A New Approach to the Teaching of Structural Mechanics

N. T. K. Lam

Department of Civil & Environmental Engineering, University of Melbourne, Australia

Abstract

This paper illustrates the innovative use of EXCEL spreadsheets for introducing some elementary concepts of structural analysis in undergraduate teaching. The interactive and transparent attributes of the spreadsheet environment have been well exploited. This style of delivery has been extended to solving much more advanced structural analysis problems the illustrations of which have been cited in the paper.

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1. Introduction

EXCEL spreadsheets are widely used in design offices for providing assistances to the design of engineered structures. These spreadsheet programs are typically used for accessing a database of design parameters (for the selection of products, for example) or to expedite the checking of the design against a list of criteria for ensuring code compliances. Essentially, EXCEL have been used as database managers to replace the tedious tasks of looking up design charts and tables manually, and for checking compliances.

This paper is concerned with the application of EXCEL on structural engineering design and analysis, but is exploring the potential usage of the platform for educational purposes. A similar approach can be employed for undertaking more intensive analytical tasks that are traditionally performed by proprietary structural analysis packages. Such potentials of EXCEL that are being explored have not been widely recognised.

The use of EXCEL in educating engineers with elementary structural mechanics is illustrated herein. The conventional approach to the solution of problems in engineering statics (ie. calculation of shear forces and bending moments) would always require solving simultaneous equations for determining the values of

* Corresponding author: Email: ntkl@unimelb.edu.au
the support reactions. It is demonstrated herein that with the use of EXCEL the solution could be obtained very differently by an intuitive approach. For example, the value of a vertical support reaction of a simply supported beam can be determined by trial-and-error until equilibrium is satisfied (i.e. end-moments at free ends approaching zero values). Embodied in this trial-and-error process is the educational objective of having the student to visualize the conditions of equilibrium through graphical display of the forces and moments surrounding the beam whilst different reaction values are being keyed in. Essentially, the focus of attention is on the physical conditions of the beam as displayed graphically, which is in contrasts to the conventional treatment of the problem by linear algebra. This alternative approach to engineering statics is particularly useful to students who are introduced to the concepts for the first time. The teaching of the conventional solution method could be introduced subsequently when the underlying concepts have been well understood.

The conventional method of finding deflections of a beam would require finding the values of constants in polynomial expressions based on pre-defined boundary conditions. When EXCEL is employed, the solution can be obtained intuitively in two steps: (i) deforming the beam with a constant or variable curvature along its length and (ii) rotating the beam (as a rigid-body) in the vertical plane about a support until the beam is levelled with all the supports. The trial-and-error procedure of deforming and rotating the beam about one of its support serves to engage the students into finding the deflection profile by intuition whilst alleviating the need to become heavily involved with algebra. The educational attribute can be further enhanced by the use of interactive graphics display in EXCEL. A similar intuitive approach could be employed for determining the value of the reaction at a redundant (say interior) support through visualizing the beam gradually levelling with the support point as the reaction value is gradually varied.

Another important attribute of EXCEL with engineering education and training is its transparencies. Conventional programming languages such as Fortran, C++, or Visual Basic presents the program algorithm in the usual text format, which is effectively delivering information in one dimension. Elaborate algorithms of large computer programs are therefore difficult to follow. In contrasts, algorithms in EXCEL is the worksheet itself and is delivering information in two dimensions. Algorithms in EXCEL can be introduced by a sequence of worksheets each of which presents a snapshot of the progressive development of a spreadsheet program (from a blank sheet into its final form). The presentation of a worksheet for illustrations to the users can be enhanced in a number of ways including the use of annotations, the colouring of cells (to identify which are the ones for the input of data). Thus, a program in EXCEL can be introduced to users without the need of a user’s manual. Details of every step in the computations are evident in the spreadsheet itself if only row and column operations have been used. This enables users to make modifications to the program customizing specific needs whilst having full knowledge of its operations as well as the underlying computations. The blackbox syndrome of a computer program is hence eliminated.

2. Use of EXCEL for Teaching of Beam Analysis

2.1. Cantilever beam

The teaching of elementary structural mechanics using EXCEL may begin with the cantilever beam to be used for illustrations. For any location on the beam which is measured at distance “X” from its free-end, values of \(<X – X_i>\) are calculated where subscript “i” denotes the the applied point force and \(X_i\) is the distance of the point force measured from the free-end of the cantilever. When \(<X – X_i>\) is a positive value, it is taken to be equal to \((X – X_i)\), or else is taken to be equal to zero. This formulation allows the calculation of shear force and bending moment values to be generalised into simple one-line expressions as shown by
equations 1a & 1b (based on the usual free-body diagram principles and the resolving of forces and taking moment about the point of interest).
\[ SF(X) = \sum_{i=1}^{N} F_i (X - X_i) \] (1a)
\[ BM(X) = \sum_{i=1}^{N} F_i (X - X_i)^2 \] (1b)
where $\theta_i = \frac{F_i(L-X_i)^2}{2EI}$ being slope of beam at the location of load;

Equations 2a – 2b can be combined into the one-line expression of equation 2c to facilitate computations by EXCEL,

$$\delta(x) = \sum_{i=1}^{n} \theta_i (L-x_i) \left\{ \frac{L-x}{L-x_i} - \frac{1}{3} \left( \frac{L-x}{L-x_i} \right)^2 \right\} \left\{ x-x_i \right\}^2 + \left\{ \frac{x-x_i}{L-x} + \frac{2}{3} \left( \frac{x-x_i}{L-x} \right) \right\} \left\{ x-x_i \right\}^0$$

(2c)

Figure 3 shows the deflection profile of the example cantilever beam (see line in bold) based on calculations obtained using equation 2c. Other lines appearing in the figure are deflections attributed to the individual applied point forces. Figure 4 is an annotated image of the spreadsheet that has led to the construction of the deflection profile.

