

## Spreadsheet application in beam bending calculations

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**ABSTRACT:** The application of an Excel spreadsheet as an educational tool for beam bending calculations using the Macaulay's method is presented in this article. The authors discuss the advantages of using the spreadsheet in engineering education. The spreadsheet can be applied to both statically determined and indeterminate beams. The calculations of the reactions (both forces and moments), shear force and bending moment, as well as deflections for any of four typical beam end-fixing conditions (simply supported, cantilever, propped and built-in) are demonstrated. The dimensions of the beam, the loads and their location are given as an input by the user. The spreadsheet works as a menu driven program and is designed to be user-friendly. In the article, the authors argue for the use of spreadsheets in beam bending calculations to improve students' understanding and performance in this topic.

### INTRODUCTION

The study of the strength of materials is critical, especially, in the design and construction of any engineering structure, whether mechanical or civil. The study of strains and stresses enables appropriate choices of suitable materials for any application [1]. The theory of beams is indispensable in this context and is the basic concept of strength of materials. The beam theory allows for calculation of beam stresses and deflections.

Experience dictates that for students' learning it is important to couple beam theory with a computational tool which can be used to check manual calculations. That would provide for better understanding of the theory and should generally improve the quality of learning. It is important for such a computational tool to be easily accessible, easy to use and that students can clearly see and understand how it works. All of the above criteria are satisfied by a spreadsheet.

Beam bending, as studied in a general strength of materials course, has been a struggle for generations of engineering students. Even the easiest beam calculations present a challenge for the majority of students when they study beam bending principles for the first time. In the current curriculum of the Bachelor of Engineering programmes at the Faculty of Engineering and Technology of the University of Botswana, beam bending is a part of the core course on Strength of Materials. The course is taken by engineering students of civil, electrical and mechanical disciplines during the second year of their five-year degree programmes.

This article describes the application of a spreadsheet as a teaching tool in solving beam bending problems. The application of such a tool has advantages for both learners and educators. These include a quick attainment of results for complicated problems without having to work through heavy mathematics at every instance. Learners can also use that tool to validate the correctness of their work during private study; thus, improving their ability to work on their own without supervision.

### COMPUTING IN ENGINEERING EDUCATION

Broadly, there are four levels of use of computing in engineering. At the highest level, is the use of high level programming languages like FORTRAN, BASIC, C++, Pascal, etc. Here, the student learns how to write programs for numerical solution of equations. The student must be able to know how to write the code, how to set up the equations and how to solve them so that he/she gives the computer the algorithms to follow in availing him/her the solution. Normally, many engineering students detest this and as pointed out by Wankat and Oreovicz: *Some students will do almost anything to avoid programming* [2].

Equation solving programs, such as MathCAD, MATLAB, TK! Solver, etc, are at the mid-level. Here the student writes the equations and the program lists the variables. On assignment of values to the variables by the student, the computer gives a solution or iterates to give a final one if the student has given an initial trial solution. These programs are easier and quicker to learn. They have already inbuilt algorithms, therefore, the student does not need to know how to solve the equations. But they lack logic capability, cannot do branching and each program must be learnt on its own merit.

Problem specific commercial software, such as CAD programs, ADAMS, SPICE, FLUENT, etc, are at an extreme end of computing tools for engineering. These are powerful and realistic - as they are written for the practicing engineer. However, they are extremely costly and each is unique in its application. Not everyone finds them to be user friendly and they have been reported to encourage the *black box* and the *not invented here* syndromes [2].

Most of the problems associated with the above programs are addressed by the use of generic software, especially, in form of spreadsheets.

## SPREADSHEETS APPLICATIONS

Development of spreadsheet applications since 1979 has simplified many tedious calculations without loss of understanding of the underlying physics of the problems [3]. Computers are increasingly becoming available at low prices - and the spreadsheet program - especially, Microsoft Excel - is almost universally available on these machines.

Spreadsheets are application packages that ease calculations in tabular form. They were originally developed for applications in finance and accounting, but soon entered the engineering education arena [4]. Developed first as VisiCalc by Daniel Bricklin with assistance from Bob Frankstan in the United States in 1978/79, spreadsheets have transformed to include charting, graphical interfaces, pull down menus, and point and click capabilities. Today, Excel spreadsheets are almost universal in the engineering education world. Others include Sun Star Office as used by G. Tabor in examples on Computational Fluid Dynamics [5].

Spreadsheets are characterised by arrays of cells in which data is input either as numbers or text or as formulae. Comments on data in the cells can also be input and hidden if desirable. Because of the mathematical nature of engineering studies, the use in which spreadsheet allows for numerical computations and for creation of good charts makes it the favourite tool for engineers [6]. It is, therefore, not surprising that it has become useful and inevitable tool in engineering education.

