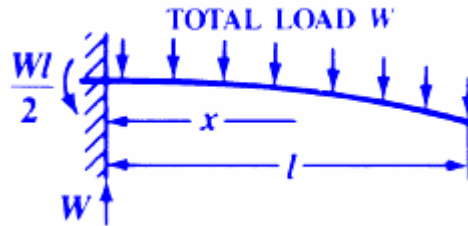
Result Generated Script

```
% File name = flexural_opt.m

% Set options
options=optimset('LargeScale','off','TolCon',1e-8,'TolX',1e-8);
% Set the lower & upper bounds for design variables
Lb = [1 1]; Ub = [500 200];
% Set initial design
x0 = [24 2];
% invoke the constrained optimization routine, fmincon
[x, FunVal, ExitFlag, Output] = fmincon
('tubularbeam_objf',x0,[],[],[],[],Lb,Ub,'tubularbeam_conf',options);
```

Governing Equations

1. For cantilevered beam with uniform load,



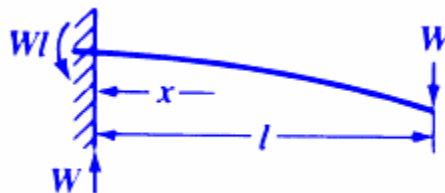
$$\text{Stress at any point, } s = \frac{W}{2Zl} (1 - x)^2$$

$$\text{Deflection at specified point, } y = \frac{Wx^2}{24EI} (2l^2 + (2l - x)^2]$$

Where:

Symbol	Description	Unit(imperial)	Unit(SI)
E	Modulus of elasticity	Psi	N/m ²
I	Moment of inertia	in ⁴	m ⁴
W	Total load on beam	Lbs	N
p	With line pressure load	Psi-in	Nm
s	Stress at the cross section being evaluated	Lbs/in ²	N/m ²
y	Deflection	in	m
Z	Section modulus		
l	Length	in	m

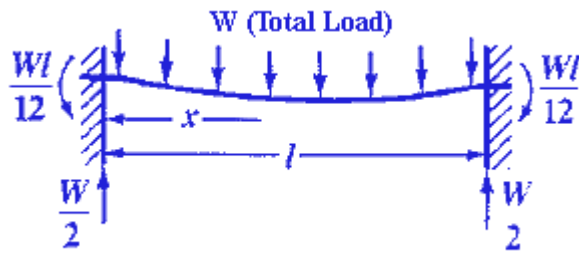
2. For cantilevered beam with a load applied at end,



$$\text{Stress at any point, } s = \frac{W}{Z} (1 - x)$$

$$\text{Deflection at specified point, } y = \frac{Wx^2}{6EI} (3l - x)]$$

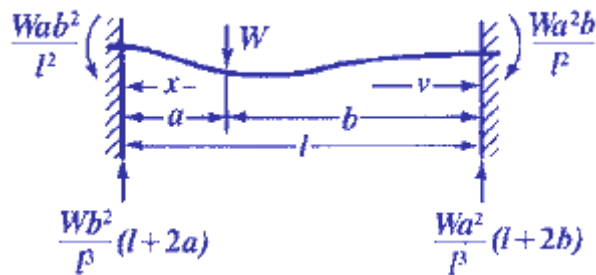
3. Both Fixed End with Uniform Loading



$$\text{Stress at any point, } s = \frac{Wl}{2Z} \left[\frac{1}{6} - \frac{x}{l} + \left(\frac{x}{l} \right)^2 \right]$$

$$\text{Deflection at specified point, } y = \frac{Wx^2}{24EI} (l - x)^2$$

4. Both Fixed End with Point Loading




$$\text{Stress at any point, } s = \frac{Wb^2}{Zl^3} [al - x(l + 2a)]$$


$$\text{Deflection at specified point, } y = \frac{Wx^2b^2}{6EI l^3} [2a(l - x) + l(a - x)]$$

Note: All the 4 pictures above are from engineeredges.com page. The author does not claim any right on the pictures shown.

Standard Dimension for Rectangular and Square Beam

Jumbo Rectangular HSS Dimensions and Properties																
 HSS24 - HSS16																
Shape	Design Wall Thickness, t	Nominal Wt	Area, A	b/t	h/t	Axis X-X				Axis Y-Y				Torsion		Surface Area
						I	S	r	Z	I	S	r	Z	J	C	
						in. ⁴	in. ³	in.	in. ³	in. ⁴	in. ³	in.	in. ³	in. ⁴	in. ³	
HSS24X12X3/4	0.698	171.16	47.1	14.2	31.4	3440	287	8.56	359	1170	195	4.98	221	2850	366	5.80
X5/8 ^c	0.581	144.39	39.6	17.7	38.3	2940	245	8.62	304	1000	167	5.03	188	2430	310	5.83
X1/2 ^c	0.465	116.91	32.1	22.8	48.6	2420	202	8.68	248	829	138	5.08	154	1980	252	5.87
HSS20X12X3/4	0.698	150.75	41.5	14.2	25.7	2190	219	7.26	270	988	165	4.88	190	2220	303	5.13
HSS16X12X3/4	0.698	130.33	35.9	14.2	19.9	1270	159	5.95	193	810	135	4.75	158	1610	240	4.47

^cSection is slender for compression with F_y = 46 ksi.

Jumbo Square HSS Dimensions and Properties												
 HSS22 - HSS10												
Shape	Design Wall Thickness, t	Nominal Wt	Area, A	b/t	h/t	I	S	r	Z	Torsion		Surface Area
										J	C	
										in. ⁴	in. ³	
HSS22X22X7/8	0.814	244.88	67.3	24.0	24.0	4970	452	8.59	530	7890	729	7.10
X3/4	0.698	212.00	58.2	28.5	28.5	4350	395	8.65	462	6860	632	7.13
HSS20X20X7/8	0.814	221.06	60.8	21.6	21.6	3670	367	7.77	433	5870	597	6.43
X3/4	0.698	191.58	52.6	25.7	25.7	3230	323	7.84	378	5110	519	6.47
X5/8	0.581	161.40	44.3	31.4	31.4	2750	275	7.88	320	4320	437	6.50
X1/2 ^c	0.465	130.52	35.8	40.0	40.0	2260	226	7.95	261	3510	355	6.53
HSS18X18X7/8	0.814	197.24	54.3	19.1	19.1	2630	292	6.96	346	4220	479	5.77
X3/4	0.698	171.16	47.1	22.8	22.8	2320	258	7.02	302	3690	417	5.80
X5/8	0.581	144.39	39.6	28.0	28.0	1980	220	7.07	257	3120	352	5.83
X1/2 ^c	0.465	116.91	32.1	35.7	35.7	1630	181	7.13	210	2540	286	5.87
HSS16X16X7/8	0.814	173.43	47.7	16.7	16.7	1800	225	6.14	268	2920	373	5.10
X3/4	0.698	150.75	41.5	19.9	19.9	1590	199	6.19	235	2560	326	5.13
HSS14X14X7/8	0.814	149.61	41.2	14.2	14.2	1170	167	5.33	201	1910	281	4.43
X3/4	0.698	130.33	35.9	17.1	17.1	1040	149	5.38	177	1680	246	4.47
HSS12X12X3/4	0.698	109.91	30.3	14.2	14.2	631	105	4.56	127	1030	177	3.80
HSS10X10X3/4	0.698	89.50	24.7	11.3	11.3	347	69.4	3.75	84.7	578	119	3.13

^cSection is slender for compression with F_y = 46 ksi.