2.2. Simply-supported beam

Next, consider a determinate simply-supported beam which has a second vertical support on the left (where reaction force denoted as $V_L$ is positioned). The approach adopted herein for solving the shear forces and bending moment values is applying minor modifications to the spreadsheet that has been developed for solving the cantilever beam problem. First, the point force positioned on the left hand side of the beam (used for solving the cantilever problem) is now treated as a reaction in support of the simply supported beam. The position of this point force will have to be updated to match with the position of the (new) support point. For example, $X_i = 0$ if the support point is positioned at the end of the beam. The magnitude of this reaction force ($V_L$) to maintain equilibrium could be determined by iterations, or by trial-and-error, until the moment reaction value ($M_R$) positioned at the right hand end of the beam equals zero (given that the fixed-end support no longer exists). It is recommended here in that students introduced to this calculation procedure for the first time be made to go through the trial-and-error procedure for fulfilling the educational objectives of visualising beam actions and the equilibrium of forces and moments. When students have become familiar with the concept, the value of $V_L$ could be found by the conventional method of taking moment about the right hand support position in order that the calculation becomes fully automatic. Cells are coloured in red on the modified spreadsheet (Figure 5) to highlight the value of $V_L$, $V_R$ and $M_R$. Diagrams showing the corresponding load configuration, shear force and bending moment values are shown in Figures 6a – 6c.

![Figure 2](image_url)  
**Figure 2** EXCEL calculations for shear force and bending moment values
The deflection profile could also be obtained for the simply supported beam from exactly the same spreadsheet developed for the cantilever beam except for an extra step. The additional transformation to undertake is a rigid body rotation of the beam about its support point at the right hand end. The amount of rigid body rotation is calibrated (or obtained by trial-and-error) in order that the beam is levelled at the support points at both ends (refer Figure 7). Users introduced to the procedure for the first time is encouraged to apply the trial-and-error process in order to be given the opportunity to visualize spatial compatibility of the deflected beam at the various support points. Alternatively, the amount of rigid body rotation can be calculated by the spreadsheet based on the amount of uplift at the support point in the “initial” deflection profile. Calculation is then fully automated. In essence, little extra work is involved in extending the techniques (developed initially for analysis of a cantilever beam) to solve a simply supported beam.
Reaction $V_L$ calibrated to make $M_R = 0$

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<th>$X &lt;X-X2&gt;$</th>
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Reaction $V_R = -3.44$

CHECK: $V_L + F_2 + F_3 + V_R = -3.56 + 4 + 3 - 3.44 = 0$

2.3. Indeterminate beam

The spreadsheet developed for analysis of the cantilever beam and simply supported beam can be extended further into the analysis of an indeterminate beam which has a third (redundant) interior support as shown in Figure 8a. The point force at $X = 0.6m$ is now used to represent this redundant reaction. The reaction value of 3.75 kN at this support point was obtained by calibration (or by trial-and-error) in order that the beam is levelled with the interior support as well as end supports.

Refer Figures 8b – 8c for the calculated shear force and bending moment diagrams and Figure 9 the deflection profile. Again, little extra work is involved in extending the spreadsheet that has been developed initially for analysis of the determinate beams. The developed spreadsheets could be similarly extended for the analysis of indeterminate beams with more redundant supports and applied point forces.

The spreadsheet procedure for the calculation of shear force, bending moment and deflection values illustrated herein is based only on three expressions: equations 1a, 1b & 2c which can be adapted for solving both determinate and indeterminate beams with redundant supports provided that the conditions of equilibrium and spatial compatibility have been ensured.

3. Discussion and Conclusion

The use of EXCEL in undertaking structural engineering computations have been demonstrated in this paper. At the elementary level, the analysis of determinate and indeterminate (continuous) beams can be analysed by an intuitive approach which alleviates the need of going through tedious algebraic calculations. This is made possible by the interactive nature of EXCEL in the presented trial-and-error procedure. What have been demonstrated in this paper were only some examples of the applications of EXCEL on
elementary structural analysis of beams. At the intermediate level, the analysis of lateral resisting elements in the building including moment-resisting frames, structural walls and wall-frame elements are well within the capability of EXCEL by virtue of its built-in matrix operational functions (and this will be described in a chapter written by the author in a E-book which is under preparation). At the advanced level, time-history simulations of the dynamic response of structural systems can be undertaken by a forward marching algorithm that could be implemented easily on EXCEL. The solution of eigenvalues and eigenvectors in the dynamic modal analysis of a multi-storey building involving iterations are also well within the standard row and column operations of EXCEL as illustrated by Lam et al. (2010a). EXCEL could also be used for simulating the response of structures to low velocity impact as illustrated in Lam et al. (2010b) and for calculating the moment curvature relationship of cracked reinforced concrete sections as illustrated in Lam et al. (2010c).

Figure 6  Shear force and bending moment diagrams of example SS beam
Figure 7 Deflection diagram of example SS beam

(a) Loading configuration

(b) Shear force diagram

(c) Bending moment diagram

Figure 8 Shear force and bending moment diagrams of indeterminate beam

Another important attribute of EXCEL is its transparencies in that the program algorithm is the worksheet itself. As shown in the illustrations of some complex programs the algorithm of an EXCEL program can be presented by a sequence of worksheets each of which shows a snapshot in its progressive development. Thus, EXCEL programs can be made intelligible to the potential users without the need of
writing up a user’s manual as is done conventionally with programs developed and implemented on other platforms.

![Deflection profile changes interactively as value of redundant reaction is varied](image)

**Figure 9** Deflection diagram of indeterminate beam

**References**