Many studies have been performed to show the applications of spreadsheets in engineering. A special issue of the International Journal of Engineering Education published in 2004 was dedicated fully to different forms of application of spreadsheets in engineering education. A comprehensive and instructive review was done by S.A. Oke of the University of Lagos in 2004 [3]. He credits electrical engineers for pioneering the use of spreadsheets in engineering education. Examples of researchers and practitioners in electromagnetism, logic networks, antenna design, microprocessor systems, Fourier series for harmonics analysis, etc, are given. In general engineering, numerical analysis, differentiation, integration and solution of partial differential equations are highlighted.

While in mechanical engineering, research on heat transfer and finite element applications was highlighted. In chemical engineering, work by Rives and Lacks on supplementing analytical methods with numerical methods using spreadsheets applications in teaching process control is cited. A review of spreadsheet applications in electrical engineering is presented by Chehab et al [7]. There are other examples of the use of spreadsheets in different areas of engineering education; electrical engineering [8], environmental engineering education [9], chemical engineering [10][11], energy, thermodynamics and fluid mechanics [12-14]. Tabor discussed the solution of the Navier Stokes equations in computational fluid dynamics for incompressible fluid flow [5].

At the University of Botswana, spreadsheets have been successfully used by Mechanisms and Control Engineering lecturers in solving simple vibrations problems [15], calculating the Routh-Hurwitz coefficients and making the Nyquist and Bode plots for systems with up to five poles [16]. The lecturers described the layout of a well-designed spreadsheet which enhances student understanding of the physics and mathematics behind the programmed equations.

All of the investigations convincingly make an argument that spreadsheets are an ideal tool for engineers and therefore should be used, taught and applied in the process of educating future engineers. The arguments are based on the following points, which can be considered as attributes of commonly used spreadsheets:

- The basics of spreadsheets are easy to learn - typically within one to two hours - much unlike any other computational program.
- The tedium of iterative calculations is easily removed letting the student to concentrate on scenario building and motivating discovery learning at virtually no cost.
- Spreadsheets encourage structured thinking - thus, leading to better thought out solutions to physical problems.
- They are easy to document and debug. Hence, it is much easier to follow the logic of the computations and the solutions.

- Through their charting feature, quality presentations are easily distilled from the mass of numbers that they generate so quickly. Hence, they are a favourite among scientific and business executives.
- They are generic and available almost on every personal computer. Experience in one is adequate to enable a student easily adapt to any other.
- Most important for the student, competency in use of spreadsheets builds confidence and prepares him/her to learn higher level software and programming.
- A skill that can be used in areas outside engineering can be acquired; thereby, enhancing life-long learning. In a controlled experiment by R Venkatasubramanian and Skromme of Arizona State University for example, electrical engineering students who were exposed to Excel spreadsheets solutions in their course reported that they used the method on their own several times elsewhere outside class [17].

Because of these facts, some investigators have actually recommended that spreadsheet literacy should be one of the criteria for admission to an engineering degree course [3].

The main disadvantages of spreadsheets have been reported to be the low speed in cases of very large problems and the difficulty in large scale branching [18]. In fact almost all the above investigators agree that spreadsheets should not completely substitute the higher level software like MATLAB and discipline specific software used in industry. There are other disadvantages of spreadsheets in engineering calculations. For example, Joung cites concrete and costly examples of errors in their applications [19]. The propensity to error stems from the way the equations are entered in the cells. The syntax buries the physics of the problem in parentheses, and for long complex equations, it is very difficult to discover one's own mistake. Studies have also shown that a second checker will miss over 50% of such mistakes [19]. Thus, the argument is for use of spreadsheets in less mission critical calculations in industry and/or where one user develops it for his/her own use - not to be shared with others over big engineering projects.

In engineering education, both undergraduate and below, problems are not always as complex as in the real world in industry. Besides, at that level, in the absence of a spreadsheet, the choice is between manual and high level programming calculations - neither of which is ideal for a start-up learner. The application of the spreadsheet as a teaching tool in beam bending is the best example of such a case.

## BEAM THEORY

A beam is a structural element that is capable of withstanding load primarily by resisting bending. The bending force induced into the material of the beam as a result of the external loads, own weight, span and external reactions to these loads is called a bending moment. Beams are used as simple bridges and also as structures consisting of beams supported on columns. Beam structures are of common usage both in single span and multi-span form. A major advantage is that they lend themselves to prefabrication in elements for ease of transportation and site erection [20].

In engineering mechanics, beam bending refers to the behaviour of certain structural elements in a physical design. An element can be considered a beam, if it is solid and homogenous and its length is many times its height or width. The primary function of the beam is to resist bending; this stands in contrast to structural elements that primarily resist tension, compression or shear stresses. The structural properties of a beam in bending are determined by its dimensions, materials and cross-sectional shape. The calculation of beam stresses and deflections under different loading is a fundamental element of solid mechanics.

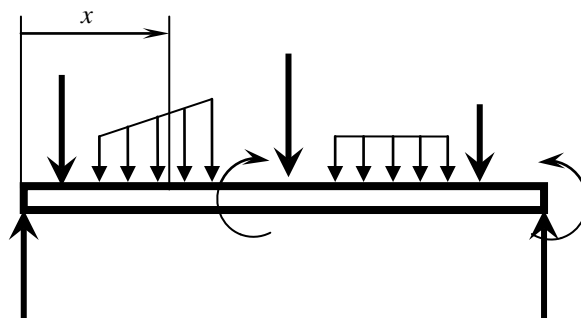


Figure 1: Loaded beam.

The basic equation governing the slope and deflection of beams is given by the following equation:

$$EI \frac{d^2y}{dx^2} = M , \quad (1)$$

where M is a function of x.

When a beam has a variety of loads (Figure 1), it is difficult to apply the above theory because loads may be within the limits of  $x$  during derivation but not during the solution at a particular point. Hence, it is normally necessary to have a separate expression for the bending moment for each section of the beam between adjacent concentrated loads or reactions. Each section will produce its own equation with its own constants of integration. It is appreciated that in all but the simplest cases, the work involved is laborious, the separate equations being linked together by equating slopes and deflections given by the expressions on either side of each *junction point* [21].

The Macaulay's method for the deflection analysis of Euler-Bernoulli beam, subject to multiple or discontinuous loads, is a convenient simplification of solving beam deflection problems. Using Macaulay's notation an expression for the internal bending moment and, hence, curvature, is valid at all locations along the beam and the deflection curve can be calculated by integrating twice with respect to the axial coordinate. The notation prevents the need for matching of multiple constants of integration for the various sections of the beam. Use of Macaulay's technique is very convenient for cases of discontinuous and/or discrete loading. It is the reason that the method was used in preparing the spreadsheet for beam calculations.

## SPREADSHEET SOLUTION FOR BEAM BENDING PROBLEMS

Microsoft Excel is a *number crunching* application, which provides engineers with a very powerful computational tool. Microsoft Excel is widely available (MS Office) and easy to use. Once a few basic skills have been mastered, many spreadsheets may be developed in much the same way as one would proceed with pencil, paper and calculator, but with higher speed, precision and flexibility. Microsoft Excel has a range of functions that can be utilised for the analysis and presentation of results. Interactivity of Excel is hugely extended by the use of the so-called Macro. A Macro is a set of instructions that tells Microsoft Excel to perform one or more actions for programmers. Macros are like computer programs, but they run completely within Excel. That can be used to automate tedious or frequently repeated tasks. Another tool, which will be used in programming Excel is Solver. Solver can handle problems that involve many variables and cells, and can help the user to find combinations of variables that maximises or minimises a target function. It also specifies constraints that must be met for the solution to be valid. Its ability to manage a large number of constraints makes it very useful in solving beam problems, which normally involve systems of equations.

The principle of spreadsheets is to drag and, therefore, repeat a calculation on a point to a large number of points. To be able to take advantage of this feature, it is necessary to proceed with closed form equations. That is why energy method for beam calculations cannot be used in Excel.

The beam bending spreadsheet has been prepared as a tool for use in Fundamental Strength of Materials course in the Faculty of Engineering and Technology of the University of Botswana. It can be applied to both statically determined and indeterminate beams. It calculates the reactions (both forces and moments), shear force and bending moment, as well as deflections for any of four typical beam end-fixing conditions (simply supported, cantilever, propped and built-in). The dimensions of the beam, the loads and their location are given by the user. It gives also the possibility of choosing the modulus of elasticity. The spreadsheet works as a menu driven program and is designed to be user-friendly.

The data for the beam is entered in the input data worksheet (Figure 2). By a click of the mouse, appropriate figures are shown for different support conditions (simply supported, cantilever, propped and built-in) with visualisation in respect of the data labels. The spreadsheet has hyperlinks to text files with theoretical information on the buckling theory. These files can be also reached by clicking on a button. Students may also investigate relationships between different loads, supports and material properties on the reaction forces and deflections. The results are presented in a separate worksheet (Figure 3), which is reached by clicking the appropriate button in the input worksheet.

Units	
length	meter
forces	kN
Moment	kN.m

Geometry	
beam length	20
Abscissa support A	0
Abscissa support B	10
Second moment of area	3600000000 mm <sup>4</sup>
Step	0,1

material properties	
Young Modulus	71,7 Gpa

Concentrated forces					
Force			Moment		
Values	Location		Values	Location	
F1	100	8 K1			
F2	0	0			
F3					

distributed forces					
Force			Moment		
Value	Location		value	Location	
u1	20	3 m1	0	0	0
u2	70	14 m2	0	0	0
u3					
u4					

Figure	Results
Figure ssb	SSB
Figure Cantilever	Cantilever
Figure Propped	Propped Cantilever
Figure Built-in	Built-in beam

Figure 2: Input data worksheet.

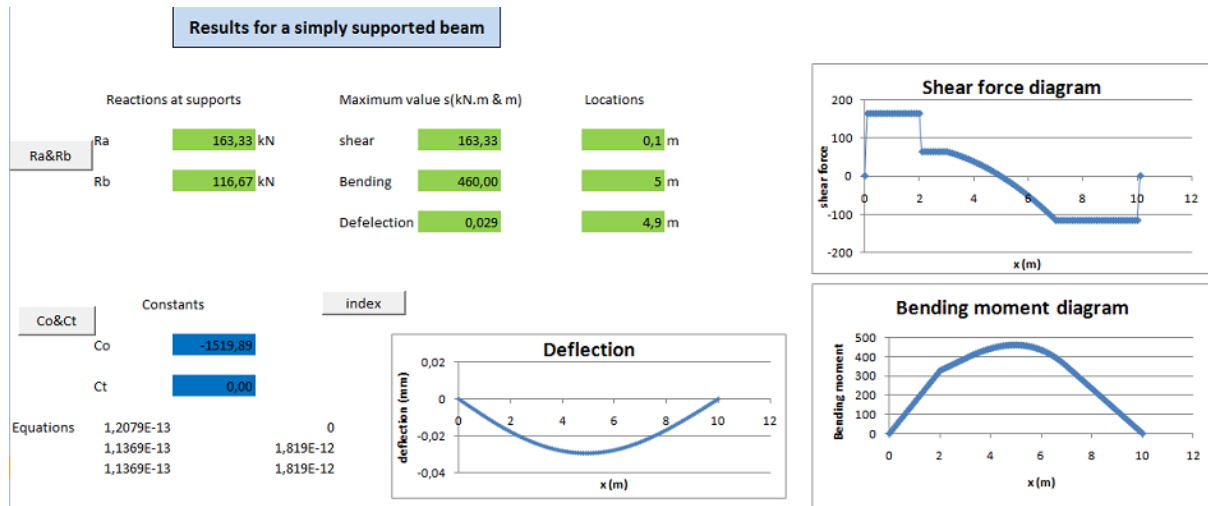


Figure 3: Results worksheet.

There is an additional worksheet available with the name *Processing*, which presents values of Macaulay's functions. In this sheet, functions are evaluated giving its values in a large number of points along the beam. That gives the student an option to see and trace the solution for a particular point on the beam.

## DISCUSSION AND CONCLUSIONS

The work reported here is based on well-known solutions of Macaulay's method in beam calculations. The aim was to create a tool that might be used as a learning aid for students. There was a need for a user-friendly instrument, which would not be viewed by students as a *black-box* that they could not explore. The transparency of a spreadsheet tool helps to avoid any student perception that the work is something beyond his or her reach. The Excel spreadsheet gives the student the ability to manipulate the problem for various conditions and also to see how the calculations are done. It allows the students to introduce variations in the input data and, then, observe how changes in data affect the response. All this demonstrates that spreadsheets are useful and readily available computational tools. They also aid the teaching on how to exploit the in-built functionality of spreadsheets to solve everyday engineering problems without resorting to expensive and specialised software packages. In general, the above shows how effectively a spreadsheet can be used in introducing the engineering concept to students.

In summary, the advantages of such spreadsheets to a distance practicing learner are as follows:

- They are easy to use and apply to real life problems at no cost.
- They bridge the gap between abstract concepts of engineering theory and problem solving.
- There is motivation to structured thinking and analysis in solving engineering problems.
- They are self-confidence building and lead to recognition by work colleagues as some problems get correctly and accurately solved in reasonable time.
- They allow for the acquisition of a skill that can be used in areas outside engineering, and hence, enhancing life-long learning.

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